CITRUS ROOTSTOCKS: THEIR CHARACTERS AND REACTIONS

(an unpublished manuscript)

ca. 1986

By

W. P. BITTERS
(1915 – 2006)

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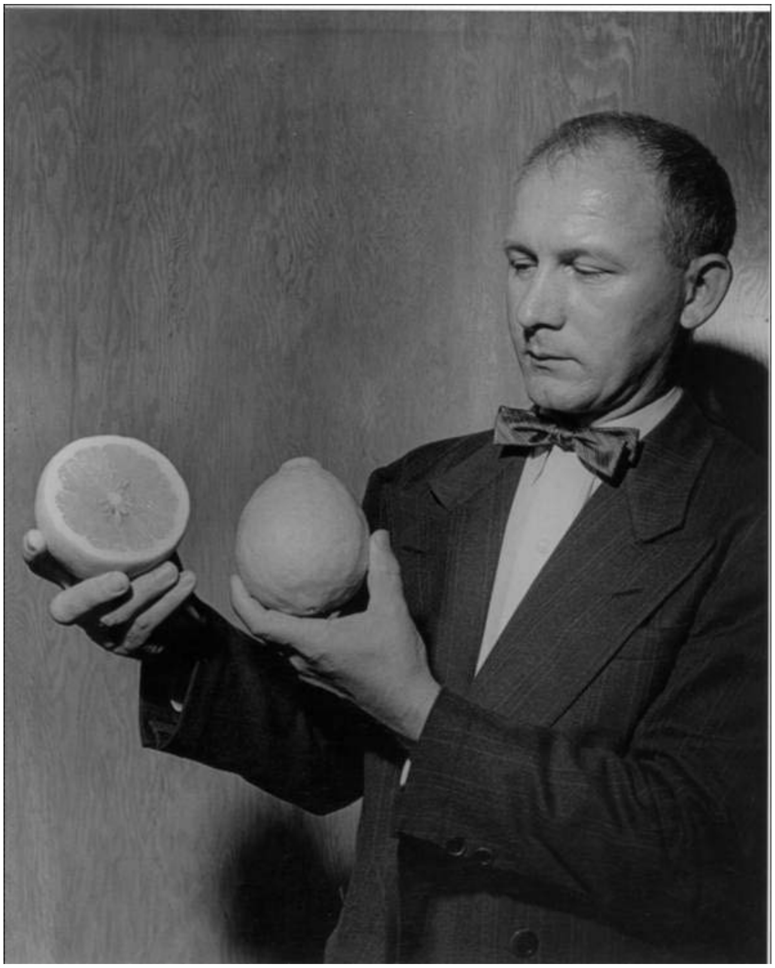

ca. 1955

ca. 1970

IN MEMORIUM

Willard P. Bitters

Professor of Horticulture, Emeritus
Riverside
1915-2006

Born in Eau Claire, Wisconsin, in June, 1915, Dr. Willard “Bill” Bitters earned his bachelor’s degree in biology from St. Norbert College and his master’s degree and Ph.D. from the University of Wisconsin. After earning his doctorate, he first worked as the superintendent of the Valley Research Farm of the University of Arizona in Yuma, and joined the Citrus Experiment Station, in Riverside in 1946 as a Horticulturist. In 1961, Dr. Bitters became a Professor in the newly established University of California-Riverside.

His initial assignment was to work on horticultural aspects of tristeza, a serious vector-transmitted virus disease which threatened to destroy California citrus orchards. Tristeza was already in California and spreading in 1946. At that time most citrus trees in California were grafted on a rootstock that was known to be susceptible to tristeza. Dr. Bill Bitters was responsible for screening of over 500 cultivars to determine which rootstock-scion combinations were resistant to this disease and yet possessed suitable horticultural characteristics. Of the 500 screened, most were susceptible, but several successful ones were selected and released to the industry. Among these were ‘Troyer’ citrange and *Citrus macrophylla*, which continue to be important rootstocks worldwide. The industry greatly benefited by such releases. Another important contribution was his developmental work with ‘Flying Dragon’ trifoliate rootstock, which is able to dwarf most standard cultivars by 90 percent, making them easier to harvest.

Perhaps Dr Bitters’ most important contribution was his work with the Citrus Variety Collection. Herbert John Webber, the first director of the Citrus Experiment Station, had initiated and overseen the Citrus Variety Collection up until his death in 1944. When Dr. Bitters became the curator of the collection in 1947, it had been somewhat neglected. Dr. Bitters was instrumental in increasing the number of accessions in the collection from 600 to 1200. This collection is still recognized as one the major collections of citrus genetic resources in the world. During his time working with the Citrus Variety Collection, Dr. Bitters traveled extensively throughout the citrus growing regions of the world. He became known as a world authority on citrus scion and rootstock cultivars, and was well versed in many other areas of citriculture. Dr. Bitters was the author of 99 publications of significant benefit to citrus researchers and growers throughout the world. In 1967, Dr. Bitters received the Annual Citrograph Award in recognition of his many outstanding contributions resulting in the utilization of rootstock and scion varieties that produce improved tree growth and fruit quality.

After his retirement in 1982, Dr. Bitters continued to work with other University of California Riverside researchers to improve the quality of the Citrus Variety Collection, advise others working in citriculture, and to serve the public through the University of California Cooperative Extension Master Gardeners Program.

He was a member of many academic organizations, including the American Society of Horticultural Science, the International Society of Citriculture, the Japanese Society of Horticultural Science, and the California Lemon's Men's Club.

Tracy L. Kahn
Carol J. Lovatt
Robert R. Krueger
Jodie S. Holt

EDITOR'S PREFACE, DIGITAL VERSION

Substance and Context

The Citrus Experiment Station, established in 1907, is the world-eminent citrus research center, and its publications were consulted by citrus growers and scientists everywhere. The Citrus Experiment Station undertook a revision of The Citrus Industry, originally published 1943-1948, in the early 1960's. This was to be a comprehensive landmark work that included all the Citrus Experiment Station research up to that time, as well as research from other citrus scientists from around the world, in all areas of citriculture.

Dr. W. P. Bitters (1915-2006) began his career at the Citrus Experiment Station in 1946. His assignment was to study citrus rootstocks, their disease resistance, and their graft compatibilities with various commercial citrus varieties. Dr. Bitters undertook a series of comprehensive experiments that involved hundreds of trees, at three different locations in California, and lasted more than 20 years. This was truly a historic and landmark undertaking, never done before, and never repeated. It is still considered the seminal research on citrus rootstocks. Over the years Dr. Bitters became renowned as a world authority on citrus rootstocks and many other areas of citriculture. The published results from his experiments, and personal consultation until his death, form the basis of all current experimentation on citrus rootstocks.

A chapter on citrus rootstocks by Dr. Bitters was to be part of the 5th volume of the The Citrus Industry, revised edition, 1967-1989. Ultimately the chapter was not included, and efforts to publish it as a separate volume were not successful. After Dr. Bitters' death in 2006, a typescript draft of this chapter was found among his papers. It was determined that this draft was the latest. Dr. Bitters ceased work on the manuscript ca. 1986. This monograph is a comprehensive work on citrus rootstocks, not only reporting the results of Dr. Bitters' landmark experiments and research, but aggregating and correlating those results with all other known experiments on citrus rootstocks from all over the world, a truly landmark work. The bibliography alone is a significant historical record of citrus rootstock research from every part of the world, and includes many references to published materials that have rarely, if ever, been referenced elsewhere. The monograph also includes unpublished research results from Dr. Bitters work, and from various growers' experiments, observations, and experiences.

Dr. Tracy Kahn, Curator of the UC Citrus Variety Collection and longtime friend and colleague of Dr. Bitters, suggested digitizing the manuscript. Permission to publish an electronic edition of this unpublished monograph was granted by Dr. Bitters in his lifetime. Subsequently, Dr. Kahn received permission from Dr. Bitters' heirs to publish a digital version. She brought the manuscript to Marty Nemeth, a librarian retired from the UC Riverside Science Library (now the Orbach Science Library), who was responsible for previous digitization efforts.

Condition of the Manuscript

The manuscript is a typed carbon (2 copies), double-spaced, on yellow paper. It consists of 17 headed sections, including an introduction and a bibliography, in 262 consecutively numbered pages with no hand-written annotations, so there are no questions about how the material should be organized. Tables are included as part of the text. There are some blank spaces and lines, indicating an intent to complete the thought or reference at a later date. In addition, some text references lack dates and/or lack a corresponding entry in the bibliography. There are references to figures, but no images in any format are attached or specifically designated for inclusion. Some sections were added subsequent to the main portion, and are not as polished, but nonetheless contain invaluable information and unpublished data from Dr. Bitters' experiments and observations.

Editorial Practices

In general, the editorial guidelines used were those of copy editing only.

All editorial annotations are in italics within brackets.

Copy editing:

Copy editing guidelines: all spelling errors have been corrected, without annotation; punctuation was inserted, where appropriate, without annotation; occasionally, if a word was needed to clarify the meaning of a sentence, it was inserted without annotation (beyond that no rewriting was done); the author's phrasing, word selection, and general style were not altered and no annotations of "[*sic*]" were made; blank lines in the manuscript, which were left to indicate the intent to complete the sentence or thought at a later editing, were indicated by an explanatory annotation; the numerous textual bibliographic references to unpublished materials, many without date, were not included in the bibliography because there is insufficient information to identify or verify them.

Fact checking:

- All citrus names, geographic areas, technical terms, etc were checked and have been corrected, without annotation.
- All references were verified; corrections were made where necessary, without annotation.
- References in the text for which there are no dates (just authors) and/or for which there are no corresponding items in the bibliography, were identified, where possible, by correlating information in the manuscript with the referenced item in hand, and the verified items were added to the bibliography without annotation.

Illustrative materials:

- Some photographic slides, among the hundreds that were among Dr. Bitters' papers, were identified as corresponding to references in the manuscript; these are included in this digital version.
- Figures have been numbered consecutively throughout to avoid confusion. Those figures that lack corresponding images, either because of copyright restrictions or because images could not be located, are annotated.

The typescript of the draft monograph from which this digital version was made, and all editor's working papers can be viewed on request. Please contact Dr. Tracy Kahn (tracy.kahn@ucr.edu) or Toni Siebert (toni.siebert@ucr.edu) if you would like to view the manuscript or have any comments on this digital version.

Marty Nemeth
Editor, digital version
January, 2012

INTRODUCTION

Many varieties of Citrus grown commercially will reproduce reasonably true to type from seed through a phenomenon known as nucellar embryony as described by Frost and Soost (1968). These include sweet orange, Rough lemon, Cleopatra mandarin, Troyer citrange and others. Other varieties such as the pummelos, citrons, Algerian tangerine, Temple orange, etc. are monoembryonic and will not reproduce true to type from seed since they only produce hybrid progeny. Still others, such as certain lemons, Mexican lime, nansho-daidai, yuzu, etc. have relatively low polyembryony. On the other hand, some varieties such as the Washington navel orange, Bearss lime, Satsuma mandarin, and Pixie mandarin are seedless, or nearly so, and it would be impossible to obtain seed in adequate quantities.

Seedling trees of most varieties are vigorous upright growers, extremely thorny, and are late in coming into bearing. Many citrus species and varieties also do not inherently possess adequate hardiness to cold, resistance to soil-borne diseases, tolerance to salinity or high water tables, and other desirable qualities that would enable them to survive long in their planted environment as seedlings. Consequently, some are therefore occasionally propagated by some vegetative means such as cuttings, layers, or marcots, but generally by grafting or budding onto a rootstock of some closely related variety, species, or even genera, or hybrids thereof, to take advantage of the rootstock's influence. The latter method is the one generally used in the propagation of citrus varieties, and the general technique is described by Platt and Opetz (1973).

The rootstock and the scion interact with each other to produce stionic effects which may have a three-way influence. First, there is the influence of the scion upon the stock. For example, the scion may increase the sodium uptake of the rootstock. Lemon scions may also increase the susceptibility of the rootstock to gummosis. The depth of root penetration or the extent and configuration of the root system may vary on a given rootstock, depending upon the scion variety budded upon it.

The rootstock may greatly alter the scion. It may dwarf or invigorate it. Yields may be increased or decreased; fruit size may be altered; fruit quality can be affected; hardiness of the scion may also be influenced; and maturity and precociousness of the scion are other considerations.

The union of a stock and a scion may give rise to a combination which may be affected by an external factor which by itself affects neither the stock nor the scion individually. Such a situation exists when the virus disease tristeza is present. The sweet orange by itself is not measurably affected; the sour orange by itself is not viscerally affected. However, when sweet orange is budded upon sour orange and tristeza virus is present, the combination will decline or die from the disease. If sour orange is budded upon sweet orange, there is no expression of the disease, even though the virus is present.

While it has long been recognized that the stock and scion have a reciprocal influence on each other, there must be a certain affinity or congenial relationship between them for healthy development of the composite plant.

Different rootstocks vary in their adaptability to grow on different soils and under different climatic conditions, as well as with different scion varieties. All of these factors will be thoroughly discussed in depth individually at a more appropriate place in this monograph.

It is ridiculous to assume that any one rootstock will have the general qualities to meet each grower's needs, yet each individual grower's specific rootstock need is a critical choice for the success of his orchard. The successful choice of a rootstock is important because it is to be a permanent part of that orchard and cannot be changed at will like a cultural practice, a fertilizer program, and irrigation schedule or pest control procedures.

A considerable fund of information has accumulated in recent years throughout the citrus producing regions of the world concerning rootstock reactions under different conditions. A recent comprehensive, but concise, review of much of the body of knowledge has been made by Wutscher (1979). The last previous detailed treatment of the subject was by Webber (1948) and Batchelor and Rounds (1948).

The purpose of the present monograph, therefore, is that it will emphasize the importance of careful rootstock selection for different commercial citrus varieties. It is an attempt to evaluate the response of the rootstock to the influence of its total environment; describe the difficulties commonly encountered in choosing desirable rootstocks; stress the need not only of considering the results of scientifically planned field experiments, but also the findings and observations of discriminating growers; and review critically the results of rootstocks and related experiments. In addition, much original data and observations on trials conducted by the writer during a 40 year period at the Citrus Research Center of the University of California, Riverside are presented. These are based on nearly 500 rootstocks and 100,000 trees grown by the author and supplemented by numerous observations in commercial orchards throughout the world.

THE IMPORTANCE OF CHOOSING SUITABLE ROOTSTOCKS

It is just as important to use carefully selected rootstocks of superior performance as it is to use selected superior fruit varieties. The selection of a rootstock should be for the purpose of enhancing the merits of a scion variety, or adapting it to its total environment, rather than merely to follow local custom. The selection of improved fruit varieties has been in progress for centuries, but the choice of the best rootstocks to use has not received much attention prior to a hundred years ago, and most of it has been in the last fifty years. Although propagation by budding and grafting was understood many centuries ago in China and elsewhere, it was mostly considered a curiosity rather than a practical measure, and most commercial citrus trees throughout the world were grown as seedlings.

Schenk (1962) states that citrus was budded in China before the time of Christ. The author finds this acceptable but extremely difficult to document. In Han Yen-chih's "Chü Lu" written in 1178 A.D., and translated into English in 1923, he does describe the grafting process. However, he does indicate the method for grafting trees will be found in the work called "Ssu Shih Tsuan Yao," which I have not been able to find a record of. Greek and Roman references are numerous.

According to Condit (1951*a*, 1951*b*) the grafting and budding of fruit trees were common practices in the time of Theophrastus, who said, "The ingrafted part uses the other as an ordinary plant uses the ground. Whenever they have split the trunk, they insert the scion which they have fashioned to a wedge-shape; then with a mallet they drive it in to fit as snugly as possible." Virgil in his Georgics and Ecologues, according to Condit (1951*a*, 1951*b*), provided an explicit as well as a poetic account of grafting. Briefly it is as follows: "Nor is there one sole way to graft and bud, for where young eyes from the trees bark swell forth, bursting their slender sheaths, a slit is made just as the knot; and here they fasten in the shoot from stranger tree and bid it thrive in the moist sapwood. Or, smooth trunks are gashed and wedges through the solid timber driven. Then fruit scions set; in no long time the tall trees skyward lifts its laden boughs and sees with wonder what strange leaves it bears and fruitage not its own." According to Gallesio (1811), Palladius, who is thought to have written at some time in the 5th century states, "They graft the citron in April in warm districts and in May in colder latitudes, placing the graft not upon the bark, but opening the stem or trunk near the ground." Also, wood cuts from Ferrari's "Hesperides" (1646) clearly show the grafting technique being practiced in an ancient herbarium (Figure 1).

In the early history of citrus culture, especially in the western world, consumption of the fruit was principally restricted to the area in which it was produced. As faster and more convenient transportation developed, new consumer markets developed, which in turn stimulated new plantings. New plantings created new problems. Probably the general use of grafted or budded trees first became an accepted practice as a result of the outbreaks of "foot-rot," (mal-di-gomma, gummosis) in the middle of the 19th century, as pointed out by Fawcett (1936) as it occurred in the Azores in 1834.

It was observed in the Mediterranean area that the sour orange was resistant to the disease and could be successfully used as a rootstock in place of the susceptible sweet orange varieties.

The introduction of seedless commercial varieties such as the Valencia Orange, Pera, or Marsh grapefruit to the industry also gave impetus to propagation by budding. Since the middle of the 20th century, considerable attention has been given to the choice of the best rootstocks for the different varieties and soil conditions. However, for the most part, relevance has been placed on the results obtained in a given area with one stock, or at best with only two or three others for comparison. For nearly half a century in California, rootstock choice was based on the adage, "Use sweet orange on the light soils and sour orange on the heavy soils." If a rootstock gave commercially successful results, it was generally considered satisfactory, with little incentive to search for a better one. This attitude still prevails in many citrus producing countries today. The greater part of the information available in any locality, with reference to successful stocks, was based on the experience of the growers, and often this is the most reliable available. It must be recognized, however, that such local experiences are inadequate, as they do not include replicated trials with a sufficient number of stocks or scion sources over a long enough period of time to supply valid comparisons. This is a situation which has prevailed in nearly every citrus growing area, but since the 1940's growing emphasis has been given to systematic trials, especially in the United States and Brazil.

Probably the one single factor which has given more impetus than any other to the recent emphasis on citrus rootstock trials around the world is the occurrence of tristeza, and the intricate response of various stock-scion combinations to its presence. While the disease has primarily affected the sweet orange and certain other scions on sour orange rootstock, many other rootstocks and combinations can be affected. See the section on tristeza elsewhere in this monograph.

Studies on the etiology of tristeza focused greater attention on other diseases caused by transmissible agents which are often influenced in their reaction by certain rootstock-scion combinations or the rootstock itself (Wallace, 1978). The inroads of disease usually necessitate growing citrus where other citrus has previously grown, and the complex replant problem becomes a serious consideration. Rising production costs economically demand greater production per acre either in tons of fruit or pounds of soluble solids. Greater production necessitates new markets and the competition increases demands for better quality fruit, both for fresh fruit and for concentrate or other purposes. In order to solve these problems, it becomes increasingly necessary to obtain the greatest production at the least possible cost. To achieve this one needs a healthy, productive, long-lived tree. It is increasingly evident that one of the most basic factors in achieving this end is the use of the best available rootstock. The initial cost of a good tree is no more than a bad tree; but it sure makes a difference over the life of the orchard.

ROOTSTOCKS COMMONLY USED IN THE PAST

Since rootstock requirements in the different citrus growing regions of the world widely differ, it is not surprising that there is, and has been, a wide range of diversity in citrus rootstocks used throughout the world.

Fawcett (1936) pointed out the resistance of the sour orange (*Citrus aurantium*) to gummosis or foot rot after the disease had decimated trees on sweet orange rootstocks (*Citrus sinensis*) in the Azores about 1834. Also see Klotz (1978), and Klotz and Calavan (1969), or the section on disease later on in this monograph. This discovery led to sour orange rootstock being the most widely used in most of the Mediterranean areas of Europe and Africa, in South America and the United States, and to a lesser extent in Australia, Central America, Mexico, the Caribbean, Iran, Iraq, Jordan, etc. The occurrence and spread of tristeza (Bitters and Parker, 1953; Wallace, 1978), a virus disease which is insect transmitted and affects principally various scions on sour orange rootstock, precluded its general establishment in South Africa, and later rapidly eliminated plantings in Brazil, Argentina and other countries of South America, in California and Florida, and more recently in Spain and Israel. Sour orange may still be the world's leading rootstock because of existing plantings as yet unaffected by tristeza, especially in certain of the Mediterranean countries, western and northern South America, Central America, Mexico, and the Caribbean. However, the use of sour orange as a rootstock is rapidly decreasing because of the imminent threat of tristeza to all citrus areas.

The discovery of mal secco disease in Sicily about 1923 (Fawcett, 1936; Klotz, 1978), to which the sour orange rootstock is particularly susceptible, has discouraged somewhat its use for lemon plantings in that area. The disease is caused by a fungus (*Deuterophoma tracheiphila*) and rootstock resistance would be desirable. The future of sour orange in California, where mal secco does not occur, appears to be limited to certain types of Lisbon lemon, because of phloem necrosis with Eureka types and sour orange necrosis (Schneider *et al.*, 1978). The sour orange never became established as a rootstock in Japan, China, and Taiwan, which grow predominantly mandarin types of citrus, because growers for decades were aware the two were not congenial—perhaps, again, due to the presence of tristeza disease.

In the United States during the early citrus developments in both Florida and California, sweet orange seedlings (*Citrus sinensis*) were commonly used. In the period after 1870, the expansion of commercial orange growing in Florida included the topworking of scattered areas of sour orange seedlings growing wild in that state. The success of these top-worked groves in the often imperfectly drained but rich "hammock" lands of eastern Florida focused attention to the success of sour orange as a rootstock for sweet orange varieties. When gummosis became prevalent in sweet orange seedling orchards, the sour orange was generally adopted as a rootstock. Later experience in Florida indicated that the sour orange stock was not satisfactory on the deep, well drained, very sandy soils of the "ridge area" in the central part of the state, nor in the shallow oolitic limestone soils of the southeastern coastal section. Thus, it came to be that the Rough lemon (*Citrus limon* or *C. jambhiri*) became the dominant stock until the 1970's. At that time it became clear that a disease known as "blight," or "young tree decline (YTD)" was particularly devastating on Rough lemon stock (Wutscher, 1979; Reitz, 1974).

In California, budded trees were first employed instead of seedling trees after the introduction of the Washington navel in 1873 and the Chapman Valencia in 1876. Sweet orange was commonly used as the rootstock because at that time there were thousands of sweet orange seedlings in the Riverside area and probably very few sour oranges. After 1900, the sour orange and the sweet orange were used almost equally, with the predominant use of the sour orange in the heavier soils and the more saline and calcareous soils of the desert and adobe soils elsewhere. After 1920 the tendency was somewhat away from the sour orange, especially for lemons and oranges, but not for grapefruit. Thus, more sweet orange rootstock was probably used in California than elsewhere. There was very little use in Florida and in South Africa. The identification of the virus nature of tristeza by Fawcett and Wallace (1946) almost completely eliminated the further use of sour orange in California. The threat of tristeza around the world to trees on sour orange rootstock will result in complete replacement of this rootstock in the very near future.

About 1952, the trifoliate orange (*Poncirus trifoliata*) and a hybrid, the Troyer citrange, were introduced to the California growers (Batchelor and Bitters, 1952), and the use of sweet orange has since been on a marked decline. In California, trees on sweet orange stock would not generally be grown by the nurserymen today, except on special order. There may still be some interest in South Africa, but it cannot be used in areas where gummosis is a serious hazard. In spite of the fact that there is no problem with tristeza, sweet orange is now almost completely replaced by other rootstocks.

Until recently, Rough lemon was probably the world's second leading rootstock behind sour orange. Rough lemon has long been used in India, where it is commonly known as "jambhiri" and other names. In South Africa it was in use before 1900 due to the failure of sour orange stock because of tristeza. It is frequently referred to there and in Australia as the "citronelle." Rough lemon had been extensively used in Florida for many years in the sandy "ridge" section and along the southeast coast. However, in recent years the incidence of "young tree decline" (YTD) or "blight" on this stock has almost eliminated its use in Florida (Reitz, 1974; Wutscher, 1979). It was never widely used in California except in the sandy soils of Coachella Valley, and most plantings since about 1950 in the sandy soils around Yuma, Arizona are predominantly on this stock. Recent decline of trees on Rough lemon stock in the Yuma area are a matter of great concern. The decline appears to be principally from the severe incidence of gummosis, which was probably aggravated by their cultural practices and irrigation methods. *Citrus volkameriana*, Pasq. used in Italy and Sicily since the mid-l900's as a mal secco resistant stock for lemons, is one of the many Rough lemon cultigens. It would best be called the "Volkamer" lemon and not "volkameriana." This cultivar is not recognized as a valid species by Swingle (1943), Tanaka (1954), and Hodgson (1961), or anyone else. Tests show that it has exactly the same isozyme pattern as the type specimen of Rough lemon, which suggests that it is not a hybrid. Taxonomically the variety should be referred to as *C. limon* under the Swingle system and *C. jambhiri* under the Tanaka system.

The grapefruit (pomelo), *Citrus paradisi*, has not been used extensively as a rootstock. Although tried to some extent in Florida, it did not gain favor, and this is also true in California. In California perhaps its best performance was with lemon tops, but its low and variable yields, its erratic performance, and its sensitivity to tristeza with orange scions have all but eliminated its use as a rootstock anywhere. To some extent it may still have some limited use in some of the citrus growing areas of the Caribbean.

The pummelo, or shaddock (*Citrus grandis*) has never been used commercially as a rootstock, although it may have been tried experimentally in a few areas—the

Philippines, Indonesia and parts of the Malayan archipelago. The fact that the species is monoembryonic and produces only hybrid seedlings indicates variability would have been the most serious problem. As a rootstock the species is extremely susceptible to tristeza, which would further remove any consideration. The Cuban shaddock is an obvious hybrid. It differs from the regular shaddocks in that it is highly polyembryonic and that as a rootstock it is tolerant to tristeza. In the early 1900's it saw limited use as a rootstock in Cuba, and hence the name. It was incorporated into the 1927 rootstock trials at the Citrus Experiment Station, Riverside, but its performance was only mediocre and did not result in any commercial plantings. An ornamental citrus nurseryman in California does use it as a dwarfing stock for some of the Citrus varieties he grows.

The trifoliate orange, *Poncirus trifoliata*, has been used for decades in Japan as a rootstock for Satsuma mandarin (Unshiu) and other mandarin and pummelo types. Japan grows over 400,000 acres of citrus on this stock, making it the principal user of trifoliate orange. The People's Republic of China also has extensive plantings, principally mandarin, but some oranges and miscellaneous. In Taiwan it is also very popular. These countries predominantly use the "small-leaved" ("small-flowered") strains of the trifoliate orange as rootstocks. This rootstock has been used sparingly in Australia, Argentina, South Africa, Spain and Turkey, but is now seeing extended usage. Most plantings were in subtropical areas where there was always a threat of frost. This rootstock's cold hardiness, precociousness, and disease resistance have been its biggest assets. When interest was high in the United States about 1900 regarding establishing a Satsuma mandarin industry along the coast of the Gulf states, the trifoliate orange was also introduced and tried as a rootstock. The introduction of citrus canker and the freeze of 1916-1917 essentially eliminated all orchards and the use of the stock, except for a limited area south of New Orleans, Louisiana. In California, old orchards on this stock were a curiosity and most were seriously affected by exocortis. Large commercial plantings did not start until around 1950 after the seriousness of tristeza was recognized, accompanied by the release of nucellar strains of the major varieties which were free of exocortis. In some areas of Japan, for some reason, it has been a relatively short-lived stock, necessitating inarching with Yuzu (*Citrus junos*) at an early age. Since about 1980 in California there has been interest in the Flying Dragon strain as a true dwarfing rootstock and high density plantings. Also in Australia, considerable interest involves the use of selected trifoliate orange strains inoculated with a graft transmissible agent (GTA) to attain controlled dwarfing or "viroidal dwarfing" as it may be called. All these aspects of the trifoliate orange will be discussed in detail at more appropriate sections of the text.

The mandarins (*Citrus reticulata*) have not been widely used as rootstocks. In the People's Republic of China, the Ponki and Sunki have been principally used, although the Ponki is not used today. Taiwan also uses the Sunki (Suen Kat). The Cleopatra mandarin has been used to a slight extent in Florida, particularly on the heavier soils, but it did not gain favor in Texas or Arizona. In California it was used to a limited extent after 1950, but that use has declined, although a few plantings may still be made on saline or alkaline soils. The Empress mandarin (a selection of Ponkan) was used sparingly as a rootstock in South Africa. Ponkan types have been occasionally used to a very limited degree elsewhere. Interest has persisted in the Philippines in the use of mandarin stocks, and current interest for nearly the past 50 years is centered on the Calamandarin. The taxonomic status of the variety is not known. The heen-naran and the nas-naran have occasionally been used in India.

The limes (*Citrus aurantifolia*) have been frequently tried as rootstocks, but few have endured. The East Indian lime (Mexican lime, or Kaghzi of India) has been used to some extent in Iran and Egypt and in a few other areas, but mostly with little success or commercial importance. In Israel, the Palestine sweet lime (*Citrus limettioides*) was the most commonly used stock for over a half century. Because of xyloporosis, it was short-lived and was inarched with sour orange at an early age. Both it and the sour orange are susceptible to tristeza and the recent occurrence of this disease has forced Israel in pursuit of new rootstocks. The sweet lime has also been used to some extent in Egypt, where it is sometimes referred to as the Beledy, or Egyptian sweet lime. The mitha of India and Pakistan appear to be identical to the Pakistani sweet lime, as is the lime dolce. The Columbian lime, the Gallego lime, and one used in Iran are similar. Some use has been made of the stock in the sandy soils of Central Florida. It is no longer a rootstock of major commercial importance.

The so-called Japansche citroen is an acid mandarin type probably identical to the Rangpur lime. It was used to a limited extent in Indonesia prior to World War II, but its present status there is not clear. Since the 1950's, the Rangpur has been the major rootstock in Brazil, where nearly a million acres are planted on it. The Rangpur lime created some interest in Texas because of its salt tolerance—but since it is a rootstock sensitive to cold, the freezes of the 1950's and 1960's have altered that. The Kusaie lime is nothing more than a light-colored Rangpur type and gives a comparable response.

The commercial lemon types do not make satisfactory rootstocks because of extreme susceptibility to gummosis, tristeza, and frost. The true sweet lemons, or limettas, such as Millsweet, and Limonette de Marrakech, are extremely sensitive to tristeza and have never been accepted as rootstocks.

The citron (*Citrus medica*) has frequently been tried as a rootstock, probably because of its vigorous nursery growth. It perhaps gained its greatest acceptance in Egypt and India, but has briefly been tried in Cyprus, Greece, Turkey, the Philippines, and elsewhere. The China lemon, a citron hybrid, was tried briefly as a rootstock in Florida and California about 1900 or before, and was not generally accepted. Trees on citron rootstock are very short-lived because of gummosis and xyloporosis. It no longer is a common practice to use them as rootstocks. Some of the citron hybrids such as Kharna khatta, have gained greater acceptance, but are still of very limited commercial importance.

Within the papeda group, Yuzu is used to some extent in Japan, either directly, or, in some areas where trifoliate orange has not performed well, it is used as an inarch. The Alemow (*Citrus macrophylla*), has been widely used as a rootstock for lemons in California, but with no other scion varieties because of tristeza.

Specific details on all the various rootstocks, good or bad, are discussed in a later section of this monograph.

WHY USE ROOTSTOCKS?

The question is frequently asked, “Why use rootstocks for growing citrus trees? Why not use seedlings or cuttings and avoid all the problems associated with the bud union?” Certainly, seedlings or cuttings would be easier to grow as compared to conventional nursery propagation practices, and could be obtained in a shorter period of time. With most *Citrus* cultivars the seedlings in general come highly true to type from seed and provide a uniform clonal progeny to be used as rootstocks, an asset which few other tree crops possess. However, cultivars of the shaddock, Temple orange, Bearss lime, Clementine mandarin and others are monoembryonic and produce only variable progeny. Many of the most important citrus cultivars like the Washington navel orange, the Satsuma mandarin, the Shamouti orange, the Valencia orange, Ovale orange, Berna orange, and others, are seedless or nearly so, and could not provide adequate amounts of seed for propagation purposes. However, even with varieties which are highly polyembryonic one can find considerable variation in the progeny when large populations are grown. Reasons for this variation are not always clear (Cameron and Frost, 1968; Frost and Soost, 1968). The author had occasion in the 1950’s to observe the Hughes orchard near Orlando, Florida, which consisted of 20 acres of seedling Valencia oranges. The tree to tree variation was surprising. The author has also observed other seedling populations of Valencia cultivars in California and noted similar variations, although some were very slight. In one of my experimental projects to develop nucellae, I grew seedlings from 25 Washington navel orange cultivars. While most of the clonal selections produced a highly uniform progeny, a few clonal selections produced only apparent gametic seedlings or worthless offsprings from somatic variation. Similar seedling variations have been observed with other major varieties such as grapefruit or lemons, to a greater or lesser extent.

Although most citrus varieties are nucellar and true to type, some of the pink pigmented varieties found in selections like the Thompson Pink grapefruit, Burgundy grapefruit, Dobashi-beni satsuma, Puka valencia, Perry valencia, Newhall navel, Sarah, and others, are periclinal chimeras in nature, and the color factor is not transmitted through the seed even though nucellar embryony has occurred (Cameron and Frost, 1968).

Cameron and Frost state that many forms of citrus and their progenitors may have reproduced almost entirely through nucellar embryos from remote antiquity. Differentiation of varieties, in such a group as the sweet orange, may have occurred mainly by somatic change without frequent sexual reproduction. The low variability among the true lemons, similar to the sweet orange, may also represent mainly somatic variation. Mandarins, however, have a broader genetic base and suggest more differentiation by sexual reproduction. However, even here we must point out the almost excessive variation in the Satsuma, Clementine, and Willow Leaf mandarins.

Citrus seedlings, including nucellars, exhibit marked juvenile characters. They are exceptionally vigorous and soon attain excessive heights. They are also excessively thorny, and the thorns may be exceedingly long. Seedlings of some species or varieties are considerably delayed in coming into bearing. In the case of the seedling valencias grown at the Citrus Experiment Station at Riverside, it was 13 years before the trees first flowered and fruited, and it was nearly 20 years before they set any kind of a commercial crop. There is also a tendency for the seedlings to alternate bear more than budded trees, at least in the early fruiting years. Grapefruit seedlings will come into bearing sooner than Valencia orange seedlings, so there are species and varietal differences as well as climatic, cultural, and perhaps rootstock, influences. Seedlings have been reported as being more prone to uprooting by high wind velocities, and this might he associated with their excessive height rather than with the anchorage of the tree. If seedling orchards were to be grown, they would certainly be restricted to only a few cultivars, with sufficient merit to withstand the total environment to which they would be exposed. Seedling orchards have been grown for centuries and the early citrus industries of California and Florida were based on seedling orchards. Today, seedling orchards persist in only a few countries. The Mexican lime (West Indian) is still to be found as seedling orchards in Mexico, the Gold Coast, and elsewhere. The Calamondin in the Philippines is still grown as a seedling for reasons which will be discussed later. The advantages of using rootstocks over seedlings has become quite obvious and has been the standard practice for nearly the past hundred years, not only with citrus, but with most fruit tree crops.

What about marcots or cuttings? They avoid many of the disadvantages of seedlings. Cuttings are clonal propagations and they are therefore uniform. They do not show the juvenile characteristics of seedlings and therefore are not excessively vigorous, nor are they excessively thorny. Also, since they are non-juvenile, they will come into bearing at an early age and do not generally display the alternate bearing phenomenon so characteristic of nucellar seedlings. There is also ample vegetative growth within an orchard to provide sufficient cutting propagating material to establish new orchards.

There are also, however, disadvantages to cuttings or marcots. They are somewhat difficult to handle as aerial cuttings or in a cutting frame. Some cultivars root with ease, others with more difficulty. The root systems are generally not typical of the species or variety. While most seedlings produce tap roots, the author has observed that most citrus cuttings generally produce a large abundance of lateral roots, which persist under orchard conditions even in trees 30 years old.

Marcots have been used occasionally to propagate the Bearss lime in Florida. They are used much more extensively in the orient, for example Thailand, Indonesia, and the People's Republic of China, where they are commonly used to propagate the pummelo and other citrus varieties. Pummelo orchards established in this fashion have been quite successful in those countries, and may be even more successful than those propagated on rootstocks, particularly when poor drainage or high water tables are an important consideration.

Cuttings of several major scion varieties were included in the 1927 rootstock trials at the Citrus Experiment Station, Riverside. The results were quite variable (see section on yield and tree size later in this monograph). In general, the cuttings were smaller, shorter, and more spreading in habitat than their rootstock counterparts. Best performance was obtained using Valencia orange cuttings (six replications of five trees each). Tree size and yield were essentially identical to Valencia trees budded on sweet orange rootstock. When the trees were pulled after 34 years of age, the root systems were very similar. Where sweet orange could effectively be used as a rootstock, Valencia cuttings could be a practical substitution (consult section on roots later on in this monograph).

The situation with navel cuttings in this experiment was quite different. As compared to navels on sweet orange stocks, the cutting trees were much smaller in size, shorter, and more spreading in habitat on three replications of five trees each. The yields were less, but somewhat comparable. The root systems, however, varied widely. The cuttings had only two or three large laterals which ran parallel to the surface of the ground with little or no penetration below a depth of two feet.

The grapefruit cuttings in these trials (three replications of five trees each) were also stunted compared to their counterparts on grapefruit root, and were perhaps more spreading in habitat than any of the other scion cuttings. The root systems were intermediate between those of Valencia and navel, yields were quite good, and grapefruit cuttings could certainly be considered for use in any area where grapefruit seedlings or rootstocks could be used.

The lemon cuttings were a complete failure and few lived to any advanced age. These cuttings were made before citrus diseases were well understood. Not only were the cuttings very susceptible to gummosis, but after a few years they also broke out with shellbark, greatly adding to their rapid rate of decline. A description of shellbark may be found in Calavan (1947) and Klotz (1973), or later in this monograph. Some lemon cuttings were also used as stocks for the navel and Valencia scions. Not only were the lemon cutting rootstocks susceptible to the above diseases, but the lemon scion was in addition carrying *Psorosis*, and the navel and Valencia scions broke out with psorosis symptoms at an early age (see Figure 2). Such combinations in this planting were also susceptible to tristeza, and the trees were also more easily injured by cold.

In the early history of Troyer citrange as a rootstock in California, cuttings were made by the nurserymen from the Troyer seedlings because of the temporary shortage of Troyer seed sources. Generally, scions budded on the Troyer cuttings performed quite well. In one orchard in Tulare County in which both Troyer seedling and cutting rootstocks were used, the cuttings gave a poorer performance, but probably because they were planted in a lower portion of the orchard where drainage was a problem. In a few instances in California, Troyer cuttings were made by nurserymen from seedlings already budded to old-line scion varieties. Unfortunately, the old-line scions were carrying the exocortis viroid, and although the cuttings were disbudded and were later rebudded to nucellar lines, they were already contaminated with the disease and the resultant progeny were worthless. A great deal of caution needs to be exercised when cuttings are used as rootstocks, as compared to where scion cuttings are used exclusively.

REQUIREMENTS OF A SATISFACTORY ROOTSTOCK

There are certain characteristics a rootstock must have, in addition to the effects it produces upon a scion variety, that make it qualify as a satisfactory rootstock:

1. There must be good compatibility or congeniality between the stock and the scion. Actually, the union of a stock and a scion is an artificially induced symbiosis; each must depend upon the other and contribute whatever is necessary to carry out the physiological or metabolic functions necessary to sustain each other.

2. The union of the two symbionts must be strong mechanically. There must be complete and orderly union of their tissues to produce complete continuity of the vascular system at their interface to provide free movement of water, nutrients and other substances across this transition zone. Often times this is not accomplished, and breakage or decline of tissues may occur at the union even at a somewhat advanced age.

3. The combination must be long-lived, both physiologically and morphologically. For some reason, certain combinations may be healthy and productive for a period of 10-15 years and then decline for unknown reasons. Other combinations remain healthy and productive for 50-60 years or even longer. Such combinations may display dwarfing or vigorism, and either may not be a factor in the longevity of the combination, but the tree size factor does exist.

4. The rootstock should be adapted to the soil in which it is to be grown. There is a wide range in soil types, which may vary widely in fertility, and trees on such soils have marked differences in excesses or deficiencies of certain elements. Some rootstocks are very susceptible to chlorosis on heavy soils or calcareous soils, while others fare poorly on imperfectly drained soils. In other areas, salinity may be a problem. Nutrient uptake varies widely with rootstocks.

5. The rootstock should be as hardy as the scion variety. Most of the world's important citrus areas have a frost hazard. The author has observed instances of frost damage on young trees in which the rootstock or bud union area was seriously damaged but the scion variety was not immediately affected.

6. The rootstock seedlings should be easily handled in the nursery. This includes ability to withstand transplant shock from the seedbed to the nursery. Seedlings of *C. amblycarpa* in particular, and to a lesser degree, seedlings of Cleopatra mandarin, fall in this shock-susceptible category. Seedlings should be vigorous in the nursery, with a tendency to develop a strong central leader and a minimum of lateral branching. Seedlings of Rough lemon, Troyer citrange, and *Citrus macrophylla* fall in this group. On the other hand, seedlings of Sampson tangelo and grapefruit, for example, are prone to excessive branching and require considerable suckering in the nursery. Seedlings should also attain good stem caliper early so that the diameter is suitable for early budding and a minimum of staking is needed.

7. The rootstock variety should have a high degree of polyembryony. This will assure uniform progeny in the nursery and require a minimum cullage of seedlings. Rough lemon, sweet orange, *Citrus macrophylla*, and Troyer citrange fall into this class. On the other hand, seedlings of *Citrus taiwanica*, Sacaton citrumelo, as well as many others, which possess low polyembryony and are extremely variable, require considerable cullage in the nursery.

8. The cultivar to be used as a rootstock should be both fruitful and seedy so copious amounts of seed can be obtained. Under California conditions, the Morton citrange is fruitful, but not seedy. One of the promising citrange rootstocks (our code C-32) is neither fruitful nor is it very seedy (see discussion on citranges later in this monograph). Fortunately, rootstock cultivars like Rough lemon, Rangpur lime, Troyer citrange, trifoliate orange, and others, are both fruitful and seedy and can provide ample amounts of seed.

9. The rootstock to be used in a given area must be tolerant or resistant to the various pest and disease organisms to which it will be exposed. Obviously, one should not plant a tristeza-susceptible rootstock in a tristeza area. Likewise, if oak-root fungus is a problem, a rootstock resistant to that disease should be used. And so it goes with other diseases or soil organisms like nematodes.

10. The rootstock, in addition to its other qualities, should foster high fruit yields of the scion variety to be used. Within a clonal scion variety, yields may vary as much as 100 per cent from one rootstock to another.

11. Preferably the rootstock should enhance the quality of the fruit of the scion variety. This would include better shaped fruit, smoother texture, better color, higher solids, more juice, higher acidity, less rag, less granulation, more bouquet, and, in most situations, larger fruit sizes and other associated factors.

12. Possibly two thirds of the world's citrus areas are irrigated (Reuther, 1976). The others depend upon natural rainfall, which typically may not be evenly distributed throughout the year, so that there are alternate wet seasons and dry seasons. Consequently, on rain-fed soils, it is highly desirable that the rootstock possesses some drought resistance. Some rootstocks display this characteristic more than others.

Castle (1984) emphasizes some of these aspects as well, but also points out other considerations which may involve the rootstock and the total orchard complex. No one rootstock may possess all of the above qualifications. Under the particular circumstances that exist, a grower may need to choose one rootstock for one scion variety and a different rootstock for another. His orchard rootstock may need to differ from that of his neighbors. The rootstock having the best or the principal requirement to best respond to the total environment in his orchard is the most satisfactory rootstock to use. Citrus culture in any given region will always require a number of rootstocks, having a wide range of characteristics in order to adapt to the range of pests, diseases and ecological conditions prevailing.

RELATION OF NUCELLAR EMBRYONY TO CHOICE OF ROOTSTOCKS

One of the factors of prime importance in the selection of citrus rootstocks is the degree of nucellar embryony shown by different varieties and species, and even different genera. Since the seedlings developed from nucellar embryos are produced directly from the tissue of the mother plant without the intervention of cross-pollination and fecundation (Frost and Soost, 1968), they are likely to be as uniformly like the mother plant as they would have been if the propagation had been made by cuttings, and they will all generally show a normal and typical root development.

It is clearly a marked advantage to use a rootstock variety that will reproduce the parent type as nearly true to type as possible by such propagation. Since the embryos developed by cross-fecundated egg cells are likely to be variable, owing to the commingling of genes of different parents, it is evident that the larger number of nucellar embryos developed, the greater will be the proportion of seedlings having the same characters as the mother plant. Citrus nurserymen are interested in the trueness to type of the rootstock cultivars—not the zygotes which may be only of interest to the geneticist.

Different *Citrus* species, varieties and hybrids, as pointed out by Webber (l900*a*, l900*b*, 1932*b*), Frost (1926), Toxopeus (1930), Torres (1936), Ueno, Iwamasa, and Nishiura (1967), Frost and Soost (1968) Cameron and Frost (1968), and others, show considerable difference in the number of nucellar embryos developed. For one who is deeply interested in the subject, all references should be checked. The best summary of the subject is that of Frost and Soost (1968) in Table 4-2. Of great concern to the nurserymen, however, are such discrepancies as the Citrus Research Center (CRC), Riverside, reporting 54 per cent nucellars for Rough lemon, whereas Torres reports 98 per cent, and a 43 per cent rate for Red lime (Rangpur) at CRC, whereas everyone anticipates its nucellar rate as being in the 90 per cent range. The author spoke to Dr. Cameron about this problem, and he assured me he felt that such instances were due to the low number of seedlings examined at CRC for those varieties.

Parlevliet and Cameron (1959) postulated that one principal dominant gene controls the occurrence of polyembryony, and that a recessive gene is present in homozygous condition in monoembryonic individuals. Studies by Iwamasa, Ueno and Nishiura (1967) generally agree with those of Parlevliet and Cameron, although some geneticists may question this.

Furusato (1957), on polyembryonic studies in *Citrus*, found with three cultivars that the mean embryo number varied with position on the tree, fruits on the north side of the tree having a higher embryo count than those on the south side of the tree. Mean embryo count was also higher in fruits from old trees than on young trees. The embryo count also tended to be higher in a year of abundant fruit yield than in a year of poor yield. Cameron and Garber (1968) pointed out that identical twin hybrids of *Citrus* x *Poncirus* arise from strictly sexual seed parents and that identical twins can commonly appear in monoembryonic types.

Bitters, *et al*. (1972) demonstrated that multiple embryos can be obtained from monoembryonic types by excising the nucellus tissue from the young ovule and growing the explant on a nutrient media under sterile conditions. In this experiment, trifoliate orange was used as the marker pollen. The zygotic embryos were recognized in the egg sac and excised out and grown to maturity. All of these (ten per cultivar) showed the trifoliate leaf character and fruit character. However, all the plants derived from the nucellus (ten per cultivar) proved to be different and not as good as the parent plant when grown in the field to fruiting. Not only were lack of the seedlings within the cultivar different, but none of them displayed any trifoliate orange characteristics. The changes had to be due to somatic variation, as the seedlings were not zygotes.

Esen and Soost (1971) have shown that a high percentage of triploids (3 N) commonly occur in polyembryonic diploid types as a result of the doubling of the chromosome number of the female gamete. Nishiura, Iwamasa and Ueno (1974) report on a monoembryonic trifoliate orange. They indicate that the recessive genes causing monoembryony are present in heterozygous condition in the trifoliate orange. When the flowers from such heterozygous parent trees are self-pollinated or cross-pollinated, monoembryonic hybrids, homozygotes with recessive monoembryonic genes, can arise to some extent through gene recombination, together with polyembryonic hybrids and nucellar seedlings. They conclude that the monoembryonic trees were of zygotic origin.

Nakatani, Ikeda, and Kobayashi (1978) indicate that a higher percentage of hybrid seedlings may be obtained from a highly polyembryonic variety when grown under high temperature conditions. The total number of embryos per seed are reduced and the percentage of zygotes increases. Ohta and Furusato (1957) found heteroploid seedlings to be a frequent phenomenon in citrus. Most of these plants were 2 N + 1, some were 2 N + 2, and only one 2 N + 3. These seedlings were weak and probably would be discarded in culling from the seed bed to the nursery row. They also found some mixoploid tissue in the root tips.

In 1948, I made a large rootstock planting at Baldwin Park, California, to ascertain rootstock reaction to tristeza (Bitters and Parker, 1953). The planting consisted of six tree plots with four replications and Valencia orange scions. Alternate trees were inoculated with tristeza, the others served as checks. The rootstocks included a number of trifoliate orange selections, and in particular, a triploid trifoliate. Very poor tree performance was obtained on the tetraploid trifoliate orange which could not be attributed to the tristeza inoculations, or any other factor. A few years later, Dr. F. E. Gardner, then Director of the USDA-ARS-Horticultural Station at Orlando, Florida, also made some plantings on this same source of tetraploid trifoliate. These plantings were in the absence of tristeza and a few years after planting Dr. Gardner reported to me obtaining very poor unexplainable performance on this rootstock. In the early 1960's when I first visited Japan, Dr. Masao Iwamasa (now at Saga University) also informed me that a tetraploid trifoliate (of different origin than the CRC source) also gave unsatisfactory performance in Japanese trials with Satsuma. There is no logical explanation as to why a tetraploid rootstock should not perform well with a diploid scion based on cytological or anatomical compatibility. Perhaps Furusato (1953*a*, 1953*b*) provides the most plausible answer. Tetraploid trifoliate plants usually have leaves of a darker green color, thicker, and more leathery, larger stomata, and perhaps most important, the main root was thicker and the number of lateral roots was considerably smaller than in the diploids. In a number of citrus groves Furusato found stunted, poorly developed, slow growing trees; this poor performance could not be attributed to other factors. The poor trees were shorter in height, had smaller branches, the trunk diameter was smaller, and the number of fruits per tree was markedly reduced. On the tetraploid stocks the scions had smaller leaves, which curled inward and were of a lighter green color. The smaller fruits were firmer in texture than those on diploid stocks. Furusato states that tetraploid seedlings occur so frequently in *Poncirus trifoliata* that they cause serious loss to the groves' owners. The tendency to produce tetraploid seedlings is not just limited to the trifoliate orange, and perhaps neither is the character of the tetraploid root system.

The nature of a tetraploid root system could have far-reaching implications. Recently, there has been great interest in somatic hybridization. This technique is based on fusing two distinct protoplasts (rather than gametes) to create an asexual hybrid which may be impossible to obtain by conventional methods because of incompatibility of the two parents. If the fusion occurs between two diploid protoplasts, then the resultant somatic hybrid is a tetraploid. Recently, according to Bender (1987), Dr. Jude Grosser of the University of Florida's Lake Alfred Station has succeeded in developing somatic hybrids of *Severinia buxifolia* and *Citrus sinensis*. The hybrids are tetraploids with 36 chromosomes. Thirty-year-old grapefruit trees of *Severinia*, at the Citrus Research Center, Riverside, had the weakest root systems I ever saw. How they sustained the scion physiological, or structurally, to keep the trees from blowing over in a wind, I'll never know. Thus with an inherent poor root system which may be further reduced because of the tetraploid nature, Dr. Grosser may find it essential, or desirable, to grow haploid plants of both parents so that the haploid protoplasts can be fused to produce the normal diploid hybrid. The important point to make is that here is a method that is successful in producing hybrids which heretofore have been impossible to create. The facts are, however, that there are different phenotypes of *Severinia*; that Washington navel and Valencia orange as well as Eureka and Lisbon lemons are incompatible on *Severinia*; that oranges on *Severinia* are susceptible to tristeza. These are problems which may be overcome. Such hybrid rootstocks will not be proven and gain grower acceptance overnight; it may take decades more of research.

Esan (1973) showed that the chalazal end of the monoembryonic nucellus has an inhibitor present which prevents nucellar embryo formation in monoembryonic citrus types. When the chalazal end of a monoembryonic ovule is "grafted" onto the apical end of the nucellus of a polyembryonic type, the rate of formation of nucellar embryos is reduced. This inhibitor ought to be extracted and identified, as the compound could be useful in breeding experiments with certain species. The number of embryos produced is thus not always an indication that a variety is nucellar or that all multiple embryos are alike. In those varieties producing few nucellar embryos, such as the lemon varieties Eureka and Lisbon, most of the embryos and resultant seedlings would normally be developed from fecundated egg cells. However, those producing a large number of embryos, such as the Rough lemon, would have only a few seedlings developing from fertilized egg cells because in most instances the zygotic embryo aborts, perhaps from inability to compete with the nucellar embryos for nutrients, or maybe there is an inhibitor present. Recently, Torres, Soost, and Mau-Lastovicka (1982) have reported on the use of citrus isozymes as a means of distinguishing nucellars from zygotic seedlings. The use of the isozymes and the practice of excising the zygotic embryo from out of the young ovule before the zygote aborts should aid in producing and identifying a higher percentage of zygotes without the long delay of planting them in the field and waiting for fruiting for more positive examination. The author has felt that for too long the citrus rootstock breeder has sacrificed merit for convenience. In other words, rootstock crosses have been made knowing a higher percentage of hybrids would be obtained with the parents used, irrespective of the horticultural and pathological benefits of the two parents involved. For more detailed information on nucellar embryony, readers are advised to consult Cameron and Frost (1968) and Frost and Soost (1968).

Nucellar embryony is not peculiar to citrus, but for rootstock purposes most other tree crops do not possess and utilize this useful advantage. Some apples such as *Malus* *sikkimensis*, and most mangos, *Mangifera indica*, have this characteristic, but so far no commercial advantage has been made of this attribute.

In the reproduction of certain first-generation hybrids from highly nucellar types, such as the Sampson tangelo and many of the citranges, it has been found that the seedlings in the second generation come as true to type of the first-generation seedlings as if they had been grown from cuttings. In one experiment, 37 seedlings of the Sampson tangelo, grown at the Citrus Experiment Station, Riverside, from fruits taken from a tree open to free cross-pollination, exhibited, at the age of 12 years when in full fruit, almost no recognizable variation. This is an important point to stress. Seedling population of many highly nucellar cultivars may show slight deviations in characters, although they may all be typically Washington navels, Valencia oranges, or Troyer citranges. These slight differences will be in vigor, slightly larger or smaller fruit sizes, earlier maturity, fruit quality, etc. Perhaps these differences may not be due to the fact that they are hybrids, but there might be some slight somatic changes which cause these minute differences. Likewise, progenies of other rootstock cultivars, consisting of several hundred seedlings each from Rough lemon, Palestine sweet lime, and the Savage, Cunningham, Rusk, Morton and Coleman citranges up to three years of age, were found to be similarly uniform. Seedlings of the Sanford citrange, however, exhibited great variation and nucellar embryony is apparently less frequent or wanting. Seedlings of the Sanford citrange, in addition, show a high percentage of bark scaling when they got older, similar to psorosis. Seedlings of the Poorman's orange also exhibit a bark scaling. Seedlings of *C. taiwanica*, Yuma citrange (Sacaton citrumelo) and some of the Ichang hybrids, for example, also show a low rate of polyembryony and severe cullage is needed in the nursery. Cultivars with a low nucellar rate should probably not be used as rootstocks. However, it is possible that if the nucellar seedlings are of considerable rootstock interest, clonal propagation by *in vitro* methods could be considered in the future.

In varieties that produce a fairly high percentage of nucellar embryos, most of the seedlings can be recognized as representing the largest proportion of the progeny. They will have the same foliage and branching characters and will in general be of about the same size. They present a uniform and, commonly, easily recognizable type. Mixed with these will be a varying number of seedlings that show different characters, such as different branching and larger or smaller leaves, and that are usually less vigorous and of smaller size. However, in some instances occasional seedlings are more vigorous than the norm. Variations in trifoliate hybrids may be more difficult to detect because the trifoliate leaf character is dominant and all the hybrids exhibit the trifoliate leaf character. Here, in addition, one must look for size of leaves, leaf color, the tendency towards deciduousness, and other factors as well. These differences from the norm, in a large part, are the so-called "variant" seedlings which apparently are mainly produced from gametic embryos. It is these small, off-type seedlings or extremely vigorous seedlings which are variants and should be discarded upon removal from the seedbed, or later in the nursery row, in order to obtain uniform seedlings for use as rootstocks. In spite of all precautions, some zygotic seedlings do escape culling and are budded and ultimately end up as orchard trees. Some of these, but not all, may be culled out as budlings in the nursery row because of lack of uniformity as compared to the rest of the progeny. It is unfortunate that most of the people involved in the labor or nursery practices are not trained or qualified to recognize variants. They probably do a better job on the elimination of "goose necks" and "bench roots," which in reality may not be as important.

Seedling progeny of some of the monoembryonic cultivars such as Algerian tangerine and a number of shaddock cultivars, although all genetically different, have been remarkably uniform in the seedbed and nursery. When budded to standard scion varieties and planted in rootstock experiments at the Citrus Experiment Station, Riverside, most of the trees at 33 years of age were as uniform in size, appearance, and yield as those budded on nucellar seedlings of other varieties. Certain inherent characteristics persist in the progeny, however. Some seedlings of Algerian tangerine, shaddock, Poorman's orange and others continue to show a variable percentage of the seedlings with a bark disorder. In testing numerous shaddocks as rootstocks for tristeza resistance, the fact that every stock was genetically different did not influence the reaction to tristeza. All were susceptible.

Many of the citrus relatives which are monoembryonic also display a high degree of uniformity when grown from seeds. Thus *Clausena*, *Murraya*, *Triphasia*, *Citropsis*, and other genera will, although possessing one zygotic embryo, produce progeny which appear phenotypically identical to the mother plant.

THE IMPORTANCE OF STRAIN SELECTION, CERTIFIED SEED SOURCES, AND NOMENCLATURE WITHIN CITRUS ROOTSTOCK VARIETIES AND SPECIES

Strain Selection

In many of the world's citrus areas, the importance of strain selection within scion varieties is well recognized and put into practice by the growers and nurserymen. This is perhaps more true in Japan than any other citrus area. Japan's large Satsuma industry is divided into three fruit categories according to their maturity. The Wase group are early, the Nakates are mid-season, and the Futsu, or common group, are late. Within the Wase group are Okitsu, Miko, Miyagawa and dozens of others. The other two groups may have a few less strains. Little differences in fruit yield, time of fruit maturity, hardiness, or local preference, etc., are of considerable importance to the grower and the industry without changing the variety.

Spain has many strains of Clementines also selected for size, color, seediness, time of maturity, etc. Italy has made similar selections within the Willow Leaf (Mediterranean) mandarin. Strain selection within a variety has also been extensively practiced in California. Within the Washington navel variety are the Parent, Frost, Newhall, Tulegold, Bonanza, Thomson Imperial (T.I.), Atwood, Fischer, Dream, Lane Late, etc. Even a wider range of strains may be found within the Eureka and Lisbon lemon varieties. These strain differences are for the growers' preferential choice; the navels are all sold collectively as navels, and all the lemon strains are sold as lemons.

Strain selection, or even varietal selection, while recognized within rootstocks, is still generally not practiced, although there could be many advantages in doing so. Thus, for rootstock purposes, the citrus industry has just nonchalantly considered a sweet orange a sweet orange, a sour orange a sour orange, or a Rough lemon a Rough lemon. On the other hand, rootstocks like Troyer citrange, Sampson tangelo, Cleopatra mandarin, or Rangpur lime, are more specific; they imply one specific cultivar with no recognized variations, or strains, at least at the present time. A grower choosing one of these cultivars for rootstocks doesn't indicate to the nurseryman he wants citrange, tangelo, or mandarin as stock, because it is now a well known fact that there are other citranges, other tangelos, and other mandarins and, unless he (the grower) specifies, he may get something else.

Rootstock trials at the Citrus Experiment Station, Riverside, indicate that there are performance differences between different strains (selections) of sweet oranges, sour orange, grapefruit, etc., that justify a clonal selection within that species to take advantage of greater yields, variations in tree size, better gummosis resistance, or better nematode resistance (Batchelor and Rounds, 1948), and see rootstock yield later in this manuscript. In these trials, and across several scion varieties, the performance of the Rubidoux sour and Brazilian sour was definitely superior to that on African sour and to a lesser extent on Paraguay sour. Of course, this was before the incidence of Tristeza. The trees on African sour were significantly smaller and accordingly yielded less fruit. The CRC #343 grapefruit provided better performance results than Duncan, McCarty, Camulos, and several others. The Koethen sweet orange in the Riverside trials appeared preferable to other sweet oranges. In Ventura County, the Olivelands sweet has frequently been preferred. The established performance of rootstock cultivars warrants their perpetuation as rootstock seed sources and their choice over untested and unproven sources which a nurseryman thinks may be just as good.

Certified Seed Sources

In California, many citrus nurserymen have, or have had, their own individual seed source trees. Many had been chosen because of past good orchard performance in a specific area, or statewide. Some were the nurseryman's selection, others were obtained from the Citrus Research Center at Riverside. In either case, the nurseryman could offer the same clonal selection of rootstock year after year with some confidence in its continued good performance. The immediate and rapid acceptance and success of Troyer citrange as a rootstock in California almost had disastrous effects. With the increased plantings of young orchards, Troyer seed was in such demand that many nurserymen chose to grow seedlings for future seed sources. Prices were prohibitive for that time (early 1950's), as seed sold in most instances at a rate of ten cents each, or fifty cents per fruit, and three hundred dollars a standard field box (about 5 pounds). The author observed some of the fruit seedling sources and was able to identify a number of offtype trees. The fact that some of the trees were offtype didn't seem to make any difference to the seed supplier. Fruit from the offtype trees was harvested along with the fruit from the normal trees, either unknowingly or willingly (at those prices), and sold as Troyers. While it is one thing to be able to identify any offtype trees which can and should be discarded, another situation arises with offtypes in which there are no discernable visual differences from the mother tree. These may not be hybrid differences, but rather somatic variations which may be just as critical. The author will cite several examples, and keep in mind that this happened before the use of isozymes and other techniques were available for identification purposes. In the 1948 tristeza plantings at Baldwin Park, California (Bitters and Parker, 1953), two sources of Bessie sweet orange were used as rootstocks and half of the trees per rootstock inoculated with tristeza. One of the sources of Bessie was an old source (CRC #245) from the Citrus Variety Collection, Riverside. It served as the mother seed source for Bessie seedlings grown in 1924 for 1927 rootstock plantings at Riverside (Batchelor and Rounds, 1948). From out of these many seedlings, Dr. Webber had selected seedling #47 as being the largest and healthiest seedling of them all. This should have been the tip off. Seedling #47 was assigned CRC #1693 and also was placed in the Citrus Variety Collection, Riverside. In the Baldwin Park plantings, trees on the Bessie seedling CRC #1693 showed a reaction to tristeza and the trees on the Bessie #245 did not. Obviously the two seed sources were different. Many times my colleagues and I examined the two accessions and could not on leaf and fruit characteristics establish any differences. However, the largest and most vigorous seedling out of a progeny should never have been selected as true to type, and was probably either a gametic or somatic variant.

Webber (1932*b*, 1948) in 1924 also grew a fairly large number of sour orange seedlings for rootstock purposes. Out of a population of 389 nursery seedlings, he selected 43 he considered as variants. He propagated these variants and brought them into fruiting, and also budded the variants to a selected source of Washington navel. The author only wants to make reference to one of these variants. Just prior to my arrival in Riverside in 1946, one of the variants out of the 43 was selected for inclusion in the 1948 citrus rootstock-tristeza trials at Baldwin Park (Bitters and Parker, 1953). It was merely listed as a "sour orange variant." The author was always interested in the correct identification of the rootstock selections used in his experiments. Examination of this sour orange variant revealed leaf and fruit characters which appeared identical to Rough lemon. Showing foliage and fruit to my colleagues, including Dr. L. D. Batchelor, Dr. H. B. Frost, Dr. E. R. Parker and others, we could not differentiate between the variant and verified sources of Rough lemon. We removed the variant from the sour orange category and placed it in the lemon category, where we thought it more appropriately belonged. Upon being inoculated with tristeza, it proved to be equally, if not more, susceptible than those trees on sour orange. The standard Rough lemons showed no effect of the inoculation. Obviously, the variant was indeed a sour orange variant.

How often does this happen? A number of the accessions in the Citrus Variety Collection date back to Dr. Webber's "largest seedling" in the seedling nursery population. Many other accessions are more recent seedlings. Other seedling accessions may be more true to type than the Bessie, but do we know? Most of the accessions in the variety collection at Lindcove Field Station are seedlings, some of the accessions in the foundation block also. This is adequate cause for concern and alarm. Are they identical to the parent sources? A few years ago, Dr. John Carpenter of the USDA Date and Citrus Station at Indio, California, shocked a group of citrus nurserymen he was speaking to at Riverside, when he said many of you do not have Swingle citrumelo CPB 4475; what you have is a seedling source of Swingle citrumelo, and they are not the same. In recent years there has been considerable interest in C-32 and C-35 citranges (Cameron and Soost, 1986). As information was developing and some credence given to the future use of these two root-stocks, some nurserymen obtained seed from Riverside and planted seedlings for future seed sources. The all important question remains, are these seedling sources identical to the original sources at Riverside, and to those tested at South Coast Field Station for tristeza resistance (Bitters, 1972)?

The author was somewhat surprised during several visits to Florida in the 1960's, that in an area where Rough lemon was then the predominant rootstock, several large nurseries did not have their own seed source trees. Some relied upon in-trained personnel going into the hammocks and collecting fruit from feral trees. Such practices undoubtedly resulted in some hybrids and offtypes being gathered and contaminating the total seed source. Fortunately, the inroads of the burrowing nematode led to the selection of resistant or tolerant lemon types like Estes and Milam. The future status of Rough lemon as a rootstock in Florida is uncertain since Rough lemon is very sensitive to "young tree decline." Whether or not there is any clonal tolerance within a rootstock to this disease is currently unknown, but certainly a better history of known seed sources might have been helpful.

Citrus industries around the world have recently had the foresight to recognize the importance of clonal variation and the necessity of selecting superior performing cultivars of both scions and rootstocks as perpetuated, controlled, and supervised foundation plantings of disease-free, true to type sources of scion budwood, rootstock budwood, and seed sources. Perhaps California was the first to see the need for and initiate such a program. Readers should consult Calavan, Mather and McEachern (1978) on the registration, certification, and indexing of citrus trees. Citrus areas such as Florida, Spain, South Africa, Morocco, and others have also either successfully established certification programs as standard practices, or the programs are in the process of being developed and adopted.

Nomenclature

Since the 1940's, growers, nurserymen, and even research people have acquired the habit of using citrus species names as vernacular names. The practice seems to have started with the introduction of lots of new names coincident with the rapid expansion of rootstock trials associated with tristeza. Swingle (1943) in his system of taxonomy recognized only 16 species of citrus. Tanaka (1977) brought his classification up to 162 species. Swingle did pretty well in confining his species designations to polytypic species, whereas Tanaka raised many varieties to species rank, which really made them monotypic species. Thus, growers are using many of Tanaka's species names as vernacular names. For example, certain rootstocks are referred to as taiwanica, amblycarpa, macrophylla, excelsa, canaliculata, etc. The fact that there may be only one variety per species does not make the practice correct. Someday there may be more varieties. One might as well refer to sweet orange as 'sinensis,' sour orange as 'aurantium,' or the mandarins as 'reticulata.' Call the cultivars by their known vernacular names: *C. taiwanica*, 'Nansho daidai'; *C. amblycarpa*, 'nas-naran'; *C. macrophylla*, 'alemow'; *C. excelsa*, 'kalpi'; *C. canaliculata*, 'kikudaidai', etc. Once established, names are difficult to correct. The important lesson to be learned is to have the rootstocks adequately identified so that readers will understand precisely what rootstock is being referred to.

IMPROVING TREES BY SELECTION OF ROOTSTOCK SEEDLINGS

Influence of Seedling Size and Variation

In agricultural crops it is generally considered important to exercise some selection of the plants or seeds used in propagation in order to eliminate inferior individuals. The importance of such selection has been clearly demonstrated for many crops. Some selection has been commonly practiced in the propagation of citrus nursery-stock seedlings (Platt and Opetz, 1973). Proof of the desirability of such selection has clearly been pointed out by Webber (1919, 1920*a*, l920*b*, l920*c*, 1922*a*, 1922*b*, 1926*b*, 1928, 1929, 1930, 1931*a*, 1931*b*, 1932*a*, 1932*b*, 1948), and Webber and Barrett (1931). Such experiments were continued in part up until 1960, but the principal conclusions were published by Webber (l932*b*, 1948).

As the sour orange, during Webber's period, was perhaps more generally used than any other rootstock the world over and was the principal root-stock in use in California, he chose to present the data from his selection tests in considerable detail. In considering these results, Webber pointed out that it should be remembered that the percentage of nucellar embryony of the sour orange apparently varies from 70 to 80 per cent as he determined from the examination of different lots of seedlings. These percentage figures for sour orange have been confirmed not only by Webber (1900*a*, 1900*b*, 1931*a*), but also by Frost (1926), Toxopeus (1930), Torres (1936), Ueno, Iwamasa and Nishiura (1967), and Frost and Soost (1968).

Webber (1932*b*, 1948) has shown that, in a lot of 389 unselected sour orange seedlings worked with buds from one highly selected tree of the Washington navel, the seedlings that were the largest at the time of budding produced, in general, the largest trees in the orchard. In this lot of trees, the area of the cross section of seedling trunk (determined from the circumference four inches above the soil, measured just prior to budding), when compared and correlated with the area of cross section of the one-year-old budding trunk two inches above the budunion, gave a correlation coefficient of +0.736 ± 0.016, showing that among the young budded trees the large ones had been mainly produced on large stock seedlings. When the same trees were eight-year-old orchard trees (eight years in the orchard), a similar comparison gave a correlation of +0.437 ± 0.028. These correlations are high enough to show clearly that in an ordinary lot of unselected stock seedlings the size of the seedling at the time of budding has a significant influence on the size of the budlings and of the orchard trees.

In the same lot of trees, when the size of the one-year-old budlings was compared with that of the eight-year-old orchard trees, a correlation of +0.622 ± 0.021 is found to exist, showing that, in general, the large budlings produced large orchard trees. If vigorous, large-sized orchard trees are desired, these figures indicate the importance of a rigid selection to eliminate the small seedlings and small budlings in the nursery.

Variation of Rootstock Seedlings

Irrespective of the species or variety of rootstock used, variations in size such as Webber (l932*b*, 1948) found will exist. A careful examination of such a lot of sour orange seedlings also reveals that there are other differences than size: e.g., in type of branching, length of internodes, form and size of leaf, etc. Size variations of seedlings are probably due in appreciable measure to environmental and accidental causes, such as crowding of seedlings in the seedbed, but the other types of variation in seedlings grown in proximity in the nursery are not likely to be caused by environment. Such variations, in most plants, are more likely to be due to different heritage from the two parental lines commingled in the offspring. In *Citrus*, however, where a high percentage of the seedlings of most good rootstock types are developed from nucellar embryos, variations due to the crossing of different types are not so frequent. Here a large percentage of seedlings come from nucellar embryos and are likely to be genetically of the same type and thus to exhibit similar characters.

If one studies carefully a field of nursery seedlings of a sour orange variety it will become evident that the great majority of them, some 70 to 80 per cent of the total, are very much alike, and the other 20 to 30 per cent will differ from this prevailing type in various characters, such as reflexed branches, short bunchy growth, smaller leaves, rounded leaves, more pointed leaves, narrower leaves, and the like. These offtype seedlings, which are mainly smaller and apparently weaker than the general run of seedling of the prevailing or normal type, are designated "variants" because they do vary.

Nature and Importance of Seedling Variants

While the seedlings of the prevailing type are evidently in greater part from nucellar embryos, it is probable that the seedlings of the variant types are mainly from embryos which are of zygotic origin, and that these seedlings are therefore genetically different from the nucellar-embryo seedlings of the prevailing type. All of these seedlings are from the sour orange, but Webber asks the question "are all equally satisfactory to use as rootstocks?"

An examination of the lot of 389 nursery seedlings of sour orange that Webber (1932*b*, 1948) referred to revealed that 43 of them should be classed as variants because of characters, visible in the nursery, differing from the prevailing type. Webber numbered all of these seedlings and budded them at the same time with buds from one selected tree of Washington navel, and the resultant trees were then grown in the orchard at the Citrus Experiment Station, Riverside. With one or two exceptions, all of the trees classed as variants produced orchard trees showing some degree of dwarfing, and most of them produced marked dwarfing.

These variants apparently occur normally among citrus seedlings, regardless of the source from which they are derived, but the number of variants produced can vary with the rootstock cultivar. Since the majority of them are constitutionally weak and below normal size, a rather large proportion of them die before reaching the age and size for budding. Many are doubtless discarded from the seed bed because they are too small to transplant successfully, but a sizeable number of them, if not recognized and discarded, are finally budded and transplanted into orchards, causing irregularities in size and lowered production.

The fact that those trees budded on the variant stocks were dwarfed should not have been overlooked. Dwarfing is not objectionable if the trees are uniform, healthy, and productive. Small tree size can be compensated for by planting more trees per acre. While Webber was aware that many citrus hybrids produce true to type offspring, there is no evidence that he attempted to find this out with these variants. Even if a variant with desirable dwarfing characters didn't come true to type from seed, it could be propagated by asexual means, as with the East Malling stocks for apples. This variant planting survived Webber's death in 1946 and was still in existence when the author arrived in Riverside in the fall of 1946. Unfortunately, the plot was terminated a few years later before the author became fully acquainted with it. One of these variants has already been discussed and was used in the 1948 tristeza trials (Bitters and Parker, 1953). Variants may be a practical approach to dwarfing, but of course not with sour orange variants because of the tristeza problem with this cultivar and most of its hybrids. There may be some other problems in that perhaps some of the variants are not fruitful. The author selected dwarf variant seedlings out of seedbeds of Rough lemon, Rangpur lime and a few other cultivars with the idea of later using them for dwarfing rootstocks. However, after 10 to 12 years in the orchard, they had not flowered or fruited and were discarded. One enterprising nurseryman in Southern California who was interested in growing dwarf citrus trees for home use was growing Rough lemon seedlings and throwing away the nucellars and only budding on the variants. Of course, this practice does not assure any degree of uniformity as far as size of tree is concerned, but it does demonstrate that the use of variants may be a practical approach to dwarf citrus trees.

The fairly high correlation (+0.437) that Webber (l932*b*) found between sizes of nursery seedlings and sizes of eight-year-old orchard trees was caused, in large part, by the presence of these variants. When the 43 variants were excluded and the size of the nursery seedlings, as shown by area of cross section of trunk of the remaining 346 trees, was compared at different intervals with the trunk and size of the budlings, the following gradually decreasing correlations were obtained: with one-year-old budlings, +0.459 ± 0.026; three-year-old trees, +0.125 ± 0.036; six-year-old trees, +0.010 ± 0.036; and with eight-year-old trees, -0.021 ± 0.037. In the nucellar population, consisting of the seedlings after the variants were removed, the small degree of correlation at first existing had disappeared by the end of the sixth year in the orchard. This is corroborated by the fact that with the same population (variants excluded) the correlation of trunk size of seedlings with the trunk size of stocks and with volume of tops, of the eight-year-old trees, had fallen -0.054 ± 0.032 and -0.012 ± 0.036, respectively, indicating that there was no correlation.

The yield of the trees during the first eight-year period does, however, show a low correlation. Here, with the population of 346 trees (exclusive of variants), when area of trunk cross section of stock seedlings was compared with the total five-year yields of the eight-year-old orchard trees grown on them, there was obtained a correlation of +0.135 ± 0.035. Although this is a positive correlation, it is so low as to be of doubtful significance.

Importance of Eliminating Variants

In view of the fact that, after the variants are removed, the variation in size of the remaining seedlings shows no significant correlation with the size of the orchard trees at the end of eight years, it seems clear that the important factor in nursery selection is removal of the variants. This can be achieved with fair success by discarding the small seedlings when they are dug from the seedbed, and by a further elimination of the small seedlings and variant types in the nursery just before the budding, and of weak trees after the budding. Unfortunately, many of the citrus nurseries have become extremely large and this physical work is done by untrained persons who are unaware of this problem. Some variants do get by and end up as orchard trees.

Influence of Budling Size on Tree Size and Yields

With the population of the 389 sour orange trees that Webber referred to above, the correlation of area of cross section of scion trunks of the one-year-old budlings with that of the eight-year-old orchard trees gave a coefficient of +0.622 ± 0.021; a similar correlation for the 346 trees remaining after the variants had been eliminated was reduced to +0.182 ± 0.034. When, with the entire population of 389 trees, budling size was correlated with total five-year yield of fruit per tree in the eight-year-old orchard, the coefficient was +0.233 ± 0.025; and with variants removed, this was reduced to +0.233 ± 0.034. It seems, thus, that even with the variants removed, there is an appreciable correlation between tree size and yield of orchard trees.

Webber obtained almost the same correlation for a population of 1,506 ten-year-old orchard trees of Washington navel on sweet orange stocks, from which all small budlings had been vigorously eliminated before planting (variants thus removed). Here the area of cross section of scion trunk of the orchard trees, taken one year after planting, correlated with the area of cross section of trunk when nine years of age and with average total seven year yield per tree, gave coefficients of +0.158 ± 0.017 and +0.229 ± 0.016, respectively (Webber, 1931*a*).

These results, together with other data, led Webber (1930) to conclude: "It thus seems that it is fairly safe to assume that after all variants are excluded from a population a small correlation still exists between budling size and tree size and between budling size and orchard yield, amounting to a coefficient of approximately +.15 to +.18 in the former, and +.22 to +.23 in the latter. These are positive correlations, but are small and thus of rather doubtful significance and leave one somewhat in doubt whether any selection other than that intended to eliminate the variants is important."

Comparison of Seedling and Budling Selection

In the experiments with sour orange trees referred to previously, detailed records of each tree were retained and it was thus possible to arrange and test the results of different methods of selection (Webber, 1931*b*; Webber, 1932*b*). Records of the entire population of 346 trees (variants excluded) were used and two methods of selection were tested, one based on the diameter of the stock seedling just prior to budding, the other on the diameter of the scion trunk of the one-year-old budlings just before they were transplanted to the orchard.

In the selection based on seedling size, seedlings 2.1 cm or more in diameter were graded as firsts (or large), and those 2.0 cm or less in diameter were graded as seconds (or small). In the selection based on budling size, a similar classification was employed: budlings having scion trunks 1.8cm or more in diameter were graded as firsts (large), and those having scion trunks 1.7cm or less in diameter were graded as seconds (small) (Figure 3 [*Image could not be located*]). The average total five-year yields of all the trees in each grade were then brought together for comparison.

An examination of Table 1 shows that, when the selection (segregation) was based on diameter of seedling trunk, there were 237 seedlings in grade one (large) and 109 in grade two (small) and the average five-year yield of trees in grade one was 56.2 pounds per tree greater than that of trees of grade two. When the selection was based on the diameter of the budling trunk, there were 242 trees in grade one and 104 trees in grade two. The average five-year yield of the trees grown from grade-one budlings was 47.2 pounds per tree greater than that of trees from grade-two budlings.

Webber in 1927, 1928, and 1929 started extensive rootstock trials with all the major scion varieties grown in California and made one planting of each at the Citrus Experiment Station, Riverside; others were planted with grower cooperators. The trees at Riverside were planted in five-tree plots and randomized with two to five replications. In many scion-stock combinations, he had also segregated the trees into large and small categories for further comparisons. Webber (deceased 1946) or Batchelor (deceased 1958) never reported on this aspect of the Riverside rootstock trials, but these trees remained in the orchard until 1960 when inroads of tristeza were apparent in the block. At that time nearly 30 years of accumulative yield data were available and final tree size was recorded prior to removal of the orchard trees. The final results of these tree size comparisons and yields is reported by the author in Table 2 for some of the combinations. Generally, there were ten trees each for each size category; in a few cases, fifteen. The comparative results indicate that selection based on size of seedlings before budding is fully as effective as that based on size of budlings at planting time. Furthermore, seedling selection is much less expensive than budling selection, as a discarded nursery seedling is much less valuable than a discarded budling. In either case, however, the value of the extra fruit produced on the selected trees would in a few years pay the costs entailed by the selection. Many nurserymen do not adequately grade their seedlings or budlings. Nurserymen who ball trees more than twice out of a nursery row are really cheating the growers on the inferior trees produced by the third selection. The advantage of a large budling over a small budling is a lasting effect. It can readily be seen from the examples provided in Table 2 that after 33 years in the orchard the largest budlings in almost every instance grew the largest tree, and almost in all cases yielded the most fruit. Growers are advised to know the integrity of the nurseryman and inspect his nursery prior to purchase of trees.

Permanence of Improvement by Selection

The elimination of variants is of primary importance in the cultivation of citrus, as trees propagated on variant seedlings remain, with few exceptions, permanently dwarfed and unproductive.

In the studies reported above, differences in size of trees and in yields, as the result of selection after elimination of variants, were especially marked during the first few years. These differences gradually minimized, but in most cases were still apparent after 30 years in the orchard. The benefit resulting from the selection of variant-free progenies and larger-sized progenies was interpreted by Webber (1932*b*) as due to the holdover influence of large size and vigor in the young seedlings, which maintain that advantage apparently throughout the life of the orchard. It was not supposed that the heritage of the plants was influenced by the selection, but rather that the effect was similar to that obtained by the selection of large seeds and enabling the tree to get off to a good start.

Careful studies on rootstock size as it affects the size and yield of orchard trees were also carried out by Mendel (1940) in Israel. Mendel used stocks of the Palestine sweet lime budded to Shamouti sweet orange. Four plots of 20 trees each on small stocks and four plots of 20 trees each on large stocks were set out in alternate arrangement in a test orchard and their comparative development recorded. Mendel found that the difference between the groups of small and large stocks which, at the time of selection in May 1931, amounted to 43.6 per cent (the diameter of the large stocks being equal to 100 per cent), decreased gradually until the time of transplanting into the test orchard in

March 1934, when the difference was only 7.3 per cent. At this time, a second selection was made, which raised the difference to 20.5 per cent. Following this, Mendel stated that the difference between the small and large stocks was reduced to 5.1 per cent in June 1939. The growth of the scions, on the whole, showed the same tendencies as that of the stocks, and differences between the groups with regards to yield were not significant from the first year of fruiting onward. He concluded that the elimination of deviating phenotypes (variants) was therefore all that mattered in the selection of sweet lime stocks. This does not agree with the rootstock data presented by the author where different scions and different rootstocks were involved, variants were supposedly eliminated, and yet the difference in response of size of budlings was still evident after 33 years with most of the combinations.

Mendel's conclusion somewhat confirms Webber's findings in his earlier experiments (Webber, l932*b*), but not the latter. Mendel, however, worked with Palestine sweet lime, which develops a very high percentage of nucellar embryos and thus reproduces nearly true to type through the seed, exhibiting only about 2 per cent of variant seedlings. It is difficult to believe that Webber didn't eliminate most of the variants in all the combinations he had. As Webber pointed out, the variant seedlings are usually small and weak, and are mostly eliminated in transplanting from the seedbed to the nursery, or are usually easily detected and eliminated in the nursery at the time of budding. This same condition holds with the Rough lemon, Sampson tangelo, and such citranges as the Morton, Troyer, Savage, Rusk, and others, the embryos of which are from 98 to 100 per cent nucellar. With such stock varieties, selection to eliminate the small number of variants is less troublesome; but with seedling stocks of some sweet oranges, sour orange, grapefruit, some mandarin varieties, *Citrus macrophylla*, etc., where the proportion of variants may range from 20 to 30 per cent, removal of the variant seedlings becomes highly important. Furthermore, experience indicates that in transplanting seedlings from the seedbed to the nursery, and to some degree in transplanting budlings to the orchard, the small plants are more likely to die than the larger ones, and for this reason also, the small plants should commonly be discarded.

Gardner and Horanic (1959) also report on the relation of citrus nursery tree size 1/2 to 7/8 inches in diameter to ultimate size of tree and production. They found in a 17-year-old rootstock test block of two varieties on seven rootstocks, that although the tree size and yield were profoundly influenced by the rootstock variety, there was not pronounced correlation between the initial sizes studied and ultimate size, or between initial size and yield, within the various rootstocks. There was, of course, a positive relationship between final tree size and yield.

Seedling Selection in Commercial Nurseries

The application of the principles of nursery selection in commercial nurseries is not difficult and requires only careful observation and attention. No other single cultural factor has more influence on the uniformity and quality of the end product: a healthy, productive orchard tree (Newcomb, 1974). The person doing the selection should have full knowledge, however, of the commercial rootstock varieties being grown, including all their morphological characteristics. Selections should be made at three different times: (l) when the seedbed is dug, (2) in the nursery just prior to or during budding, and (3) when budlings are dug for planting.

Selection at Seedbed

When the seedbed stock is being dug and transplanted, the policy of discarding all small individual plants should be rigorously followed. The proportion that should be destroyed will depend upon the degree of variation exhibited by the particular lot of seedlings. If they are grown from seeds taken at random from trees of varying types as with the "bulk seed" so commonly used by many nurserymen, it is probable that 20 per cent or more of the total number should be eliminated. Crowding of the seedlings in the seedbed might necessitate a heavier cullage. If the seedlings are grown from seed from selected trees known to produce fairly uniform seedlings, the percentage of discards should be smaller. If the seed is from special varieties in which nucellar embryony is high, such as in Palestine sweet lime, Rough lemon, *C. macrophylla*, or Troyer citrange, then the percentage of discards at the seedbed may be limited merely to the size that can be properly handled at transplanting. In instances where *C. taiwanica*, Sacaton citrumelo (Yuma citrange), or other low polyembryonic types are used, cullage may run as high as 50 per cent.

At this time also, all malformed seedlings, such as extreme cases of "goose-neck" or "bench root," should be discarded. However, if care is not exercised in transplanting the seedlings, small seedlings in particular can have the tap root markedly bent on insertion into the planting hole. Maybe this isn't too serious. We know of no record where growers have willfully planted budlings with bench roots. However, it was intentionally done at Riverside with Valencia oranges on Morton citrange stock in 1944. There were three five-tree plots with normal root systems and three five-tree plots having bench roots. There were never any observed differences between these two lots of trees. When the trees were pulled in 1960, 26 years later, the trees were the same size, there was no difference in yield, and the ultimate root systems looked alike at time of pulling. While elimination of bench roots is advisable, it is not critical if some occur in the nursery. It is of course difficult to eliminate bench roots in balled nursery trees or container grown trees, but not in bare root trees.

Selection at Time of Budding

When the seedlings growing in the nursery have reached the size and age for budding, preferably just before the budding is started, the nursery should be examined, row by row, and all the inferior or offtype plants removed. At this time also, a considerable number of the small plants should be eliminated. The budder or his helpers can do this at time of budding. This is the last time that the characters of the seedlings can be examined, and it is the most important time to do a thorough job. If there was a fair elimination at the seedbed, the rogueing in the nursery should not require the destruction of another 5 to 10 per cent of the total number of plants.

Budling Selection

When the budded trees have reached the age and size for transplanting into the orchard, they may vary considerably in size, owing to differences in manipulation, in the time the buds started growth, etc. If, however, the seedling stocks have been carefully selected, all should produce good trees, except rarely where the buds did not heal well, or were defective. At this time all particularly undersized, weak, or sickly budlings should be eliminated. Nurserymen in California should be aware that in some areas where the nursery is located adjacent to natural vegetation, natural spread of stubborn disease is particularly high, and obviously infected trees should also be discarded. With properly selected stocks and good buds, the elimination of budlings should be slight, probably not more than 5 to 10 per cent. Even at this time, the trees have a relatively low value in comparison with the value they will have after a few years in the orchard, and the importance of having every tree a good tree, in a long-term crop like citrus, can scarcely be over estimated.

Selection in Field Grown Nurseries vs. Container Grown Trees

The nursery practices described by Platt and Opetz (1973) deal primarily with field grown nurseries, which for many citrus growing areas are now obsolete. The trend since 1973 has been toward container grown citrus. South Africa, since about 1985, grows only container grown plants. Spain and Australia are principally into container growing, with field grown nurseries rapidly disappearing. Container growing is more efficient, cheaper, requires half the growing period of field grown trees, plus other advantages. Perhaps the greatest advantage of container citrus is that each plant is treated as an individual, not a mass of thousands. Each plant can receive more careful care, treatment, and scrutiny. The individual handling of each plant should result in better observation and the likelihood that offtypes and variants will be more readily noticed and discarded. The fact that certified trees must be identified and logged adds additional confidence.

HEIGHT OF BUDDING

Although knowledge of the art of budding, or grafting, goes back several millennia (Condit, 1951*a*, 1951*b*; Schenk, 1962), it was only in the late 1800's that budding of citrus became a general practice. The change was partly due to the introduction of superior varieties like the Washington navel orange, the Valencia orange and other named cultivars in which it was a disadvantage to grow seedlings or marcots, and partly because of the susceptibility to soil pests and diseases (Klotz, 1978). The height of budding in most citrus areas has been somewhat standard and probably varies from a height of 5 to 15 cm, although it is now changing. However, the height of budding in some instances has varied from the ridiculous to the sublime. Nowhere are trees budded higher than they are in Italy, where sour orange seedlings may be budded at a height of 90 to 150 cm in attempts to escape gummosis, which so severely devastated their seedling orchards in the 1800's (Fawcett, 1936). On the other hand, the author years ago observed a nursery near Fairhope, Alabama, in which the nurseryman hoed the soil away from the base of trifoliate orange seedlings and fall budded them to Satsuma mandarin just above the crown roots. The wrapped buds were then covered with soil to prevent them from freezing.

In California, height of budding has generally tended to be directly related to the inherent vigor of the kind of rootstock seedlings grown. Vigorous seedlings like Rough lemon tended to be budded somewhat high; low vigor seedlings like trifoliate orange, somewhat low. Seedlings of sweet orange, grapefruit and Cleopatra mandarin were budded at more of an intermediate height. When trees were in great demand, even the vigorous seedlings might be budded low, and occasionally nurserymen have selectively budded the largest seedlings in the nursery row and left the slower growing seedlings for a later budding. In addition, those rootstock cultivars which tend to branch and sucker excessively and thereby develop a bushy character were often budded lower than cultivars with a strong central leader merely because the nurseryman didn't want to go to the expense of continually removing the lower suckers and branches.

Figure 4 [*Image could not be located*] is a composite picture of six typical rootstock cultivars used in California citrus nurseries in the early 1950's. The sweet orange, grapefruit, and Sampson tangelo seedlings were characteristic of the slow-growing category which tended to branch and sucker excessively, requiring a great deal of pruning. They were not conducive to high budding, although the trunk caliper was fairly good. The Cleopatra mandarin seedlings grew more upright, but tended, in the nurseryman's terms, to be "leggy", of slender caliper, and often times in need of staking for support. Cleopatra does grow more rapidly and obtain better caliper under tropical conditions. The Rough lemon and the Troyer citrange (as well as many other trifoliate hybrids) tend to send out a strong central leader and a minimum of lateral branches. Troyer seedlings, of course, do not attain the caliper of Rough lemon seedlings, but can easily be budded to desired heights.

Within the trifoliate orange, there is also considerable variation in seedling types comprised of the small-flowered, large-flowered, and of course the flying dragon. Figure 5 shows a nursery comparison of Rubidoux trifoliate (small-flowered) on the left, compared to Pomeroy trifoliate (large-flowered) on the right. The Rubidoux seedlings do not have the strong central leader and are quite prone to lateral branching. Whether all small-flowered trifoliate strains have the same nursery characteristics as the Rubidoux, or all large-flowered strains have the same nursery characteristics as the Pomeroy, has not been verified by adequate observation, but it would seem to be a likely possibility. The flying dragon trifoliate is something else. It is more spindly than the other trifoliates, with a twisting, corkscrew type of trunk growth, making bud insertion difficult at some points on the trunk. The retrorse, or strongly recurved, spines hinder the budding procedure.

The first significant experiment on height of budding was reported by Murray (1951) in Trinidad. Included in a series of rootstock trials was the height of bud insertion of grapefruit and Jaffa sweet orange scions on sour orange rootstock. Six heights of bud insertion were used: 5, 13, 25, 38, 51, and 64 cm. There were eight trees of each combination and the trees were completely randomized. There was some incidence of gummosis in these experiments, and while the incidence was low, it was obvious that to avoid gummosis the trees should have been budded at 38 cm or higher. The effect of bud insertion on average number of fruits per tree, average total weight of fruit per year over a ten year period, as well as final stock and scion girth measurements in 1945 are presented in Tables 3 and 4. Several things deserve to be pointed out. The largest trees were those budded at the 5 cm height, and the size of the tree became successively smaller with each increment increase of height. The sour orange stock was noticeably larger than the scion at the 5 and 12 cm insertion, the stock and scion girth was about equal at the 25 cm insertion, but above the 25 cm insertion, the girth of the scion was larger than the sour orange rootstock. The greatest number of fruits per tree per year was at the 5 cm level, but there does not appear to be a significant difference in number of fruits at the different heights of budding. The average yearly weight of fruit seemed to be less at the 5 and 13 cm levels and was greater at 25 cm and above.

Somewhat of a parallel situation existed with the Jaffa sweet orange (see Table 4). While there was no reversion in budunion character, the largest trees were those budded at 5 and 13 cm, with a break in size at 25 cm, and the smallest trees were at the 64 cm level as in grapefruit. Highest yields were at the 5 cm level of insertion, and a rather marked reduction in yield at the 64 cm level. Fruit weight gradually increased from the 5cm level up to the 51cm level, with a sharp drop at the 64 cm level. Since these plantings were replicated and the experiment ran for 13 years, Murray concluded that the combinations gave the overall best performance budded at a height of 38 cm.

Blondel (1953), in Algeria, budded Clementine mandarin on trifoliate orange stock at essentially three height groups. There were 24 trees budded 0-10 cm; 102 trees at 10-30 cm; and 65 trees budded over 30 cm. Observations were made on the presence or absence of exocortis, character of the budunion, volume of the trees, and yield over a four-year period. He found that at the 0-10 cm budding only 13 per cent of the trees showed exocortis; at 10-30 cm, 58 per cent of the trees showed exocortis; and those budded over 30 cm, 86 per cent of the trees showed exocortis. This variation is a little difficult to explain merely on the height of budding and also the knowledge now available on mechanical transmission of the disease by contaminated budding knives (Garnsey and Jones, 1967).

Blondel also found a marked variation in the size of the trees at the different budding heights, which he divided into three classes; large, medium, and small. At the 0-10 cm level, 70 per cent of the trees were large, 13 per cent were medium, and 17 per cent were small. At the 10-30 cm level, 31 per cent of the trees were large, 16 per cent were medium, and 53 per cent were small. However, at the 30 cm level and above, only 10 per cent of the trees were large, 1.5 per cent of the trees were medium and 89.5 per cent were small. Obviously, the trees became smaller with increased height of budding and this might be due in this experiment to the increased incidence of exocortis.

The character of the trifoliate stock also changed with the height of budding. At the 0-10 cm level, 91 per cent of the stocks were ribbed and 49 per cent were smooth. However, at the 30 cm level or higher, only 15 per cent of the trifoliate stocks were ribbed and 85 per cent were smooth. The author has also noticed that the budunions of trifoliate stock and trifoliate hybrids become smoother with increased height of budding (see Figure 6).

Yields declined with height of budding. For the four-year period 1948-51, yields on the 0-10 cm height averaged 25 kg, at the 10-30 cm height it declined to 21 kg, and at the 30 cm level plus, it averaged only 13 kg. While it is unfortunate that Blondel's experiment was confounded by the presence of exocortis, the results still agree pretty well with what Murray found in Trinidad, and with subsequent observations the author has made in California.

Batchelor and Webber (1948) set out very extensive rootstock plantings with all the major scion varieties at the Citrus Experiment Station, Riverside, and also with grower co-operators, during 1927, 1928, and 1929. The trees were budded at from 15-30 cm, somewhat higher than commercial practices at that time. The reason for this was to provide full budunion expression, and permit the girth of the trunk to be measured 10 cm above the union and 10 cm below the union as an index of scion or rootstock volume, and avoid any measurements near the union where there might be overgrowths or undergrowths or flaring of the crown roots. A comparison of these old experimental rootstock trees and trees in commercial orchards (which were budded at lower heights), suggested that the greatest single difference between the two groups of trees was the height above ground at which the trees were budded (Bitters *et al.*, 1957; Bitters, Brusca, and Cole, 1967). Further observations indicated that while budunion malformations are greatest with lemons (Figure 7 [*Image could not be located*]), it might also occur with other scions to a lesser degree, and also differ with rootstocks. This fact is consistent and obvious. The higher the trees are budded once a critical height is reached, the smoother the budunion. The lower the trees are budded, usually the more malformed the budunion. The incidence of gummosis was lower on the higher budded trees. With lemons affected by shellbark (Calavan, 1947), shellbark is slower in expression on the high-budded trees and the severity of the symptoms is much less (Figure 8 [*Image could not be located*]). Lemon shellbark would not be a problem if the trees were budded around 90 cm. The author felt that around 30 cm was a fairly critical height and, pending more observations and research, recommended to nurserymen in California that this height be considered as a bare minimum, especially for lemons. Reasons for the variation in tree response and budunion reaction with the height of budding are unknown. Some researchers say that it changes the top-root ratio, but it is difficult to understand how a few cm of trunk more or less can have such an effect on budunion and scion reaction. Neither can it be explained by the root-stem transition area. While in some plants the transition area is completed at leaves above the cotyledonary nodes, In the subgenus *Citrus*, the seeds are hypogynous in germination and the cotyledons remain below ground. Hayward and Long (1942) found that in *Citrus*, the transition area was completed at the cotyledonary node.

In 1937, L. D. Batchelor (then Director of the Citrus Experiment Station, Riverside) planted out a small experiment with different heights of budding. The experiment consisted of two trees each of Eureka and Lisbon lemon budded on Rough lemon rootstock at heights of 30, 45, 60, 90, 120 and 150 cm. Unfortunately, they served as guards for another experiment, were next to a road adjacent to a eucalyptus windbreak, and suffered some pilferage. Consequently, the trees were somewhat neglected and observations were few and sporadic. However, 20 years' yield data is available. It must be pointed out that lemon trees in California are usually pruned annually. The trees were finally pulled in 1960 when the trees were 23 years old. Some final measurements of height and width and resultant top volume was done at that time. The data are presented in Table 5. From these final measurements of volume, the largest Eureka trees were those budded at 60 and 90 cm and the smallest at 128 cm. The largest Lisbons were those budded at 14 cm and the smallest at 60 and 90 cm. Why the replanted trees were larger might be explained by the fact that they could have been a different bud source than the original trees, but this facet is unknown. The Lisbon trees were somewhat smaller than the Eurekas, which is not surprising since they carried wood pocket (lignocortosis) (Wallace, 1978), which is apparently a genetic disorder. In spite of being smaller trees, the Lisbons produced the most fruit over the 20-year period 1941-60. Greatest yields on the Eurekas were those budded at 90 cm, which were also the largest trees. Lowest yields were at the 120 cm height, which were also the smallest trees. Yields were proportional to the size of the trees. With the Lisbons, greatest yields were at the 45 cm height of budding and also the largest trees. Lowest yields were on the 120 cm height of budding—which were not the smallest trees, but were four years younger in age since they were replants. Yields were again well correlated with size of tree. The height of budding effect is not restricted specifically to Citrus. The author has noted similar effects on other fruit and nut crops in California, especially persimmons and walnuts. Hutchinson and Upshall (1964) established that the size of cherry trees was reduced by budding 38 cm higher than normal on the trunk of Mahaleb cherry rootstocks.

In a small experiment in 1958 at South Coast Field Station (coastal area of California), the late R. W. Hodgson planted 12 pairs of Valencia orange on trifoliate orange budded at approximately 5 cm and 20 cm. The plot was turned over to the author shortly afterwards. In accord with Blondel's (1953) results, it was soon obvious that the trees budded at the lower height were noticeably larger than those budded higher (Figure 9-1 and 9-2). Also, it took much longer for the skirts of the high budded trees to touch the ground. Unfortunately, this block was pulled in 1965 to make way for another experiment.

An opportunity to study this intriguing problem further arose in 1965 at South Coast Field Station when three year-old seedlings (one year in the seed bed, two years in the nursery) were available for budding. Seedlings of both Cleopatra mandarin and Troyer citrange were of adequate size to be suitable for budding at any reasonable height. Therefore they were budded with Campbell nucellar Valencia at heights of *5,* 15, 30, 45, 60, and 90 cm at the same time. The buds were carrying vein enation and tristeza, but were free of psorosis, exocortis, cachexia and other viruses. Both stocks are tolerant to vein enation and tristeza, so this was not a significant complicating factor. The trees were planted in 1966 in single tree plots with seven replications. The planting as of 1976 was thus ten years old and a summary of the data is presented in Table 6.

The first thing apparent was that for the five-year yield period 1972-76, most trees on Cleopatra mandarin out-yielded the trees on Troyer citrange, whereas in an adjacent rootstock block planted in 1960 (same bud and rootstock sources) the trees on Troyer significantly out-yielded the trees on Cleopatra. Secondly, in the rootstock block the trees on Troyer stock were larger than the trees on Cleopatra, but in the height of the budding experiment the trees on Cleopatra particularly budded up to 30 cm were larger than the trees on Troyer budded up to 30 cm. The largest trees on Cleopatra were at the 5-15 and 30 cm heights, with the smallest trees budded at 45 cm. Trees budded at the 45-60 and 90 cm level were all significantly smaller than those budded at the lower levels. Highest yields on Cleopatra were at the 30 cm level, with a much lower yield at the 60 and 90 cm level. With the trees on Troyer citrange stock the largest trees were at the 30 and 45 cm level; the smallest trees, like those on Cleopatra, were at the 90 cm level.

Greatest yields on the Troyer were at the 5 and 15 cm level with a noticeable drop above those levels, except at the 90 cm level, which cannot as yet be explained. It is of interest to note here that in a height of interstock insertion experiment, the yields on Cleopatra are also best at the 30 cm height of insertion of the Troyer interstock, a height of budding effect rather than interstock effect (see Interstocks, later in book). A similar pattern existed for the trees on Troyer rootstock interstocked with Cleopatra. Best yields were again at the 30 cm level insertion of the interstock. It would seem that with both stocks approximately 30 cm is the critical height of bud insertion, and that the trees tend to become smaller when buds are inserted above that level. Over the five-year yield period, yield is not directly correlated with tree size, but this factor may change as the trees become older.

It should be emphasized that this planting is in a coastal area where an alternate bearing situation is commonplace. All of the trees are not in the same bearing cycle. Fruit quality and fruit size measurements have been taken in two of the "on" years. There are differences in fruit quality between the trees on Troyer citrange and those on Cleopatra, with the trees on Troyer providing the highest fruit quality, which is to be expected, but there was no difference in fruit quality discernable with heights of budding. The trees on Troyer citrange also had larger fruit sizes than the trees on Cleopatra, as would be expected, but there was no correlation of fruit size with height of budding.

Leaf samples were obtained from the trees in this experiment in September of 1973 and 1974, and subjected to analysis (Labanauskas, Bitters and McCarty, 1976). The data are presented in Table 7 [*text incomplete*] an optimum range on both rootstocks at all heights of budding. Nitrogen was statistically but irregularly affected by budding height. Phosphorus concentration showed a curvilinear relationship, r = .931**. The highest phosphorus concentration was found when the trees were budded at the 30 and 45 cm levels. Phosphorus concentration at all budding heights was in an adequate range for optimal citrus production, and was not a limiting factor. Potassium concentration increased with an increasing height of budding, r = .749**, but in all cases was again in range for optimal yield production. Leaf magnesium concentration was correlated with budding height, r = .719**. Leaf chloride concentration decreased with an increase in height of budding, r = -.818**. Zinc concentration in the leaves increased with an increased height of budding, r = .947**. Differences due to height of budding in nitrogen, calcium, sodium, copper, and boron concentrations in the scion leaves were statistically significant, but did not fit linear or curvilinear curves. All of these nutrients were in the range for optimal citrus production. Manganese and iron leaf concentrations were not influenced statistically by budding height. Thus, reduction in yield of fruit due to increased heights of budding cannot be attributed to nutrient deficiencies or toxicities. Concentrations of chlorides in the leaves of trees growing on Troyer citrange rootstock was significantly affected by the height of budding, but not on Cleopatra mandarin rootstock. Also, leaf boron concentration was significantly influenced by budding height on Cleopatra mandarin, but not on Troyer rootstock.

In conclusion, it appears that height of budding does have an effect on yield, tree size, character of the bud union, disease incidence, and nutrient uptake. What these effects are due to is presently unknown. The effects may vary with the scion variety or with the rootstock—and perhaps soil and climatic factors. These studies should be continued in order to obtain more pertinent data as to the cause of these effects.

INTERSTOCKS OR INTERMEDIATES

Since a height and length of reciprocal interstocking experiment was made in conjunction with a height of budding experiment, and considerable correlation existed between these plantings, data on interstocks is presented here.

Interstocking of citrus trees usually results as an after-thought, or an error in judgment, by either the nurseryman or the grower. The act of interstocking is usually a direct result of a wish to change the scion variety, with little consideration of what the advantages or disadvantages may be. In other words, it is considered the lesser of two evils, because a severe economic problem is the major consideration. For example, a nurseryman may find that he over-propagated the number of Valencia orange trees for sale when the current market demand is for Washington navels, and the nurseryman rebuds to navels with a resultant Valencia interstock. Or a lemon grower may find his orchard site is too cold for this crop and topworks to oranges, which are more cold tolerant. Occasionally, interstocking may be done by marching (substituting another root system) and doing so below the budunion when damage or injury has occurred to the rootstock.

When interstocks occur, they usually provide little change in the physiology of the combination, since most of the effect is exerted by the rootstock. However, certain interstocks may provide a marked disadvantage. For example, lemon interstocks, with orange scions, have rendered that scion variety more susceptible to cold. Lemon trunks are particularly prone to disease, and the lemon sandwich may be affected by shellbark and phloem necrosis. Many lemon scions carry psorosis in which the lemon top shows no symptom expression, but it may affect the new scion if topworked to oranges. Almost all old-line Eureka scion sources and many old-line Lisbons carry the exocortis viroid, and if topworked onto oranges, the disease affects susceptible rootstocks. In California, lemons topworked onto sweet orange trees have generally resulted in good trees because the lemon trunk has been eliminated and shellbark is no longer a severe problem.

Topworking, and thereby interstocking, may change the susceptibility of the resultant combination to a disease such as tristeza (Bitters and Parker, 1953). For example, lemons budded on sweet orange stock are tolerant to tristeza. However, if topworked to oranges, the combination becomes susceptible to tristeza because oranges grown on commercial lemons as rootstocks are susceptible. The interstock does not prevent the movement of the virus through it; and if either the interstock or the stock is susceptible to the disease, a tristeza reaction will occur.

Unforeseen incompatibilities may result from topworking if the reaction of all component factors is unknown. For example, the satsuma mandarin is compatible on trifoliate orange rootstock. In Japan in 1976, the author observed some trees of this combination topworked to Uwa pummelo, and an incompatibility occurred at the pummelo-satsuma union (see Figure 10). This was not previously known since the satsuma does not lend itself to use as a rootstock.

Interstocks can be used to prevent a localized incompatibility. This has been established in the case of the incompatibility shown when Eureka lemons are budded directly upon Troyer citrange, Carrizo citrange, or trifoliate orange (Bitters, 1952). Field trials by the author have shown that insertion of a sweet orange interstock such as Valencia, or even a *Citrus* relative such as *Citropsis gilletiana*, will prevent the problem. The work of Nauriyal, Shannon, and Frolich (1958*a*, 1958*b*) confirms these results.

Correspondingly, the work of Olson (1958) has shown that, while Red Blush grapefruit on Calamondin rootstock or Calamondin on sweet orange rootstock is incompatible, the former combination can be corrected with a Cleopatra mandarin interstock and the latter, to some extent, by the use of Rough lemon interstock. The author elects to discuss the use of interstocks to prevent incompatibilities with that section later in this book, and the brief references here only illustrate the point. The length of the interstock insertion makes little difference in the performance of the combination and the height of the interstock insertion seems to be more correlated with the height of the insertion rather than the interstock itself.

In 1966, a height of budding, reciprocal interstocking experiment was planted at South Coast Field Station in California. Results of budding height effects were reported previously in this volume and also by Bitters, Cole, and McCarty (1982*a*, 1982*b*). The experiment was made possible because three-year-old seedlings (one year in the seedbed, two years in the nursery) were available for budding experiments at greater heights than normally used in conventional nursery practices. The seedlings were 'Cleopatra' mandarin (*Citrus reticulata* Blanco) and 'Troyer' citrange (*Citrus sinensis* (L.) Osbeck X *Poncirus trifoliata* (L.) Raf.). The rootstocks were reciprocally interstocked to each other as well as to themselves. The double-budding required additional time, but most of the combinations were completed at the time of field planting in the spring of 1966, or within several months thereof. Valencia oranges on both rootstocks, not interstocked and budded at a standard height, served as check trees. The experiment consisted of two phases: (1) height of interstock insertion; and (2) length of interstock insertion. The experiment was terminated in 1980, so 14 years' data are available. Nine years' yield data were obtained. Final canopy volume was taken in 1980. Fruit size and fruit quality were determined on several of the 'on' fruiting years. Leaf samples over a two-year span were analyzed (Labanauskas, Bitters, and McCarty, 1976). All treatments were single tree plots with seven replications.

In the height of the interstock insertion experiment, reciprocal buds were inserted into the rootstock at the 5-, 15-, 30-, and 45-cm levels. When the interstock growth was of adequate size, it was in turn budded to Valencia orange, retaining only a 15-cm interstem. Thus, a constant length interstock of 15 cm was simply moved up the trunk. Data for the 'Troyer' citrange interstock insertion is shown in Table 8. For the trees on Cleopatra rootstock, the critical height of interstock insertion appears to also be at the 15-cm level. This level agrees exactly with the height of budding experiment on Cleopatra described elsewhere in this volume. Both yield and canopy volume are greatest at this point, and both yield and volume decline progressively when the interstem is higher. Valencia orange budded directly on Cleopatra mandarin at 15 cm had an equivalent yield, but the trees were slightly larger. The interstock trees were smaller than the non-interstocked trees and yielded slightly less fruit. Of considerable interest is the fact that when the Cleopatra was interstocked to itself, inserting a 15-cm interstem at 15 cm, the trees had less yield and smaller canopies than any of the interstock trees or the non-interstocked trees.

A similar comparison using Cleopatra as the interstock on Troyer citrange rootstock is shown in Table 9. The critical height of interstem insertion appears to be slightly higher on Troyer citrange than on Cleopatra mandarin, as in the height of budding experiment. Maximum yield occurred at the 30-cm interstem insertion rather than at 15 cm. Largest tree size occurred at the 5-cm insertion, but the second largest trees occurred at the 30-cm level—with less yield and smaller tree size when the interstem was inserted above that level. While there was little difference in yield and tree size of the Valencias on Cleopatra budded at the 15-cm level to the 15-cm interstem insertion, in the case of the scion budded directly on Troyer at the 15-cm level, both yields and tree size were significantly greater. The interstocked trees had lower yields and smaller canopies than the non-interstocked trees. When the Troyer rootstock was interstocked at 15 cm with a 15-cm interstem, the trees were about half the size of those without the interstem, and yielded considerably less fruit. It is significant that both rootstocks budded to themselves have the same type of results. In both reciprocal grafts using a constant length interstock but increasing the height of insertion, there was no effect on fruit size or fruit quality other than rootstock effect. The Troyer citrange rootstock produced the largest fruit size and the best fruit quality. Leaf analysis of these combinations showed some slight differences in nutrient levels. However, with all combinations, both the macro- and micro-elements were within the normal range, and the principal effect was from the rootstock.

In the second part of the experiment, the interstem was inserted at a constant level of 15 cm, but the length of the interstock was 5, 15, 30, 45, and 60 cm budded to Valencia orange. Thus only the length of the interstem was changed. Trees without an interstem budded at 15 cm served as checks. There is also a comparison with the self-interstocked trees.

The effect of length of Troyer citrange interstock insertion on yield and canopy volume of Valencia orange on Cleopatra mandarin rootstock is shown in Table 10. Results obtained with variable interstock lengths, inserted at a constant level, vary greatly from different heights of interstock insertion. Canopy volume is greatest with a 15-cm interstem and tends to be reduced with increased length of interstem. Canopy volume of the interstocked trees is slightly less than the non-interstocked check trees. Yields show no correlation with tree size. Lowest yields were obtained with a 30-cm intermediate, but yields were higher with both shorter and longer interstocks. Both average yields and tree size were somewhat comparable to those of non-interstocked check trees budded at 15 cm. However, when the rootstock was interstocked to itself, both yield and tree size were greatly reduced.

Data for the effect of length of Cleopatra mandarin interstock insertion on Troyer citrange rootstock is shown in Table 11. It is quite apparent that, when the height of the interstem insertion is constant, the length of the interstem has little or no effect on tree size. The average yield per tree was very erratic and showed no trends. Highest yields were at the 15- and 45-cm lengths, next highest at the 30- and 60-cm lengths, and lowest at the 5-cm length. Average yield of the interstocked trees was slightly less than half that of the standard non-interstocked trees, and tree size was about two-thirds as large. The combination interstocked to itself yielded less fruit than the reciprocally interstocked trees, but tree size was slightly larger.

There was no significant effect of the length of interstock on fruit size, fruit quality, or nutrition. It would appear that the height of the interstock insertion has a much greater effect than the length of the interstock. The question is always raised in interstocking as to what effects are attributed to the double bud union and what effects arise from the interstem piece. It is possible that this might be answered by interstocking each rootstock to itself. The fact that these effects occurred with both rootstocks used is significant. A reasonable explanation of why the effects of self-interstocked rootstocks were greater than the reciprocally interstocked ones is not presently available and needs to be investigated further.

Nauriyal, Shannon, and Frolich (1958*a*, 1958*b*) had some difficulties with a 2.5-cm interstock insertion in the Eureka lemon-Troyer citrange incompatibility, but after an initial disharmony, the trees recovered and remained normal in appearance.

Russo (1969) reported a difference of sweet orange interstock in the growth of Monachello lemon on sour orange stock in Italy. An Ovale orange interstock produced a good union with both the sour orange and lemon junctures, and most of the trees showed no decline after 25 years of age. However, a Moro blood orange sandwich behaved differently, producing a good union with the sour orange, but did not avoid the overgrowth of the lemon scion. When an Avana mandarin (Willowleaf) sandwich was used, it grew more slowly than either stock or scion and showed a constriction of the interstock, but after 25 years, the trees were normal in appearance.

Labanauskas and Bitters (1973) found that five trifoliate orange cultivars, when used as interstocks on sweet orange root and budded to Valencia orange scions, had no significant effect on mineral nutrient content of the scion variety when compared to trees on sweet orange rootstock with no interstock.

Iwasaki, *et al.* (1961) interstocked the vigorous strain Tachikawa satsuma with Noda, a dwarf satsuma strain, as well as with Yuzu and *C. tachibana*, all on trifoliate orange rootstock, and summarized effects after ten years of observation. The interstocks of the dwarf satsuma strain showed less vigor, less yield and less growth of the rootstock with progressive effects as the trees became older. Trees on the *C. tachibana* interstock were the most vigorous and correspondingly gave the best yields; those interstocked with Yuzu, the poorest. Effects were somewhat complicated by apparent incompatibility and stem pitting.

Mielke and Issa (1977) reported on the effects of several interstocks on fruit quality of Red Blush grapefruit on Cleopatra mandarin rootstocks. Interstocks used were two local selections of sour orange, two unidentified mandarin types, chinotto orange, *C. depressa*, *C. sunki*, and *C. amblycarpa*. In general, slightly smaller fruits resulted with the *C. depressa* and *C. sunki* interstocks and those on chinotto interstock were slightly larger. One of the unidentified mandarins increased peel thickness and one of the local sours and *C. amblycarpa* reduced peel thickness. No effect was noted on juice content, total soluble solids or total acidity. However, soluble solids to acid ratio was generally lower with *C. sunki* interstocks and higher with the chinotto interstock.

Khalidy (1957), using rootstocks of sour orange, Rough lemon, trifoliate orange, grapefruit and sweet orange, reciprocally interstocked them, as well as with a Valencia intermediate, and budded them to Valencia scions. He states that, when trifoliate orange was used as an interstock in field plantings, it appeared (for the five-year duration of his experiment) capable of decreasing plant growth. However, when more vigorous citrus species were used as intermediates, they did not enhance plant growth. There was no effect in the greenhouse with interstocks after 11 months. Perhaps his experiments did not progress long enough, and maybe two replications were inadequate. He also found that, in certain cases, the interstock species appeared to influence the ratio of total solids to total acids. A rootstock which induced a higher ratio also induced a higher ratio when used as an interstock. Khalidy also found that, when Rough lemon was used as an interstock, it appeared to decrease the transpiration rate of the combination, but to a lesser extent than when it was employed as a rootstock. On the other hand, when sour orange was used as an interstock, it did not impart an increased transpiration rate as it did when used as a rootstock.

The interstock species in certain cases did exert definite effects upon the inorganic composition of scion leaves. However, it was not necessarily in the same direction as the influence it imparted as a rootstock. Rootstock effect on inorganic composition in most cases predominated over the interstock effect. In his studies, Khalidy also found that boron content of the scion leaves was less with a sour orange intermediate, but that a Rough lemon interstock appeared capable of increasing boron content. His studies indicate that there are cases where the interstock behaved similarly, as when it was employed as a rootstock, and still other cases where the interstock effect was opposite to that when it was used as a rootstock.

Gardner (1968) double budded Hamlin and Valencia sweet orange trees with interstocks of Rough lemon on sour orange rootstock and sour orange interstocks on Rough lemon rootstocks. The sweet orange varieties were also budded directly on these two rootstocks. The interstocks were of two lengths, 7.5 cm and 15 cm. After six years in the field, there were the usual differences between Rough lemon and sour orange in tree size, yields and fruit quality of the scion variety, but there were no significant differences caused by the interstocks. Gardner concluded that the results indicated that the rootstock was the only controlling factor influencing tree growth, yield and fruit quality and that the interstock did not alter the rootstock influence in any of these aspects.

In Israel, Safran and Bental (1968) used interstocks of sour orange, Rough lemon and sweet lime with Shamouti orange, with Shamouti on sour orange as checks. The results were very much confused by the presence of stem-pitting (probably cachexia). The Shamouti/sour orange/Rough lemon combination made strong trees with the highest yield of all the double-worked combinations, but not as good or productive as the Shamouti on sour. A high percentage of the trees with sweet lime as an interstock declined or remained small and was accompanied by severe stem-pitting. There was slight stem pitting on the Rough lemon and a budunion malformation at the juncture of the Shamouti on Rough lemon.

Robinson (1934) reported that various tangelos, as well as the Temple orange (a tangor), when grown directly on Rough lemon rootstocks in Florida tend to produce fruits which become puffy, coarse, semi-dry, and pithy as they reach maturity. If the Rough lemon rootstock was originally budded to grapefruit or sweet orange scions and then topworked to the mandarin hybrids, the following crops did not produce the adverse fruit effect referred to above. Strong interstock effects like these are not typical.

Webber (1948) reports that in a letter he received in 1943 from W. M. Mertz, a small orchard (5 acres) near Upland, California, was planted about 1903 to (Dancy) tangerines on sour orange rootstock. The trees were topworked to lemons about 1931. As of 1943, Webber reported the orchard was making good growth and satisfactory yields. The author visited this same orchard several times in the mid-fifties and perhaps as late as the mid-sixties. The planting was still productive and in excellent condition, but probably soon afterwards succumbed to a housing development.

Lemon trees topworked onto orange trees, regardless of rootstock, have done very well. Again, Webber (1948) discusses a letter from W. M. Mertz received in 1943. Mertz described two orchards in Orange County, California, in which navel oranges on sour orange rootstock were topworked to lemons. In 1941, the original rootstock and sweet orange “sandwich” were 45 to 50 years old and the lemon tops were 26 years old. There are many similar topworking examples too numerous to mention. Eliminating the lemon trunk, which was usually so susceptible to shellbark, appeared to have the same effect as high budding and eliminated the shellbark.

Trees affected by known diseases probably under no circumstances should be topworked. In some instances topworking may result in an incompatibility. For example, in 1976 while visiting Japan, the author was shown some satsuma trees on trifoliate orange rootstock which had been topworked to Uwa pummelo. An incompatibility occurred at the juncture of the Uwa pummelo and the satsuma. In other instances, the topworking may result in the susceptibility to a disease which would not have affected the original combination prior to the topworking. To illustrate the point, lemon trees on sweet orange rootstock are not susceptible to tristeza. However, if the combination was to be topworked to sweet orange (in a tristeza area) the new combination would be susceptible to tristeza (Bitters and Parker, 1953). Trees showing symptoms of tristeza should not be topworked to lemons; but susceptible trees can be topworked successfully if done before tristeza occurs (Batchelor and Bitters, 1953; Schneider and Wallace, 1954*a*, 1954*b*).

Growers in Spain, until the occurrence of tristeza, probably did more topworking than in any other citrus area of the world. Citrus diseases are easily spread through topworking, either by the mechanical means of contaminated tools, or the use of scion varieties in which symptoms of the presence of a pathogen were not expressed. In 1983, Dr. Luis Navaro, Director of INIA at Moncada (Valencia), Spain, told a group of participants at the First International Society of Citrus Nurserymen that of all the Spanish citrus cultivars entered into the new budwood certification program established in Spain, over 50 per cent of the cultivars were carrying three or more viruses.

Platt (1959) thoroughly discusses the pros and cons of topworking. To make this information more available, Platt (unpublished data, 1982) prepared a handout on citrus topworking compatibility. It is reproduced intact in Table 12. While Platt prepared this information specifically for California growers, citrus growers in other areas will find that many of the recommendations can be appropriately applied to their orchard conditions as well.

The largest related incidence of topworking in the California citrus industry occurred in the early 1960's. The incident had nothing to do with tristeza directly, but was associated with the rapid increase in citrus plantings in the 1950's, particularly in the San Joaquin Valley, following the destruction of orchards in the Los Angeles basin by tristeza. The causal factor was a citrus bud variation referred to as the "acid-navel." (Soost *et al.*, 1961). This was a mutant of the 'Frost' navel which was so extensively propagated at that time. The variant was a fruit mutation characterized by smaller fruit, coarser rind, and other undesirable external characters. However, the interior of the fruit had a more watery-appearing flesh with juice of a higher than normal citrus acid content; hence the term "acid-navel." The fruit characteristics were completely unacceptable for commercial purposes. Since the trees were disease free and no incompatibilities were involved, most of these trees were topworked, generally to another navel orange of the grower's choice. Hundreds of acres, literally thousands of trees, were topworked. The episode stresses the importance of nurserymen cutting buds for propagation from fruiting trees so that the fruit characteristics of the scion variety can be observed.

Interstocking of citrus trees has not always proved useful. Diseased trees should not be topworked, and when and if topworking is necessary, it should be with full knowledge of the consequences involved. The fact that citrus interstocks, except for preventing certain incompatibilities, have had so little effect on the physiological response of the scion should not imply that they may never be successful. Most citrus interstocks have been genetically close and oftentimes commercial varieties. Maybe there are non-commercial citrus cultivars or citrus relatives which may produce desirable effects. The success of interstocks with a tree crop like apples cannot be overlooked.

Ring Grafting, Bark Inversion, and Phloem Blocks

Coincident with any discussion of interstocks are other horticultural procedures, which may not be so difficult to perform, but perhaps could produce effects similar to interstocks, and actually be considered as modified interstocks.

The first of these procedures is the ring graft. Considerable interest was generated in the 1930's through the 1950's in the technique (Roberts, 1934, 1935; Furr, Reece, and Hrnciar, 1945; Murneek, 1941; Yeager, 1944). Much of the work was done with apples and other tree crops. The procedure is accomplished by using knives such as linoleum knives or grape knives with a curved point at the top of the blade. The knives may have spacers between the blades or handles so that parallel cuts can be made around the trunk or branches of the tree. Considerable pressure is put on the cutting implement so the blades penetrate through the phloem (bark). It is impossible to control the pressure and, as a result, the knife blades cut not only through the phloem but also through the cambium and into the xylem elements. Penetration into the xylem may easily range from 1/32 to 1/8 inches (approximately 1-3 mm). Thus, not only are the phloem elements severed, but xylem elements also, resulting in a xylem block as well as a phloem block.

A single cut through the bark (and xylem) of the tree trunk is referred to as girdling or ringing (Lewis and McCarty, 1973). The technique is used almost exclusively to increase fruit set in navel oranges, although it is occasionally practiced with some mandarin varieties. The cut is not protected in any manner from desiccation. The resulting severance of both the phloem, cambium, and xylem tissues apparently heals quickly. Furr, Reece, and Hrnciar (1945) found there is a return to normal nutrient absorption two weeks after girdling, which suggests that the break in the cut tissues may be at least partially healed over in two weeks. Curtis and Clark (1950) reported that regeneration of new phloem within 10 to 15 days resulted in translocation so nearly normal that no difference could be measured between control and treated shoots in analysis for sugar, starch, nitrogen, and ash. Murneek (1941) showed that apple fruit set was increased an equal amount whether girdling affected carbohydrate and nitrogen levels or not. Thus, carbohydrate and nitrogen levels appear to be of little importance in single, knife-cut girdling (Lewis and McCarty, 1973).

Sax (1954) reports that phloem blocks induced by killing a small section of the stem with heat prevented the downward movement of vitamins, organic carbohydrates, and grow-regulators (Crafts, 1951). Bonner (1944), in girdling stems of tomato plants, found that in a few days there was an accumulation of thiamin, pyridoxine, pantothenic acid, riboflavin, sucrose, and nitrogen above the girdle. Lewis and McCarty (1973) state that it appears possible that the severance of phloem tissues causes a temporary increase or decrease in a growth regulator influencing fruit set.

Much of the effects of girdling have thus been done with a single cut. However, other studies of girdling physiology have involved more severe cuts (usually two), including the removal of a band of bark (phloem) from the tree trunk. This is what happens with a ring graft. With a ring graft the strip of bark which is removed from around the tree trunk is immediately replaced with a comparable sized strip of donor bark. The donor strip in this instance is replaced in the proper polar orientation. The ring graft can consist of a bark strip from sweet orange, sour orange, Rough lemon, sweet lime, trifoliate orange, Morton citrange, whatever the researchers' choice. In unpublished data by the author, plastic electrical tape, or duct tape, was used to hold the donor bark strip in place and prevent desiccation. Since the procedure of a ring graft is somewhat more severe than a simple girdle, the healing process may be a little longer, perhaps weeks, or even months.

When the ring of bark is removed from the parent tree, the bark separates at the cambial tissue. Enough cambial initials remain to form new xylem elements to the inside and new phloem tissues to the outside. The strip of donor bark inserted into the removed bark area also has cambial initials on its inner surface. Again, xylem elements are found to the inside, phloem elements to the outside (Yeager, 1944). Roberts (1934, 1935) was one of the pioneers to explore the use of ring grafts in apples. The author was a graduate student of Roberts in the early 1940's and recalls in several discussions that Roberts was quick to point out that the effects did not last since the donor bark strip soon became nonfunctional and sloughed off as with a cork cambium.

Sax (1953, 1954, 1956) extensively investigated the aspect of bark inversion of the donor bark strip so that the polarity of the conducting cells is at least temporarily reversed and transport of nutrients, metabolites, etc. reduced. Sax (1954) considered inverted bark strips as phloem blocks. Reversed polarity is only a temporary problem in bark regeneration (Sax, 1956). Sax (1954), referring to the work of Roberts (1935), states that the inverted rings checked the growth of the trees, but without the deleterious effect resulting from girdling. He further emphasizes that apparently this work was not continued by Roberts. The author had the pleasure of a long discussion with Sax in 1957, and Sax admitted that the effects of bark inversion were temporary and had very little overall effect on tree growth.

In 1956 (unpublished data), the author had conducted some bark inversion experiments with a grower cooperator. The trees were young lemon trees of uncertain destiny since the cooperator indicated the orchard would be removed in one to three years. Replicated treatments were made and the size of the tree trunks above the girdled area measured. The treatments consisted of different widths of inverted bark from 1/4 inch to 2 inches (approximately 5 mm-5 cm). In some treatments, height of the ring insertion varied. In other treatments, a double ring of bark was inverted, approximately 10-15 cm apart. Another treatment consisted of an incomplete inverted ring with a 2.5 cm wide strip of normal bark at 180°. See Figures 11 – 21 [*Image for Figure 21 could not be located*]. Observations were limited because the orchard was pulled before final measurements could be made. In no instance was there any observable difference in tree growth with any treatment as compared to the checks. The width of the inverted ring did not seem to make any difference, the 5 mm was as effective as the 5 cm. Perhaps the use of two inverted rings had more effect than a single inverted ring. The most notable effect was with the incomplete rings where small islands of normal bark were left at 180°. The effectiveness of the blocks was clearly demonstrated since the nutrients and metabolites were translocated to the two normal bark strips resulting in accelerated growth increase in that area.

The use of ring grafts using other varieties or species of citrus genetically different from the parent tree produces no permanent effect on the parent tree. Imposing the additional effect of bark inversion to alter polarity is also a temporary effect.

GRAFT-INCOMPATIBILITY IN CITRUS TREES

Since nearly all commercial citrus trees are budded, it is not surprising that, like other budded or grafted fruit tree combinations, they may be subject to incompatibilities. The terms compatible and congenial refer to healthy long-lived combinations, and incompatible and uncongenial refer to combinations which are not healthy and long-lived. Sometimes the generalization is made that compatibility is a function of the closeness of genetic relationship between the stock and the scion, but there are certainly many exceptions to this hypothesis. If the generally accepted systems of citrus classification are used, there is a wide diversity in the germplasm available within the conservative classification of Swingle (1943), who lists 16 species, and that of Tanaka (1969), who lists 159 species. However, within the Family *Rutaceae*, subfamily *Aurantioideae*, there are a total of 33 genera available with considerable interspecific and intraspecific crosses and bigeneric and even trigeneric hybrids available. It is possible to graft any *Citrus* with *Citrus*, and apparently many genera with many other genera, but the degree of success may vary greatly.

While the author is unaware of *Citrus* being successfully grafted on any genus outside the subfamily *Aurantioideae*, he has kept orange buds alive for one year when grafted on *Casimiroa edulis*, but the buds did not push. In a 1977 conversation with Professor Giovanni Fatta Del Bosco of Palermo, he indicated that mandarin scions will grow, but poorly, on this cultivar. Within the *Rutaceae*, subfamily *Aurantioideae*, *Citrus* grows poorly on the Tribe *Clauseneae*, subtribes *Micromelinae*, *Clauseninae*, and *Merrilliinae*. It does somewhat better with the Tribe *Citreae*, subtribe *Triphasiinae*, but there are no promising combinations as yet. As might be expected, *Citrus* grafts best within the subtribe *Citrinae*, but again, there are many incompatibilities. In this subtribe, *Citrus* can grow successfully on such genera as *Poncirus*, *Severinia*, *Microcitrus*, *Citropsis*, *Eremocitrus*, and *Clymenia*, either directly, or through or with the use of certain interstocks. Within the *Balsamocitrinae*, *Citrus* has been grafted successfully on *Swinglea*, *Aegle*, and *Feronia*. Conversely, *Hesperethusa* grows very well on sweet orange, and *Pleiospermium* grows well on *C. taiwanica*. A more detailed discussion of the role of citrus relatives as citrus rootstocks may be found in this text.

This section will deal primarily with incompatibility problems with *Citrus* on *Citrus*, and the closely allied genera *Poncirus* and *Fortunella* and their hybrids with *Citrus*.

A great deal of reference material is available on graft incompatibilities of tree crops in general. Among the best of these are Hartmann and Kester (1968), Mosse (1962), Herrero (1951, 1955*a*, l955*b*, l956*a*, 1956*b*), and Scaramuzzi (1955, 1959). There are no comprehensive publications dealing exclusively with incompatibilities with *Citrus* and therefore an attempt will be made to emphasize this area of discussion.

Kinds of Incompatibilities

According to Mosse (1962), there are basically two types of incompatibility in fruit trees. These are translocated incompatibility and localized incompatibility, and most known cases can be grouped into one or the other of these types. Mosse's proposal embodies the scheme by Scaramuzzi (1955, 1959), in which he suggests that incompatibility reactions in fruit trees fell broadly into three groups distinguished by their response to the introduction of a third mutually compatible variety. Scaramuzzi's three groups thus consisted of: 1) those where incompatibility is cured by the interposition of an intermediate (interstock) between two incompatible graft components; 2) those where incompatibility is not cured by an intermediate; and 3) those where incompatibility is induced between two normally compatible graft components by top-working with another variety.

Herrero (1956*a*) suggested four categories of incompatibility which included the following: 1) graft combinations where the buds failed to grow out; 2) graft combinations where incompatibility was due to virus infection; 3) graft combinations with mechanically weak unions, in which the cause of death was usually breakage, and ill health, if shown it was due to mechanical obstruction at the union; and, 4) graft combinations where ill health was not directly due to abnormal union structure but was usually associated with abnormal starch distribution. Whether this is the cause of ill health or the effect is not known.

Regardless of whose system of incompatibility categories are followed, it is a recognized fact that *Citrus* has incompatibilities which may fall into any of these designated groupings. It is essential, therefore, that the types of incompatibility be defined for clarification purposes.

According to Hartmann and Kester (1968), translocated incompatibility includes those cases in which the incompatible condition is not overcome by the insertion of a mutually compatible interstock because some labile influence can apparently move through the interstock. This type of incompatibility involves phloem degeneration, and can be recognized by the development of a brown line or necrotic area in the bark, and often designated as budunion crease. Consequently, restriction of movement of carbohydrates occurs at the graft union, with an accumulation of starch above the budunion and a reduction below. Usually a swelling of the scion immediately above the budunion results in a bulge, but not always. Reciprocal combinations may be compatible. In the various combinations in this category, the range of bark tissue breakdown can extend from virtually no union at all, to a mechanically weak union with distorted tissues, to a strong union with normally connected tissues.

Virus-induced incompatibility can be considered a translocated incompatibility. One component of the combination may carry the virus and be symptomless, but the other component may be susceptible to it. Such is the case with tristeza. The sweet orange component alone is not affected by it, and the sour orange component alone is also not affected by the disease. When sweet orange is grafted on sour orange and the virus is present, the adverse reaction occurs. Some lethal metabolic substance is produced in the sweet orange scion which, when translocated to and below the budunion, causes, according to Schneider (1954), hyperplasia and hypertrophy, callusing of the sieve plates, necrotic sieve tubes, and other anatomical abnormalities of the vascular system in the sour orange stock, or in any other tristeza susceptible stock. The reciprocal is not affected, so the toxic substance is not produced in the sour orange leaves, only in certain scions, and only affecting certain rootstocks. The use of a resistant intermediate does not prevent the toxic material from being translocated through it (see the tristeza section).

A translocated incompatibility can be introduced into a compatible combination by the introduction into the system of a third component. Any time a tree is topworked, the compatibility of the two previously existing compatible components may change. Eureka lemon trees on Rough lemon root may be considered as compatible and tolerant to tristeza. In a 1976 visit to Japan, the author observed similar difficulties. The most popular tree combination is Satsuma mandarin on trifoliate orange rootstock. Due to overplanting and overproduction and resulting low prices, growers are indiscriminately topworking to miscellaneous new varieties, and numerous incompatibilities are now appearing. Whenever the insertion of a third component is made, the performance of the resultant combination is much in doubt unless previous experience indicates otherwise.

According to Hartmann and Kester (1968), localized incompatibility includes combinations in which the incompatibility reactions apparently depend upon actual contact between stock and scions, and separation of the components by insertion of a mutually compatible interstock overcomes the incompatibility symptoms. In the incompatible combination, the union structure is generally mechanically weak, with continuity of cambium and vascular tissues broken, although in some instances the union is strong and the tissues join normally. Oftentimes external symptoms develop slowly, appearing in proportion to the degree of anatomical disturbance at the bud union. Root starvation eventually results due to translocation difficulties across the defective graft union. In some cases actual breakage may occur due to the masses of parenchymatous tissue rather than normally differentiated tissues which are commonly found at the budunion.

In *Citrus*, an example of this would be the decline of Eureka lemon on Troyer citrange rootstock, first pointed out by Bitters, Brusca, and Dukeshire (1954), and later confirmed by Weathers *et al.* (1955). Weathers states that this incompatibility cannot be prevented by an intermediate stem piece such as sweet orange. However, this was successfully done by Nauriyal, Shannon and Frolich (1958*a*, 1958*b*). The author in 1951 budded Cook Eureka on a Frost Valencia intermediate on Troyer citrange rootstock involving numerous trees, and those trees, as of 1987, are still vigorous, healthy, and productive. Mechanically weak unions and breakage occurs readily; for example, Figures 22 [*Image could not be located*] and 23, Limoneria 8A Lisbon on *Citrus taiwanica* and also Frost Lisbon on Ponkan mandarin.

There are also delayed symptoms of incompatibility. In these instances, the stock-scion combination grows in a normal fashion for perhaps 15 to 20 years or longer, and then the trees decline. One of the best examples of delayed incompatibility is the so-called "black-line" of walnuts in California, Oregon, and France. Serr (1959) reports that when varieties of *Juglans regia* are grafted onto seedling rootstocks of *J. hindsii*, the northern California black walnut, or onto Paradox roots (*J. hindsii* X *J. regia*), affected trees grow normally, bearing good crops, until they reach an age of 15 to 20 or more years of age, then the difficulty begins. This disorder has recently been identified by Mircetich, Refsguard, and Matheron (1980) as being caused by a graft-transmitted virus, namely, the cherry ring spot virus. Comparable types of delayed incompatibility occur commonly in citrus. Examples are the decline of Satsuma mandarin on Troyer citrange at 16 to 18 years, Washington navel on trifoliate orange and Morton citrange at 15 to 20 years, and a lemon budunion disorder of both Eureka and Lisbon cultivars on Sampson tangelo, Cleopatra mandarin, and many other stocks at 5 to 10 years of age. The role that viruses may play in these disorders is unknown. Hoy, *et al.* (1984) discovered that prune brownline disease was caused by the tomato ring spot virus, and that the organism was spread by the dagger nematode. The disease affected French prune, Empress prune, and President plum cultivars on Myrobalan plum and peach rootstocks, but Marianna #2624 was not affected.

The above mentioned citrus maladies are accompanied by a swelling or bulge at the budunion and compression girdling results. The swelling and girdling occurs above the union with the lemons on Sampson tangelo, and below the union with the Satsumas on Troyer or the navels on trifoliate orange. While swellings at the budunion are often believed to be a positive indication of incompatibility (Webber, 1926*b*), in Citrus there are many combinations in which the scion severely overgrows the stock, and others in which the stock severely overgrows the scion, and yet the combinations are healthy, vigorous, and productive at 30, 40, or even 50 years of age. Obviously, other factors may be involved, as with other tree crops. A more extensive discussion of individual incompatibilities will be detailed later in this section.

Hartmann and Kester (1968) point out that graft union malformations resulting from incompatibility can usually be correlated with certain external symptoms. The following symptoms may be associated with incompatible graft combinations:

a) Failure to form a successful graft or bud union in a high percentage of cases.
b) Yellowing foliage following shoot growth, or later in the growing season, followed by early defoliation. Decline in vegetative growth, appearance of shoot dieback, and general ill health of the tree.
c) Premature death of the trees, which may live only a year in the nursery, or early death in field plantings.
d) Marked differences in growth rate or vigor of stock and scion.
e) Differences between stock and scion in the time at which vegetative growth for the season begins or ends.
f) Overgrowths at, above, or below the graft union.

And to these might be added:

g) Gumming at the graft union.
h) Prodigious suckering above or below the union.
i) Dryness of the bark at the cambial face, usually both above and below the union.
j) External cracking or rupturing of the bark at the bud union.
k) Budunion crease.

In view of the fact that all stock-scion incompatibilities involve some type of anatomical difficulties at the budunion, it seems appropriate to briefly detail what is known about the anatomy of the citrus budunion.

Anatomy of the Citrus Budunion

The anatomy of the citrus budunion has been studied rather intensively by Goldschmidt-Blumenthal (1956), Randhawa and Bajwa (1958), Mendel (1936, 1937), Khan and Salam (1959, not seen), and Malik (1964). Not only were different stock-scion combinations investigated, but also different aged trees. Probably the most comprehensive study of the budunion of newly budded trees is that of Mendel (1936, 1937), in which he investigated the "healing in" of buds of Shamouti orange on the sweet lime and sour orange rootstocks. A summary of Mendel's work is presented by Platt and Opetz (1973). However, for the convenience of readers, a brief general description of the formation of the graft union is abstracted from Hartmann and Kester (1968), and includes Mendel's studies.

1) Freshly cut scion material capable of meristematic activity is brought into secure, intimate contact with similar cut stock tissue in such a manner that the cambial regions of both are in close proximity.

2) The outer exposed layers of cells in the cambial region of both scion and stock produce parenchyma cells, which soon intermingle and interlock; this is called callus tissue. There is no intermingling of cell contents.

3) Certain cells of this newly formed callus, which are in the line with the intact layer of the intact scion and stock, differentiate into new cambial cells.

4) These new cambial cells produce new vascular tissue, xylem toward the inside and phloem toward the outside, thus establishing vascular connection between the stock and scion, a requisite of a successful union. During the budding or grafting operation the cells cut and damaged by the grafting tools turn brown and die, resulting in gum formation. Underneath these dead cells new parenchyma cells arise from both stock and scion, coming from the parenchyma of the phloem rays and immature parts of the xylem. The actual cambial layer itself has little part in the development of the callus. The stock produces most of the callus. These parenchyma cells, comprising the sponge callus tissue, fill the space between the original components of the graft, becoming intimately interlocked and providing some mechanical support. The more or less continuous brown line between the callus arising from the stock and the scion, consisting of above-mentioned dead and crushed cells remaining from the graft cuts, are gradually reabsorbed and disappear. At the final stages of healing of the cells, the outer layer of callus becomes suberized, and exposed dead cells of the tracheids and vessels are sealed with a deposit or gum.

5) At the edges of the newly formed callus mass, parenchyma cells which are touching the cambial cells of the stock and scion will differentiate into new cambial cells. This cambial formation in the callus mass proceeds farther and farther inward away from the original stock and scion cambium and on through the callus bridge, until a continuous cambial connection between stock and scion has finally formed.

6) The newly formed cambial sheath in the callus bridge begins typical cambial activity, laying down new xylem and phloem, along with the original vascular cambium of the stock and scion. In the formation of new vascular tissues following cambial activity, the type of cells formed by the cambium may be influenced by the cells of the stock adjacent to the cambium. Xylem ray cells are formed where the cambium is in contact with xylem rays of the stock, and xylem elements where they are in contact with xylem elements. The new xylem tissue originates from the scion rather than the stock.

In T-budding (Platt and Opetz, 1973), the bud piece usually consists of the periderm, cortex, phloem, and often some xylem tissue to which is attached a lateral bud. In budding, this bark piece is laid against the exposed xylem of the stock. When the bud piece is removed from the budstick, and when the flaps of bark on either side of the “T” incision on the stock are raised, the cambium and newly formed cambial derivatives in these tissues are usually destroyed owing to their succulent nature. After cambial continuity is completed, continuity of vascular tissues soon becomes established. In T-budding, the primary union is between the surface of the phloem on the inner face of the shield and the meristematic xylem surface of the stock. A secondary type of union may occur at the edges of the shield pieces.

The various stages in the healing process of the union in T-budding of citrus have been determined by Mendel (1936, 1937) under Israeli climatic conditions as follows:

1. First cell division—24 hours.
2. First callus bridge—5 days.
3. Differentiation:
    a) In the callus of the bark flaps—10 days.
    b) In the callus of the shield—15 days.
4. First occurrence of xylem tracheids:
    a) In the callus of the bark flaps—15 days.
    b) In the callus of the shield—20 days.
5. Lignification of the callus completed:
    a) In the bark flaps—25 to 30 days.
    b) Under the shield—30 to 45 days.
6. First occurrence of meristematic layers in the callus between shield and bark flaps—15 days.

While the actual time required for bud union continuity to take place may vary with the environment, time of budding, and other factors, it is clear from Mendel's investigations that the process can be essentially completed in 45 days. His observations are in complete agreement with those of Randhawa and Bajwa (1958), who found that the normal union of Malta Blood and Jaffa sweet oranges on Karna khatta rootstock was complete in about six weeks. This time factor is in sharp contrast to the work of Malik (1964), who states that with the Valencia sweet orange and Kinnow mandarin budded onto Rough lemon rootstock, that practically no union takes place six months after budding and even after a year has lapsed, the budunion is not 100 per cent complete.

Mendel (1937) also points out that normal wood and bark elements are laid down after the formation of a common cambium; a connection of the vessels and sieve tubes is thus established. Thereafter the exact border between the graft mates cannot be determined. Thus, nothing can be detected anatomically at the border zone between the scion and the rootstock which would indicate a disturbance of the sap streams, be it in the wood or in the bark, proving the progress of the union was a normal one. The initial union of Malta Blood red sweet orange on Karna khatta described by Randhawa and Bajwa (1958) was normal, but they point out that Bajwa and Singh (1945) and Kirpal Singh and Singh (1948) indicate that this combination exhibits incompatibility in the orchard, which suggests a delayed type of incompatibility, or perhaps the entry of a pathogen.

Whereas the work of Mendel (1936, 1937) was concerned only with the anatomy of the actual union process, the work of Goldschmidt-Blumenthal (1956) was conducted on trees 20 years old. She investigated the bud-union anatomy of Shamouti orange on Rough lemon, sour lemon, sweet lime, citron, Goliath shaddock, Duncan grapefruit, sour orange, Baladi sweet orange, and Shamouti sweet orange. The grafted rootstocks did differ in their anatomical structures, especially in the number and width of vessel clusters, the amount of parenchymatous tissue, the structure of rays, and the number of idioblasts. The Shamouti scions also displayed differences in the number and cross-sectional area of the vessels, amount of parenchymatous tissue, size of rays, and the number of idioblasts. The relative water conductive area of the Shamouti scions was markedly affected by the rootstock. Shamouti scions on Shamouti, Baladi, sour orange, Rough lemon, and grapefruit stocks showed a good correlation between budunion morphology and the anatomical structure. In the remaining combinations, there appeared to be no correlation. The predicting of compatible or incompatible combinations and ultimate rootstock performance by either anatomical, chemical, or other rapid methods would be of great value to the rootstock research worker in developing improved rootstocks. However, none of these methods have proved satisfactory so far. Various laboratory methods have been developed for evaluating stock-scion incompatibility in young apple nursery trees without growing trees to maturity by Evans and Hilton (1957). These include water conductivity measurements through the graft union, macroscopic evaluation of the external appearance of the graft union, microscopic evaluation of the graft union, and breaking-strength tests.

A biochemical method used by Samish (1962) was based upon the presence of a glucoside (prunasin) associated with pear-quince incompatibility. There is a low prunasin content in one quince stock and a high prunasin content in another. Lapins (1959) was able to detect some symptoms of stock-scion incompatibility of apricot varieties on peach seedling root-stocks by macroscopic examination of discontinuity of inner bark tissue at the graft union of the young trees, but found no other correlation of anatomical structure to compatibility. Herrero (1951) made extensive studies of the size and areas occupied by fibers, vessels, parenchyma and rays in the xylem of hardy fruit trees. The width, distance between, and relative numbers of uniseriate and multiseriate rays in the cambium were also determined. He could not correlate any of these anatomical characteristics with incompatibility. Robitaille and Carlson (1970), working with five apple species on six clonal rootstocks, also report no significant correlation between anatomical characteristics and graft take. However, when histograms of the poorer groups were compared to those of the better groups, their results did contradict those of Herrero (1951), since they found that when the xylem structure of two species is sufficiently different, those two species will not intergraft with much success.

With regard to citrus, Mendel and Cohen (1966) in Israel studied the starch level in the trunk as a measure of compatibility between stock and scion. They found no clear indication of impaired carbohydrate movement through the budunion of Shamouti orange on seven rootstocks inducing low growth vigor. The starch level in the bark and wood of the rootstock portion of the budded trees was negatively correlated with tree size. They concluded that the starch level results from the growth vigor of the tree, and is not a factor which affects it. In California, Jensen, Wilcox, and Foote (1927) found greater amounts of starch above the budunion of lemons on sour orange stock as compared to those on grapefruit. This again is probably the effect of impaired translocation.

Mendel and Cohen (1966) said that an early evaluation of orchard tree performance is possible if clear correlations can be established between the behavior of, or rate of, physical processes in a young rootstock or budling and the later performance of the budded trees. This certainly will not work in the case of delayed incompatibility or virus-induced incompatibility. They also found that the total phenolic compounds (TPC) in *Citrus* buds and branches accumulate with scion growth, reach a peak with growth cessation, and decrease during the rest period between growth flushes. TPC, rather than phenols, exhibit highest correlation with growth. There was a significant inverse relationship found between the TPC level in the bark of young seedlings and with the size of five-year-old rootstock seedlings, and with budded trees three years after budding on these rootstocks. They concluded the level of TPC in the bark of young seedlings eight to ten months old is a fairly reliable indication of the performance of young trees until entering bearing age.

In Australia, Bevington, Greenhalgh, and McWhirter (1978) used reciprocal ring grafts of trifoliate orange and sour orange with Eureka lemon to study the incompatibility problem. They found an initial disturbance of tissue in the outer phloem of affected trees as early as two months after grafting. Whether this technique is suitable to study incompatibility in other combinations, or in a delayed incompatibility, is unknown. However, better indices of ultimate rootstock performance are needed.

Compared to the amount of anatomical work done on incompatibilities of deciduous fruit trees, the number of anatomical studies on similar problems with citrus has been relatively little when one considers the size of the industry and the problems that confront it. Most of the anatomical work on mature trees pertinent to budunion disorders has been done at the Citrus Research Center in Riverside, California. Without going into detail, the most informative of these are: Schneider (1954) on the anatomy of tristeza-affected trees, Schneider (1954) on phloem studies of sour orange, Schneider (1954) on effect of trunk girdling on phloem, Schneider (1952*b*) on phloem studies of sweet orange, Schneider (1955) on ontogeny of lemon bark, Schneider (1952*a*) on sour orange necrosis, Schneider and Wallace (1954*a*, 1954*b*) relevant to anatomical studies of topworked trees, and Schneider (1960*a*) on dealing with a budunion problem on *C. macrophylla* rootstock. The most comprehensive publication on the anatomy of citrus is that of Schneider (1968). In addition, a better understanding of the anatomical problems involved with the incompatibilities associated with lemon tree decline may be found in Schneider *et al.* (1978). Also, investigations of graft incompatibility among *Persea* species by Aaouine (1986) has an excellent discussion of tree crop incompatibilities and hundreds of references.

The Configuration of the Budunion

Studies of the external characteristics of the budunion, its shape, symmetry or asymmetry, bark texture, irregularities, etc. may be quite revealing and informative. Thus, Webber (1926*b*) proposed a system in which rootstock reactions were arranged in "minus" and "plus" series according to stock size (see Figure 24), and wherein "C" represents normal good congeniality of stock and scion. In "C", the budunion is even and smooth and the trunk gradually tapers or decreases in size from the roots upward as occurs normally in an unbudded tree. Such a union is obtained when Navel or Valencia oranges are budded on sweet orange seedlings or even when Eureka or Lisbon lemons are budded on sweet orange or Rough lemon. When the scion overgrows the stock, Webber classified these as C-1, C-2, and C-3 according to the degree of overgrowth, such as when lemons, navels, grapefruit or Valencia are budded on sour orange stocks. In Spain, the most common lemon variety, Berna, when budded on sour orange rootstock produces a severe overgrowth of the stock. Locally this effect has been given the name "mirinaque" because it resembles the old-fashioned hoop skirts worn by women in the 1890's. Gonzalez-Sicilia (1968) describes this condition and uses its regional vernacular terminology, but makes no mention of health, vigor, or yield of affected trees. In general, the size of the stock trunk decreases and so does the size of the scion trunk. Webber arranged in a "plus" series those combinations in which the stock overgrows the scion. Thus a C+l would be exemplified by navel or Valencia on grapefruit root. A C+2 would be sweet orange scions on trifoliate orange root and a C+3 sweet orange on China lemon. Webber also mentions that as stock size increases the scion size decreases.

The author has accepted Webber's designation, but has modified it to fractions for simplification. The author never could remember what a C+l or a C-2 was. Using the fraction system, the scion is represented as the numerator and the rootstock as the denominator. 1 = 0, 2 = slight, 3 = moderate, 4 = severe. Thus, the author proposes to have a 1/1, 2/1, 3/1, 4/1, or conversely, 1/2, 1/3, 1/4. Webber somewhat confuses normal unions in which actual stock and scion girth may be equal or different, as compared to those in which there is an actual bulge at the union. Under his system he indicates a navel on trifoliate orange as C+2, but in 40 or 50 year old trees it could easily approach a C+4, suggesting a high degree of incompatibility. There are many healthy vigorous and productive trees of this age with this type of a budunion. Bulges which usually occur in the scion and are the result of impaired translocation of metabolites are generally an indication of incompatibility. Yet there are combinations at Riverside such a *C. ichangensis* on St. Michael sweet orange (Figure 25) planted in 1933 which would easily be a C-4 by Webber's standards and in 1987 is still a healthy tree. Obviously such a classification system only serves as a guide, and good judgment must be exercised in interpreting the significance of a disparity in budunion girths. The higher a combination is budded, usually the less of overgrowth or undergrowth at the union. Dhillon (1966) also states that the budunion configuration is an important factor in relation to incompatibility of citrus trees and his observations are similar to those of Webber's (1926*b*). Khan (1964) presents some rather grotesque budunion configurations and it is a bit difficult to accept them as normal for the combination in view of the hundreds of combinations the author has grown of healthy trees. Possibly disease complications account for the disparity in such observations. Jensen, Wilcox, and Foote (1927) in reporting observations of budunion configuration of various lemon bud sources on various rootstocks, state that the degree of over-growth of the scion is negatively correlated with the volume of the top. In general, the larger the swelling or bulge at the budunion, the smaller the tree top.

On most budunions the stock is generally round and smooth as with sweet orange, sour orange, Rough lemon, etc. However, with the trifoliate orange and many of its hybrids used as rootstocks, the stock may be deeply ridged and convoluted with bark invaginations extending inward 7 to 10 cm, as in the case of the trifoliate orange or Savage citrange. These large ridges usually represent the extension of the large lateral roots. In the Troyer citrange, Carrizo citrange and other trifoliate hybrids, the stock may be slightly ridged, but in contrast with the Morton citrange, the stock is round and smooth. Most mandarin stocks will also show some slight ridging and it may be found to some degree in other stocks. Sometimes the stock ridging extends into the scion where it is usually an indication of a large lateral root immediately below it. Mandarin trunks may also be prone to slight ridging aside from the root influence.

The shape of the budunion may also be influenced by the presence of disease. Thus, when Morton citrange or *C. macrophylla* are used as stocks under oranges, the normally round and smooth appearance is changed with the introduction of the tristeza virus to a rough, bumpy, striated condition referred to as "ropey trunk" as a result of very severe stem-pitting (see Figure 26). Trifoliate orange stock affected by exocortis will not show the extreme rootstock overgrowth of healthy trees. Eureka lemons on Troyer citrange stock affected by incompatibility will not show a normal Troyer stock growth (Figure 27 [*Image could not be located*]).

Usually the budunion is easily detectable externally by the difference in size between stock and scion, but not always. Different bark texture of stock and scion may aid in determining it. While most bark textures are similar, the bark of citron or Rangpur lime may be lighter in color than the scion, and in this case will be somewhat flaky. Mandarins as rootstocks may have a slate-brown color readily discernable from the scion. Certain cultivars tried as stocks such as Poorman's orange, Sanford citrange and others have a genetically induced scaly bark condition which should not be confused with those caused by diseases such as exocortis and psorosis (Wallace, 1978).

False budunions occasionally occur in citrus, but their cause is not always definable. For example, in some areas of California subject to heavy surface flooding, budunions may have been buried under a foot or more of soil and for obvious reasons never excavated. In looking for such budunions in association with tristeza studies and proper rootstock identification, sometimes constrictions in the scion variety under the soil line closely resembled a budunion. In another case, an orchard was sprayed with 2-4-D for weed control purposes and apparently over dosed. At the soil line, the rootstock was severely constricted (see Figure 28) and appeared to be a second union. The author has grown most of his research trees and exercised close surveillance over their propagation, yet occasionally a tree has appeared to have an intermediate stem piece. In Spain during 1968, the author also observed several trees in an orchard which appeared to have an interstock (Figure 29), but the grower assured him the trees had never been topworked. While such incidences are rare, they may occasionally occur.

Usually the external location of the budunion agrees exactly with the internal location. The author has observed, however, some budunions in which the external appearance of the bark of the stock is so distinct from that of the scion variety that the external union of the two tissues is 4.5 cm away from the internal union, and in some instances more (see Figure 30 [*Image could not be located*]). Also, it is not uncommon to find scion suckers arising on the rootstock and as much as 2.5 to 5 cm below the union, particularly with trifoliate orange stock and its hybrids (Figure 31). One might attribute some of these occurrences to double budding and eventual sprouting of the latent buds, but the frequency and diversity of such observations makes one wonder if all such observations can be reconciled with such a procedure.

Occasionally, graft hybrids arise at the budunion and result from an adventitious bud which initiates from the union of stock and scion tissues. Examples of this phenomenon are the Kinkoje-unshiu (Kinkoje and Satsuma) and Kobayashi-mikan (Natsudaidai and Satsuma) of Japan. The famous "Arancio bizzarria" (sour orange and citron) of Nati (1929) is another illustration and so is that of sweet lime plus sour orange described by Casella (1935). Probably graft hybrids occur more frequently than suspected, but the common cultural practice of removing suckers from the budunion area most likely eliminates most of them before they are recognized as such. The possibility of using certain graft hybrids as rootstocks should be considered. They would of course have to be vegetatively propagated.

Known Incompatibilities

While known occurrences of incompatibility in citrus are many and varied, most instances involve specific problems with rootstocks of Rough lemon, the Calamondin and kumquat hybrids, the trifoliate orange and its hybrids, other citrus relatives, and the lemon-budunion situation. There are, of course, others, but less frequently than the above. Those not falling into these general categories will also be pointed out.

The calamondin-kumquat-hybrid complex:

Lee (1925) first pointed out that Valencia oranges in the Philippines had poor budunions on Calamondin. He also pointed out that Oneco mandarin (Ponkan) had good budunions on this stock. DeLeon (1930) indicated that Tahiti lime, pummelo, grapefruit, and lemon did poorly on this stock in the Philippines, but recommended it for limes other than Tahiti, as well as for mandarins. Temple orange and Marsh grapefruit were designated as incompatible on calamondin by Traub and Friend (1930) and Friend, Mortensen, and Stansel (1932). Later, Friend (1938) and Mortensen (1954) classified the calamondin as an unreliable rootstock in the Lower Rio Grande Valley and in the Winter Garden area of Texas. In California, Webber (1943) pointed out that Eureka and Lisbon lemons, Washington navels, Valencia orange and Marsh grapefruit did very poorly on calamondin and that many of the trees died at an early age. He makes no statement regarding the budunion, which usually shows some external symptom of the disorder, and failed to point out that Satsumas on this rootstock performed satisfactorily.

Marloth (1958) mentions that in South Africa, Marsh grapefruit trees on calamondin made such poor growth that they were removed after two years. Nagami kumquat trees on calamondin rootstock were compatible according to Traub and Friend (1930). Tanaka (1932) states that the calamondin was used as a rootstock in the Changchou area of China, although it was not specified as with what scions, but Webber (1948) implied that it was probably with mandarin scions. Baker (1934) reported that Meyer lemon did well on calamondin. Olson (1958) reports that kumquat hybrids have not done well on sour orange rootstock, and Robinson and Savage (1934) indicated that in Florida limequats succeeded on any common stock except sour orange. Traub and Friend (1930) stated that calamondin and Eustis limequat were uncongenial on sour orange rootstocks.

A budunion disorder of calamondin was called to the attention of Weathers and Calavan (1959) when it was noticed in a citrus variety collection at Santa Barbara, California. Affected trees were found on rootstocks of grapefruit, sweet orange, and Troyer citrange. Subsequently, other affected trees were discovered on rootstocks of trifoliate orange, sour orange, and lemons in other citrus areas of California. Almost all calamondin trees over four years of age, and on roots other than their own, show the abnormality. Calamondin trees growing as seedlings or cuttings show little or no evidence of the abnormality. They concluded it was a bud-perpetuated, non-transmissible disorder. The author (unpublished) observed budunion abnormalities with Valencia orange trees on calamondin in the tristeza plantings at Baldwin Park (Bitters and Parker, 1953), and in rootstock plantings made in the Coachella Valley of California (Bitters, 1960), but the trees were not in distress after 13 years of age. However, Marsh grapefruit and Eureka lemons on calamondin in the desert area were in severe decline within three to four years, but Dancy tangerines on calamondin stock performed well.

A similar budunion disorder of both old-line and nucellar-line Red Blush grapefruit on calamondin and other kumquat hybrid rootstocks was described in Texas by Cooper and Olson (1956), and Olson (1954, 1958). Many other instances of failure of calamondin as a rootstock were reviewed by Olson (1958) and Webber (1948) and will be discussed in more detail later in the text. A budunion disorder with Nippon orangequat on sweet orange was also noted by Weathers and Calavan (1959) in California. Similar budunion abnormalities were observed with Eustis limequat on Sunshine tangelo, grapefruit, and sour orange by Olson (1958).

Weathers and Calavan (1959) in California obtained no evidence of virus transmission to any inoculated seedlings of sweet orange, sour orange, calamondin, West

Indian lime, Sunshine tangelo, Rangpur lime, or Palestine sweet lime when they used buds from severely affected calamondin trees as a source of inoculum. They also grew nucellar seedlings of calamondin and propagated them on rootstocks of sour orange, sweet orange, grapefruit, Troyer citrange, Morton citrange, trifoliate orange, Willow leaf mandarin, Wekiwa tangelo, and Rangpur lime. Some of these seedlings were inoculated with buds from affected calamondin trees, others left as checks. Scions from affected old-line calamondin were propagated on seedlings of sour orange, sweet orange, grapefruit, Troyer and Morton citranges, trifoliate orange, Willow leaf mandarin, Rangpur lime, Wekiwa and Sampson tangelos, Ponkan mandarin and Rough lemon. Wekiwa and Sunshine tangelos were also grafted with seedlings of calamondin, and others were inoculated from affected trees. With the nucellar lines on sweet orange, grapefruit, Troyer and Morton citrange, trifoliate orange, and Rangpur lime there were no symptoms of decline after three years. With the nucellar line, calamondin on Wekiwa tangelo, Willow leaf mandarin, and sour orange, both inoculated and check trees declined. In the buds from old-line calamondin, all those except on Rough lemon wilted and many died. With the Wekiwa and Sunshine tangelo on calamondin inoculated with old-line calamondin buds, there were no effects after three years. The time period for observations may have been too short for some symptoms to develop. All this is very confusing. Weathers and Calavan suggest that if a virus is involved, it must be seed transmitted (which seems unlikely), and either carried in the rootstock seedlings of the calamondin seedlings. The causal agent could also be transmissible by a vector or by mechanical means.

In Texas, Olson (1954) noted Shary Red grapefruit, Webb Red Blush grapefruit, and Valencia trees on calamondin had a budunion disorder. Shary Red grapefruit or Valencia orange on lemonquat showed symptoms similar to those on calamondin. Several trees of Webb Red Blush grapefruit on Tavares limequat also showed problems at the budunion. Budded trees on Glenn citrangedin also showed budunion crease. Olson (1958) postulated that since seedlings of calamondin, lemonquat, red grapefruit, and sweet orange grew normally, whereas certain budded combinations showed budunion crease, it would seem possible that the disorder was related to interaction between specific rootstock and scion varieties. It seemed desirable, therefore, to determine whether the disorder was of virus origin and other scions were susceptible. He found that old-line grapefruit on sour orange was compatible, but observed budunion crease with the same scion on calamondin and lemonquat. Olson showed that nucellar Red Blush grapefruit, old-line Red Blush grapefruit, nucellar Valencia and old-line Valencia all displayed budunion crease on calamondin rootstock within two to three years. However, nucellar Eustis limequat, old-line Eustis, nucellar Lakeland limequat, and Meyer lemon showed no symptoms on calamondin. He also found that calamondin, Cleopatra mandarin, Columbian sweet lime, Sunki mandarin, and Rangpur lime on Eustis limequat showed no budunion problems in two years time, but on sour orange and Sunshine tangelo there were problems. He concluded the problem was not a virus, but rather a localized incompatibility, and probably could be prevented by the insertions of a proper interstock.

Olson and Frolich (1968) reviewed the calamondin budunion problem. They point out that this disorder was also reported by Salibe (1961) in Brazil and also by Salibe (1965) in Florida as well. It was also emphasized that while the work of Weathers and Calavan (1959) showed that, while six different rootstock varieties which produced budunion crease when propagated with old budline calamondin tops grew normally when budded with nucellar calamondin buds, when nucellar calamondin buds were inoculated with old budline calamondin tissue the trees also remained free of budunion crease. However, when Weathers (unpublished data) topworked old-line calamondin onto the nucellar calamondin on the same six rootstocks so that the old budline calamondin formed the tops and the nucellar calamondin formed the interstock, the trees developed budunion crease at the lower union between the nucellar calamondin and the rootstock. Evidently, something was translocated from the old budline calamondin across the nucellar calamondin interstock, because nucellar calamondin on the same rootstocks failed to show budunion crease when they were eight years old. Weathers suggested that his old budline and nucellar calamondin were different, even though the nucellar line was a seedling from the old budline (the old story of nucellar variation).

Olson and Frolich (1968) also report that at Weslaco, Texas, eight trees of old budline calamondin propagated on *C. taiwanica* had only one tree of the eight show budunion crease. They emphasize that offtype seedlings of *C. taiwanica* are common and may explain this occurrence. At Indio, California (Olson transferred from Texas to California), nucellar calamondin trees on Carrizo and Troyer citranges grew vigorously for seven years free of budunion crease. However, nucellar and old budline kumquats on the same rootstocks died a few years after budding, and they emphasized that compatibility reactions of kumquat and calamondin are not necessarily identical.

Olson and Frolich (1968) budded a large number of varieties on calamondin rootstock. Table 13 shows the varieties which were compatible and showed no budunion crease after 2-1/2 years.

Table 14 shows a list of those varieties which Olson found to be incompatible on calamondin stock and showed budunion crease at the end of 2-1/2 years.

When old budline calamondin was grown on sweet orange rootstock in California, or a nucellar grapefruit top was grown on calamondin rootstock in Texas, budunion crease developed. However, when Cleopatra mandarin on Rough lemon was used as an interstock between incompatible components, budunion crease failed to develop within a three-year period, see Table 15.

Although Swingle considered calamondin to be a mandarin-kumquat hybrid, the incompatibility reactions of the kumquats were not identical with those of the calamondin. In California, old budline (Nagami) kumquat trees grow well on calamondin and on sweet orange rootstocks, and make excellent unions. However, old budline calamondin tops with kumquat interstock on sweet orange rootstock developed mild budunion crease between the sweet orange and kumquat. Also, calamondin grows well on Rough lemon rootstock whereas kumquat does not. Old budline (Nagami) kumquat trees on Rough lemon rootstock show a swelling like a collar at the budunion. In Florida, this disorder termed “Podagra” was neither infectious nor transmissible according to Knorr (1957). Olson concludes, as do others like Weathers and Calavan (1959), that budunion crease of certain varieties of citrus on calamondin rootstock appears to result from tissue incompatibility.

Salibe (1961) in Brazil budded old-line and nucellar calamondin on Brazilian Rough lemon and Florida Rough lemon. Three years later there was severe creasing and gumming at the budunion of all trees on the Brazilian Rough lemon, but they were normal on Florida Rough lemon except there was stem pitting and wood discoloration similar to xyloporosis. Salibe (1965) also found Eureka lemon and old-line Selecta de Itabuna orange incompatible on calamondin, and nucellar line calamondin on Natsumikan, Caipira sweet orange, Coachella Eremocitrus, and Brazilian Rough lemon also showed budunion crease.

In the 1927-1930 rootstock plantings at the Citrus Experiment Station, described and discussed by Webber (1948) and Batchelor and Rounds (1948), various scions budded on the calamondin generally did very poorly. The poorest results were obtained with the Eureka and Lisbon lemon scions, and those trees were removed from the orchard very early. The Washington navel, Valencia orange and grapefruit scions did slightly better, but such trees were all discarded before the author arrived at Riverside, 20 years later. All of these combinations showed budunion crease. However, as a rootstock for Satsuma, results were quite good, the budunions were normal and there was no budunion crease. Webber (1948) shows a picture of the budunion and the root system; however, yields were only average.

In the 1948 tristeza plantings at Baldwin Park (Bitters and Parker, 1953, and other related unpublished data from the same plots), the Valencia oranges on calamondin did show budunion crease (Figure 32), but did not react to tristeza. The trees showed little distress up to the time when the experiments were discontinued 13 years later. In the same plantings, the bigaraldin (a putative hybrid of sour orange and calamondin) reacted severely to tristeza, but showed no indication of any budunion problem.

The calamondin was also included in rootstock trials by the author in the desert area of California in 1960. Scions included the marsh grapefruit, Valencia orange, and the Dancy tangerine. The grapefruit and Valencia trees showed a budunion crease problem within a few years, but managed to survive with some distress for at least 20 years. The Dancy tangerine trees did not develop any budunion crease, and were vigorous, healthy trees up to the time of their removal.

The Glen citrangedin (a calamondin hybrid) is incompatible on Carrizo citrange (and probably on Troyer). At South Coast Field Station in California, Valencia oranges on Faustrimedin (a calamondin hybrid) were incompatible, but Eureka and Lisbon lemons on this same stock were still healthy at ten years of age with no sign of budunion problems (Bitters, Cole, and McCarty, 1978). Some discrepancy in calamondin performance may be the result of incorrect identification. Even Hodgson (1967) on page 531 of volume I of The Citrus Industry, describes the calamondin as “sweet and juicy.” It is juicy, but it definitely is not sweet, possessing an acidity that ranks with commercial lemons and limes. In fact, in the Philippines where commercial lemons and limes are not grown, the calamondin is widely grown and used as a substitute for those varieties. While Swingle (1943) suggests that the calamondin “is very probably and orangequat that arose in China by insect cross-pollination of a sour, loose-skinned mandarin orange and a kumquat,” the cultivar in the first place should not have been designated as an “orangequat.” While it has some morphological similarities with the kumquat and some of its physical responses in scion-rootstock combinations also resemble certain kumquat reactions, recent unpublished isozyme studies at the Citrus Research Center, Riverside, would seem to confirm that there is no genetic relationship between these two cultivars.

As early at 1905, Coit in Florida referring to rebudding frozen trees, stated with reference to the kumquat (probably Nagami) that one does not bud directly onto the Rough lemon since it is incompatible, but rather buds onto the sprouts of the oranges and grapefruit. This may have been the first report of incompatibility with kumquat and Rough lemon. Hodgson (1967) on page 580 of volume I of The Citrus Industry shows a 30-year-old Nagami kumquat on sweet orange rootstock. In the old citrus variety collection at Riverside, Nagami did very well on trifoliate orange and sweet orange as rootstocks. Later plantings of Nagami on Troyer citrange rootstock also did well at Riverside. W. Reuther presented the author with a picture of a 13-year-old Nagami on Swingle in Venezuela. The budunion looks fine (Figure 33). Nagami can also be successfully propagated on calamondin. The problem seems to be more acute with the Meiwa variety. In Japan, the Meiwa is grown exclusively on trifoliate orange rootstock. In my many visits to Japan, the author is unaware of any incompatibility problems. The original source of Meiwa at Riverside was on trifoliate orange and was healthy up to the time of the orchard's removal nearly 30 years later. The author also has a Meiwa on trifoliate orange in his back yard, which is now 21 years old and showing no budunion problem.

In California, Meiwa kumquat is incompatible on Troyer citrange (and probably on Carrizo). It is also incompatible on the calamondin and on Citrus shunkokan (Figure 34 [*Image could not be located*]). Also, in the tristeza trials at South Coast Field Station (Bitters, McCarty, and Cole, 1974*a*), Valencia trees on Meiwa, and *F. hindsii* are incompatible (Figure 35 [*Image could not be located*]). Eureka and Lisbon lemons on these same stocks are also incompatible (Bitters, Cole, and McCarty, 1978). In the Baldwin Park tristeza tests (Bitters and Parker, 1953), Valencia oranges on Thomasville citrangequat showed no tristeza problems and no budunion problems after 13 years. Thomasville and Sinton citrangequat at Riverside have also not shown any budunion problems when grafted on several miscellaneous rootstocks.

In Italy, Russo (1969) reports that all trees of seedling Meiwa kumquat budded on sour orange showed decline symptoms within 2-3 years. He also reports observing the same situation in Spain. McClean and Engelbrecht (1958) report that Nagami kumquat budded on seedlings of Nagami were incompatible. This is not surprising since Nagami produces only hybrid seedlings.

The Rough lemon complex:

There are many problems of incompatibility of various scions on Rough lemon rootstock. Nour-Eldin (1959) noted budunion crease on more than 90 per cent of the trees of Baladi sweet orange budded on Rough lemon rootstocks. He also observed budunion crease in about 80 per cent of the blood oranges budded on Rough lemon, but doesn't state specifically the varieties of bloods. Salibe (1961), and Knorr (1957) report problems of kumquats budded on Rough lemon. Fernández Valiela (1961) also found problems of blood oranges budded on Rough lemon. Salibe (1965) found Shamouti and Pera oranges incompatible on Florida Rough lemon, but when he inoculated with Pera buds into nucellar Bahianinha on Florida and Mazoe Rough lemon, the trees were normal; however, buds from the same Pera budded into two other cultivars of Rough lemon showed budunion crease on both. The list of scion rootstock combinations exhibiting budunion crease included many sweet orange varieties budded on Rough lemon (Fernández Valiela, 1961; Grant, Moreira and Costa, 1957; Grimm, Grant and Childs, 1955; and McClean and Engelbrecht, 1958). Rodriguez (1968) in Argentina indicated all Pera sweet oranges budded on Rough lemon showed budunion crease. Bhutani, Bakhshi, and Knorr (1972) pointed out that Mosambi sweet orange and Blood red (Malta) orange showed decline on Rough lemon rootstock. In South Africa, McClean (l974*c*) found no problem with Marsh seedless and Ruby Red grapefruit on Rough lemon. However, Triumph grapefruit, probably a hybrid, had budunion crease. The same applied to Jackson grapefruit, a seedling sport of the Triumph, and also to a seedling of Jackson. Three Ruby grapefruit seedlings scions on Rough lemon also showed mild symptoms at the union following inoculation with buds from trees of sweet orange on Rough lemon with a faulty union. McClean (l974*a*) states that the abnormal union that some sweet oranges make on Rough lemon varies in degree. The most common orange varieties on Rough lemon affected are Valencia and Washington navel. He only found problems in one orchard of Valencia old-line, but most navels were affected. The Palmer navel, a seedling of Washington navel, was not affected. Mid-season varieties affected on Rough lemon are Tomango (a blood), Ruby, Shamouti, Jaffa, Hall's Midseason, and Letaba Early. There are prominent fissures on the outside of the budunion. Premier, Mid-Knight, and Mediterranean sweet showed well-defined internal budunion symptoms similar to those on Washington navel. Consequently, he recommended the use of Empress mandarin or sweet oranges as rootstocks for the South African midseason range varieties. Midseason varieties that usually make normal unions on Rough lemon are Hamlin, Clanor, and Cape seedling.

In propagating sweet oranges on Rough lemon from parent trees showing abnormal unions on Rough lemon, McClean found 100% of the progeny affected. He obtained marked internal and external bark symptoms on Addorosa, Blood, Hall's Midseason, Jaffa, Letaba Early, Maltese Blood, Shamouti, a questionable Shamouti hybrid, Tomango, and Valencia. Milder external but marked internal bark symptoms were obtained on Viciedo, Premier, and two sources of Washington navel. In an inoculation test, scions from some old lines known to make a normal union with Rough lemon, and also some seedy lines, were inoculated with buds from affected trees. Most trees from Seedy, Malta Egg, Pineapple, Valencia, and Washington navel developed abnormal unions; the checks did not. Of the old budlines there was no problem with Baths, Eloff, Rico, and Hamlin, although some trees of Moss, Pine, and Pretoria Navel did have problems. The tests indicated it was a transmissible factor and the severity of the reaction did not vary with the source of the inoculum.

In Florida, Bridges and Youtsey (1968) found no problem with nucellar lines on Rough lemon. Only certain old clonal lines of Hamlin, Pineapple, and Valencia showed budunion crease on Rough lemon. There was no correlation with the presence of tristeza, Xyloporosis, veinenation, or psorosis. If a genetic factor was involved, only individual clones are affected and not varietal groups. They felt the factor responsible was not apparently transmitted by insects or through seeds, but made no actual transmission tests.

Grimm, Grant, and Childs (1955) found a high incidence of budunion crease of sweet orange on Rough lemon in Florida. They did not find it with grapefruit on Rough lemon, or sweet orange on sour orange. The fact that some trees were free of the disorder and others were not makes it difficult to explain the situation on the basis of inherited incompatibility, and they did not specify what varieties of sweet orange were involved. Working in Brazil, Grant, Moreira, and Costa (1957) observed a budunion problem with Pera sweet orange on Florida Rough lemon, but the problem was absent on a Brazilian Rough lemon, and that didn't appear to be associated with known virus diseases. In India, Bakhshi and Singh (1966) reported a budunion crease on Malta Blood red and Mosambi sweet oranges on Rough lemon. The Malta (non-blood), Jaffa, and Valencia were not affected. In South Africa, Marloth (1938) reported Shamouti and Tomango sweet oranges developing budunion crease on Rough lemon. Marloth (1957) adds Addorosa, Cadenera, Maltese Blood, Natal, Homosassa, Ruby Blood, Ruby Early, St. Michael's Blood, and Verna on Rough lemon as showing budunion crease, but not on sweet orange. To the list, McClean and Engelbrecht (1958) would also include Viciedo, Letaba, Hall's Midseason, and a hybrid of Shamouti x sour orange. There were also some problems with Valencia, Hamlin, Washington navel, Mediterranean sweet, Pretoria navel, and other local navel varieties.

Russo (1969) reports symptoms of a budunion crease of Moro and Tarocco blood oranges budded on *C. volkameriana* rootstock. The unions are almost smooth with

Tarocco, but are a little more swollen on Moro. In spite of the severe creasing and discoloration, there were no outward symptoms of decline at ten years of age.

At Riverside, nucellar lines of Moro and Tarocco blood oranges on Rough lemon rootstock suffered from budunion crease (Figure 36-1 and 36-2). Perhaps the Moro was more severely affected than the Tarocco. It would appear that all blood oranges (those containing the pigment anthocyanin), and including Moro, Tarocco, Ruby, Maltese Blood, Malta Blood Red, Tomango, etc. will show budunion crease on Rough lemon rootstock and its counterparts, which the author will discuss later. On the other hand, there is no information on the pink varieties (those containing the pigment lycopene), other than that no incompatibilities have been reported so far. These varieties would include the Hope Valencia (South Africa), the Puka Valencia (Argentina), the Cara navel (Venezuela), and the Vainiglia (Italy).

It may be appropriate at this time to point out that many people consider the Rough lemon to be *Citrus jambhiri*, and that it is a monotypic species. To the contrary, the species contains a number of very distinct varieties. Among these are volkamer lemon, gomiri, mithi tulia, soh-jahlia, kata-jamir, soh-myndong, nema-tenga, etc. They vary considerably in their morphological characters and their reactions. A better discussion of these varieties will be found in the text under Rough lemon in the rootstock characteristics section.

Rabe and Lovatt (1986) report that phosphorus deficiency or low phosphorus content in leaves of Rough lemon can result in the accumulation of ammonia, which may approach toxic levels. Phosphorus dependency of Rough lemon is greater than Carrizo citrange (and Troyer), which in turn is greater than trifoliate orange. Perhaps under certain field conditions, the uptake of ammonia, or the accumulation of ammonia, may reach such levels as to be temporarily toxic and cause the effects observed by Ohr *et al.* (1985). Certainly it would leave little trace, and warrants speculation. Nitrite injury cannot also be ruled out. The accumulation of nitrite in soils was thoroughly investigated by Chapman and Liebig (1952). In alkaline soils, they found especially high accumulations of nitrite from the use of urea. In winter periods when the soil is cold, the nitrite sometimes persisted in soils for several months before it was converted to nitrate. No information is available on the sensitivity of Rough lemon rootstock to nitrite.

Occasionally scattered trees on Rough lemon rootstock in California have collapsed and died. Many trees on Rough lemon rootstock in California, particularly on heavy soils, will begin to decline at about 20 years of age. Recently in California, Ohr *et al.* (1985), describe the collapse of Thomson Improved (T.I.) navel trees on Rough lemon rootstock in the San Joaquin Valley. Although many possible causal factors were investigated, none could be identified as the actual cause of the collapse. The problem was specific to the T.I.-Rough lemon combination, and has not been reported as yet outside the San Joaquin Valley area.

In California, although the Rough lemon is not a major rootstock, it has been used with a large number of scion cultivars. In the author's experience, no major budunion problems have occurred. However, in the citrus variety collection at Riverside, five trees of Standard sour orange on Rough lemon at 15 years of age suddenly collapsed and died in a period of about two weeks' time in the 1950's and the cause of the collapse was never determined.

The trifoliate orange and its hybrid complex:

Although the trifoliate orange has not been intensively used as a rootstock worldwide, it has been used most extensively in Japan and Argentina and to a lesser extent in California, Australia, Spain, Turkey, etc. Exocortis disease has been its major problem. In recent years, there has been increasing interest in the use of some trifoliate hybrids like Troyer, Carrizo, Benton, and Rusk citranges and Swingle citrumelo. Most readers are aware that of all commercial rootstocks in common use, the trifoliate orange and its hybrids greatly overgrow the scion variety. Such a severe overgrowth has commonly been termed an incompatibility, although some of the combinations have remained healthy and production for 50-60 years. In some instances, however, because of the severe overgrowth, compression girdling may result at the budunion with some scions on trifoliate, Troyer, Carrizo, Morton, and Savage citranges. Some of these will be discussed later, but attention now will be directed to tree decline primarily caused by budunion crease.

In Brazil, Salibe (1961), examining a 10-year-old Eureka lemon planting, noticed budunion incompatibilities ranging from slight to severe on the following trifoliate hybrids: Savage and Rusk citranges (severe), Uvalde citrange (medium), and Cunningham and Morton citranges (slight). These observations would generally agree with those made by the author in California on those same stock-scion combinations. Salibe also budded seven old-line lemon varieties and two old-line acid lime varieties, as well as nucellar lines, on trifoliate orange and Troyer citrange stocks. Abnormal budunions appeared on both stocks within two years except with Lisbon lemon, Perrine lemon, acido lime, Tahiti lime, and Gallesio lemon. Symptoms were more severe on the trifoliate orange stock than on Troyer citrange.

Russo (1969) in Italy budded Troyer citrange onto sour orange stock, and in four years found budunion abnormalities occurring on many trees. However, after 12 years some trees still remained normal. He stated the same disorder occurred in Spain and felt the disorder was probably due to offtype sour orange seedlings, but in the author's opinion the ratio of offtype seedlings seems too high for sour orange, which is fairly highly nucellar.

Fernández Valiela (1961) observed several citrus varieties on trifoliate orange displaying budunion crease. Fernández Valiela, Fortugno and Corizzi (1965), surveying trees in the San Pedro and Delta Parana areas of Argentina, found that about 80 per cent of the Washington navel trees over 25 years of age were moderately to severely affected by budunion crease. A much lower percentage of younger trees were affected, and budunion crease was frequently seen in healthy thriving trees. The percentage of budunion crease was very low on a local variety called Naranjo Criolla budded on trifoliate. In old trees the incidence was less than 10 per cent. He did not find any budunion crease on any old trees of Valencia, Lue-Gim-Gong, or grapefruit budded on trifoliate, but did find two cases with a lemon variety called "Four Seasons" (probably Eureka).

In Brazil, Salibe (1965) mentions that some sweet orange and lemon varieties are incompatible on trifoliate orange and trifoliate orange hybrids. He tried to heat inactivate the incompatibility factor in Eureka lemon seed and budded seedlings from such a treatment on trifoliate orange and Troyer citrange and all the trees developed budunion crease. He also budded trifoliate orange onto Eureka lemon to see if some toxic substance produced by the Eureka caused the abnormality, but all the trees were affected by budunion crease. He also budded various nursery seedlings to trifoliate orange. Abnormal unions were obtained with Armstrong Seedless, Deodoro, Eureka, Genova, Harris, Siciliano, and Viscosa lemon; Seda and Selvagem lime; Umbigo sweet lemon; and Doce, Etrog, and Comprida citron. Other combinations showing creasing at the union were Eureka lemon on trifoliate orange, and Carrizo citrange and old-line Seleta de Itaboray sweet orange on trifoliate orange and Carrizo citrange.

Foguet and Oste (1968) examined miscellaneous varieties on trifoliate orange in Argentina. They found 51 per cent of the trees examined showed budunion crease. The trees were not dwarfed, but declining. With Ruby Blood, 95 per cent of the trees exhibited budunion crease, and, except for this variety, only 36 per cent showed budunion abnormalities. Pera sweet orange budded into trifoliate took six years to develop symptoms, but Salibe and Moreira (1961) found it only took two years in Brazil.

In South Africa, McClean (1974*b*) grafted seedling lemons onto trifoliate orange and Morton citrange, and inoculated some trees with buds of a Frost Eureka seedling that made abnormal unions on trifoliate orange, and observed them for 15 years. Those scions which made a normal union showed no adverse affect from inoculation, but affected trees usually showed symptoms in two years. Trees of Lisbon lemon grew well for eight years and then began to decline, but showed no abnormal budunions. All unions were normal on Morton citrange, which agrees with the author's observations in California. McClean questions the advisability of budding even Lisbon lemons on trifoliate, and again this would agree with the author's observations in California wherein the trees have not had abnormal budunions, but generally staining and gumming in the trifoliate stock was observed.

McClean and Engelbrecht (1958) also observed some problems with trees of Washington navel, Tomango, and Hamlin oranges showing budunion crease, but all had exocortis. Valencia, Pretoria navel, Du Roi, and De Wilt oranges without exocortis showed normal unions. They also point out some problems with some gametic seedlings of Marsh grapefruit and Washington navel on trifoliate.

In Japan, Miyakawa (1975) and Miyakawa and Matsui (1976) report on a budunion abnormality of Satsuma on trifoliate orange. There is a swelling of the scion variety above the union, and budunion crease at the union (Figure 37 [*Image could not be located*]). When inoculated into Valencia, Hassaku, and Yuzu on trifoliate, the inoculation also caused the disorder. When the author visited Japan in 1976 and observed some of Miyakawa's work, there was also a similar problem of Ponkan on trifoliate. The causal agent appears to be tatter leaf virus, most Ponkan mandarin trees in Japan are infected, and it has been spread somewhat indiscriminately to other scion varieties through topworking operations. The disease also appears to affect Satsuma mandarins on Troyer citrange in Japan.

In California, virus-free Meyer lemon on Troyer citrange displays budunion crease (Figure 38 [*Image could not be located*]). However, if the tatter leaf virus is introduced, the abnormal swelling of the scion above the union also occurs (Figure 39). During the author's tenure in California, he has examined hundreds of budunions with trifoliate orange rootstock. Except with lemon scions there have been no budunion abnormalities other than the usual compression girdling on older trees (Figure 40 [*Image could not be located*]). Recently (1970's), however, there has been a delayed incompatibility of Washington navels on trifoliate. The trees began to display budunion crease before they were 20 years old. The disorder is described by Schneider and Pehrson (1985). The trees examined were at Lindcove Field Station and were planted by the author in 1963. The planting consisted of Frost navel on 24 trifoliate orange selections. A progress report on the orchard performance of the plot was made by Bitters, McCarty, and Cole (1974*a*) after which the plot was discontinued, but not for orchard health reasons. The trees were thus 20 years old when examined by Schneider, and budunion crease was already quite evident on most trifoliate strains except the Rich 16-6. It is not known when the budunion crease first began to appear. Later examinations of the union by Schneider (unpublished) revealed that the Rich 16-6 also was developing creasing. Thus, the creasing develops sooner and more rapidly on the more vigorous growing trifoliate selections, but none appear to be immune. As of 1987, [*text incomplete*]

All of the trees examined were Frost navel. One must presume that all navel strains would probably provide similar results, but trees of Parent navel, Atwood navel, etc. were not examined. The fact that the Thomson Improved navel is the only navel strain described as declining on Rough lemon rootstock by Ohr *et al.* (1985) could, however, raise some questions. Shannon, Frolich, and Cameron (1960) in California gathered a large selection of trifoliate orange strains. I quote, "The authors have observed many large and productive Valencia oranges, Marsh grapefruit, and Washington navel oranges on *Poncirus trifoliate* in old orchards in Southern California." The navels had to be parent navels, and the authors categorized the trifoliate selections into large- and small-flowered types. Of the more than 30 selections, at least four had navel scions. They were the Christiansen (Christian), Taylor, Davis A, and Davis B. It would have been interesting to know the age and condition of these navel orchards, or if any of the orchards still exist. At Riverside, 33-year-old parent navel trees on Rubidoux trifoliate in the 1927-1930 rootstock plots showed no budunion crease when the plots were terminated in 1960, but did show compression girdling. With orchard trees over 30 years of age, the only ones the author has observed with breakage at the union in the removal operations were some on trifoliate orange rootstock (Figure 41 [*Image could not be located*]).

There has been no budunion problem with either navels or Valencias on Troyer or Carrizo citranges up to the present time. Recently, however, there has been a delayed incompatibility of Satsuma mandarin on Troyer citrange, but not on trifoliate. The trees begin to show stress at 16-18 years of age and while there is no budunion crease, there is compression girdling of the rootstock (Figure 42 [*Image could not be located*]). Other scion combinations on Troyer citrange will also show budunion crease. In the Citrus Variety Collection at Riverside, trees of Chironja show this disorder (Figure 43 [*Image could not be located*]) as do some of the mandarin varieties like *C. erythorosa*, Richard's Special mandarin (Figure 44 [*Image could not be located*]), Solid Scarlet mandarin, and others (Figure 45 [*Image could not be located*]). Washington navel on Coleman citrange also shows severe budunion crease (Figure 46 [*Image could not be located*]). In the tristeza trials at South Coast Field Station (Bitters, McCarty, and Cole, 1974*a*; Bitters, 1972) where nearly 200 trifoliate hybrids were tested as rootstocks, approximately 10 per cent of the combinations showed budunion crease. Price and Cook Eureka shows severe problems on #1452 Citrumelo (Figure 47 [*Image could not be located*]), Kirkpatrick, Bitters, and Foote (1962).

In the 1970's, in Tulare County of central California, trees of Minneola tangelo topworked on Clementine mandarin on Troyer citrange rootstock developed budunion crease at the Clementine-Troyer interface. Most likely this is an incompatibility of Clementine on Troyer, since in an orchard formerly owned by the author, Minneola (nucellar) and Orlando tangelo (nucellar) planted in 1960 have, as of 1987, not shown any budunion problems.

Problems with both Eureka and Lisbon lemons on trifoliate, Troyer, and Carrizo citrange have been clearly pointed out by Bitters (1952), Weathers *et al.* (1955), Salibe (1965), Nauriyal, Shannon, and Frolich (1958*a*, 1958*b*), McClean (1974*b*), and others.

However, Long *et al.* (1978) report that Eurekas grow fine on Benton citrange in Australia.

The lemon budunion overgrowth problem and phloem necrosis:

In California, it has long been recognized that lemons, especially Eurekas and some Lisbons, were characterized by the scion severely overgrowing the rootstocks, and that such trees declined at rather an early age. Budunions on sweet orange, Rough lemon and grapefruit were relatively smooth and the trees were longer lived (Batchelor and Webber, 1948). Ruggieri (1937) reported that in Italy, Monachello lemon on sour orange stock also suffered from severe scion overgrowth, and that such trees declined at an early age and some trees died at 20 years of age. With the expansion of lemon plantings in California in the 1950's, several new rootstocks were tried commercially, and others placed in experimental rootstock trials. Some older lemon plantings on Sampson tangelo still had smooth budunions in the 1970's. However, budunion overgrowths were common with all Eureka strains and with some Lisbon strains. Bitters *et al.* (1957) attempted to associate the budunion overgrowth with the height of budding (Figure 48), but while there was some correlation, the overgrowth generally occurred regardless of the height of budding. The problem was reemphasized by Kirkpatrick, Bitters, and Foote (1962), Kirkpatrick (1963), and Kirkpatrick and Bitters (1964). Severe over-growths and subsequent decline were observed in commercial plantings on Sampson tangelo and Cleopatra mandarin and in experimental plantings on Ponkan mandarin, San Jacinto tangelo, Thornton tangelo, a tangelo 'Willial' (Willow Leaf x Imperial grapefruit), Seminole tangelo, Marlow tangelo (Marsh grapefruit x Willow Leaf), Orlando tangelo, Williams tangelo, Minneola tangelo, Mency tangor, Calushu, and Clement tangelo. While Salibe (1965) in Brazil reports some budunion crease with Eurekas on *C. taiwanica*, in California, trees of Limoneira 8A Lisbon on *C. taiwanica* (Figure 49) broke off at the union, as did the Frost Lisbon on Ponkan, (Figure 50-1 and 50-2) and Prior Lisbon on Cleopatra mandarin (Figure 51 [*Image could not be located*]). Some trees of both Eureka and Lisbon showed slight overgrowth on sweet orange, *C. macrophylla*, and Stow grapefruit. No overgrowths were noted with either scion on Rough lemon and #1449 citremon, or with Lisbons on Troyer citrange.

Russo (1969) in Italy reemphasizes the overgrowth problem with Monachello lemon on sour orange, but points out that the nucellar line of Monachello at 16 years of age, although it shows some overgrowth, has not shown a deleterious affect. Russo points out that varieties of sweet orange behave differently when used as interstocks with Monachello. An Ovale sandwich produces almost smooth unions with the sour orange stock and the lemon scion. Many trees of this combination show no decline after 25 years. A Moro blood orange sandwich behaves differently, producing a smooth union with the sour orange stock, but does not avoid the overgrowth of the lemon scion. When Russo interstocked with an Avana mandarin, the sandwich grew more slowly than either the stock or the scion and consequently there is a constriction, but at 25 years of age the trees were still without any symptoms of decline. Russo also found that trees of Monachello on *C. volkameriana* have a smooth union and do not show any symptoms of decline.

The rootstock problem for lemons in California is extremely critical and it is difficult, because of the budunion overgrowth problem and phloem necrosis, to select a suitable rootstock. Some growers are reverting to using sweet orange, and there is some interest in an unidentified cultivar called the Yuma Ponderosa Lemon, which is not a Ponderosa lemon but closely resembles the Cuban shaddock.

All Eureka lemon selections and some Lisbon types like Frost, and the Jameson open type, are characterized by a genetic weakness, which is anatomical in nature and described by Schneider, Foote, and Masters (1951), Calavan *et al.* (1951), Schneider and Witt (1952), Schneider *et al.* (1961), Schneider (1960*b*), and Platt, Burns, and Schneider (1972) as being due to lemon sievetube necrosis. Such trees are prone to early decline under any conditions and on any rootstock. While such trees may remain in healthy condition longer on certain rootstocks, other rootstocks such as sour orange (Schneider, 1952*a*, 1956; and Schneider *et al.*, 1978) or *C. macrophylla* (Schneider, 1960*a*; Schneider *et al.*, 1978) are also prone to sieve-tube necrosis, and when this situation is combined with weak scions the problem is greatly aggravated and the trees may decline and collapse at a very early age—some at five to six years of age. The problem is not alleviated by passing the weak lines through the nucellar process (Schneider, 1960*a*). Genetically weak lemon selections should be avoided and precautions should be taken to choose the most suitable rootstocks in order to avoid the problem.

Other miscellaneous incompatibility problems:

In Egypt, Nour-Eldin (1959) observed a budunion overgrowth of Beladi sweet orange budded on Beladi sweet orange rootstock in 40 per cent of the trees examined, which exhibited discoloration of the phloem and stem pitting. Frolich and Hodgson (1961) report on an apparently new virus disease of Rangpur lime and citron on sweet orange, including an infectious agent. Reciprocals are not affected. Rangpur lime grows normally on sour orange and as cuttings. It does not affect Rangpur lime or sweet orange alone. Symptoms are dwarfing, chlorosis, sparse foliage, early and heavy blossoming and repression of stem thickening of the rootstock. In Argentina, Fernández Valiela (1961) reported a constricted budunion on about 8% of six year old trees of Selecta sweet orange budded on sweet orange.

In Brazil, Moreira (1938) reported symptoms of a budunion disorder in trees of Pera sweet orange and Selete de Itaborai orange on sour orange root. Salibe (1961) budded old-line and nucellar lines of both (Pera and Selete) on Florida Rough lemon and trifoliate orange, and two years later observed abnormal budunion and budunion crease at the union. In Israel, Reichert, Bental, and Ginsburg (1956) describes affected trees of Marsh seedless grapefruit on sour orange which also had abnormal budunions and constrictions or creasing at the union with no gumming, but inverse pitting in the sour orange. This condition could possibly have been xyloporosis.

Salibe (1961) also reports a budunion disorder of Lue Gim Gong on extensive stock-scion combinations in which the possibility of incompatibility is an unknown factor.

CITRUS ROOTS, ROOT SYSTEMS, AND FACTORS AFFECTING ROOT DISTRIBUTION

Most growers, in observing a citrus tree, seldom recognize that approximately half of that tree is underground. The character of the roots, the depth of root penetration, and factors affecting the roots and root penetration are extremely important in determining the total performance of the combination as an orchard tree. The nature and extent of the root system are important elements in the so-called top/root ratio which many growers consider important in the critical, and sometimes disparaging, execution of the tree's ability to reach its expected potential within an orchard.

According to Wallace and Nauriyal (1958) the citrus root system is relatively sparse and ordinarily, under field conditions, there are no root hairs. However, Monselise (1947) and others did find the presence of root hairs. Wallace and Nauriyal (1958) estimate the total root system of a citrus tree to be between 16-33 km long, which is less extensive than a single wheat plant.

The root system of the tree consists of varying amounts of fibrous roots, laterals, and tap roots, the degree and extent of which may vary with the given rootstock cultivar and the total environment to which the tree or rootstock may be exposed. Fibrous (feeder) roots vary in texture, reflective of the texture of the twigs of that cultivar as a scion variety. Thus, if sweet orange, or sour orange are considered as intermediate examples in this aspect, then the fibrous roots of grapefruit and shaddock may be a little thicker and stubbier, and the fibrous roots of the mandarins may be a little finer or thinner in texture. The color of the roots is generally a basic brown on standard stocks like sweet orange and sour orange, a little darker slate brown on mandarins, and a lighter brown on trifoliate orange, Rangpur lime, citron, etc. The roots are usually smooth, but occasional variants (shaddocks, trifoliate hybrids) may have various degrees of scaling. If the root cultivar is susceptible to shellbark or exocortis then the shelling or scaling will extend to the root extremities (Figure 52-1 and 52-2). Some roots such as on shaddocks, Clementine or several trifoliate orange hybrids, will develop corky areas on the bark which will vary from slightly raised reddish brown bands which the author terms "zebra roots" (Figure 53-1 and 53-2) to very rough, irregular, corky bands (Figure 54) up to 1 cm in thickness. In cross-section, the roots are usually round, but those of trifoliate orange are severely flattened in a vertical axis, particularly in the upper 30-45 cm of soil (Figure 55-1 and 55-2). Other roots may flatten somewhat at lower depths as they come in contact with soil stratification. Many of the roots 2.5 cm or larger may exhibit numerous "frog-eye" gummosis lesions (Figure 56). Others may be pocked with numerous scars from Fuller's Rose Beetle—particularly the lemon-lime group of rootstocks (Figure 57-1 and 57-2). The roots of most species emerge from the crown in either a vertical axis, as in tap roots, or in gently sloping angles in the laterals, others in oblique angles, as in sour orange. The roots of trifoliate orange may emerge from the crown at a downward axis and then veer laterally at sharp angles to provide a "knee-like" structure (Figure 58-1, 58-2 and 58-3).

Sometimes a surface root may become entwined around the upper root axis and girdle the rootstock trunk, causing decline and eventual death of the tree. In one ten-acre lemon orchard in Ventura County, over 100 trees, or nearly 10% of the trees, were so affected (Figure 59-1 and 59-2). Roots will frequently graft (Figure 60) with one another causing "root-grafts" (not to be confused with interstocking). Root grafts occur rather commonly and are a means of disease transmission from one tree to another (Wallace, 1978). Commonly they may occur more when the root zone is compacted by soil stratification and root density is high. They may occur more commonly within the same cultivar such as Rough lemon to Rough lemon, and less commonly between two different cultivars such as Rough lemon and Cleopatra mandarin. The highest concentration of root grafts observed by the author in California was in a Valencia orange cutting where more than 12 grafts were noted (Figure 61-1 and 61-2) in an area of 60-100 cm.

There has always been the question of bench-rooted seedlings (Platt and Opetz, 1973) and their ultimate performance, also mentioned in this text. They are usually discarded when seedlings are removed from the seedbed and lined out in nursery rows. One of the advantages of bare-rooting nursery trees is that the "bench root" budlings, or those budlings with poor root systems, could be discarded. In balled-budlings there is no such opportunity. In 1944, L. D. Batchelor, at the Citrus Experiment Station, Riverside, planted out 15 Valencia trees on bench-rooted Morton Citrange stock and compared them to 15 comparable adjacent trees with normal root systems. The author did not see the original root systems. But, when the trees were pulled in 1960, 16 years later, the author observed no differences in top appearance, tree size, yield, or the character of the root systems. Perhaps bench roots aren't as critical a problem in the orchard as growers have assumed.

The temperature requirement for root growth appears to be rather specific [*"*Check*" appears here in typescript in the margin of the manuscript – may mean check what the references say, or may mean check the generality in the first sentence*]. Wallace and Nauriyal (1958) indicate 18°C minimum; 29°C optimum; and 38°C maximum. However, they indicate the optimum temperature is never reached in the root zone in the coastal area of California since the maximum temperature reached is only 21°C. Similar minimum temperatures for root growth have been reported by Cossman (1939), Monselise (1947), Waynick and Walker (1930), Girton (1927) and others. Seasonal soil temperature cycles may be an important single factor in behavior and performance of rootstocks in varying climates (Reuther, 1973).

Root growth is cyclic, it generally alternates with shoot growth, usually precedes it, and synchronizes with trunk growth. In Israel, Cossman (1939) reports growing roots could be found throughout the entire winter season. The most intense root growth periods were in the spring and autumn and of relatively short duration. Sweet lime roots reacted to temperature fluctuations more strongly than the roots of sour orange. Monselise (1947) also states that root growth alternates in most cases with shoot growth and stresses that soil temperature and soil moisture are important factors. In California, Crider (1927) observed that roots do not grow continuously but alternate with shoot growth. Total root elongation and greatest rate of growth was much greater during the first (spring) rather than the second (summer) and last periods (fall). Total root growth as well as the rate of growth during the second or mid-season growth stage was decidedly less than the first and last period. The rate of root elongation was considerably greater during the night rather than during the day. Roots were inactive during the winter and early spring, and Crider suggests that this is the best time to cover crop or interplant.

Waynick and Walker (1930) observed in California that growth of the roots in the subsoil preceded growth in the upper foot of soil by nearly 28 days in the spring. Root growth preceded shoot growth except in the fall, when the growth cycle seemed to coincide. This condition may vary in other citrus areas. They also noted a difference in root growth with different scions and different aged trees. In October, when the last growth cycle was completed, there was only scattered growth of roots in the upper 45 cm of soil with old trees. Grapefruit Trees showed little development while Valencia trees showed a moderate growth, but only in the upper 56 cm of soil. In contrast, yearling Valencia trees in the same soil developed a heavy root growth. Waynick and Walker measured soil temperatures at 15-35 cm, 51 cm, and 66 cm. The soil temperatures at 36 cm and above were consistently lower by 2°C than lower depths until mid-April. The average subsoil temperature in [*"Check" appear here in typescript in the margin of the manuscript*] late March was 13.8°C, or just above the minimum of 12°C reported by Girton (1927). The soil temperature below 51 cm averaged 1.5°C less than that from 36-45 cm, and it was in this area that the most active root growth took place. In March, subsoil root growth was first observed. There was no root elongation above 36 cm, but root growth was general between 36-51 cm. The growth rate of the roots varied from .62—1.60 cm daily. Rootlets elongate at the rate of .32-1.27cm per day in an active cycle. Root growth ceased the first week in April, when top growth occurred. Root growth resumed in September and lasted five weeks. In a three week period the rootlets grew as much as 36 cm, and the size of the roots doubled. Their data show growth of the roots is cyclic and precedes top growth. There is a brief rest period when roots cease to elongate and the growth of the top begins. There are 2-3 month periods when the roots fail to elongate. Roots make very poor growth when severed by cultural equipment, even in two year's time. They emphasize the important relationship of irrigation and supply of nutrient to the growth cycle of the roots, and question the possible undesirable effects of the heavy application of cold irrigation water when the root cycle is just starting.

In Florida, Ford (1964*a*, 1964*b*) states that citrus root concentration fluctuates extensively during the year. It had been assumed that roots grow in alternate cycles to growth flushes, but this did not seem to apply to the situation in Florida. Root concentration was usually lowest in August and highest in September. He stresses the importance of taking root samples at the same time of year. Soil temperatures in Florida citrus orchards are higher than those in California throughout the root zone during the entire year (Reuther, 1973). Tully (1947) also noted that in citrus trees shoot and root growth usually alternate.

Root Systems

Root systems are generally observed and classified by either complete excavation of the root system, digging trenches, push and pull procedures, removal of soil cores, or use of special technical devices. Factors affecting root distribution are the scion variety, environment, temperature, age of tree, water relations, drainage, salinity, nutrition, diseases, soil types, soil stratification, pruning, cover crop, etc. Therefore, it is understandable that there is considerable discrepancy in the descriptions of root systems as described by various observers.

An old adage is that lateral roots of a tree extend radially from the trunk to a distance equal to that of the height of the tree. A 4.6 meter tall tree would thus have roots extending laterally in all directions to a distance of 4.6 meters. There are, of course, many exceptions to this rule as root distribution is affected by many factors. Under many circumstances, the lateral spread of the roots is such that at any normal orchard spacing there is considerable intermingling of roots from adjacent orchard trees.

Perhaps the earliest recorded observations on citrus root systems are those of Mills (1902) in California. On excavated trees grown on [*"Check" appear here in typescript in the margin of the manuscript*] loam soils in Ventura County, he characterizes sweet orange as having a shallow root system. The main mass of the root system of bearing trees on sweet orange stock are concentrated in a horizontal layer about 45 cm thick, the top of which was 20-25 cm from the surface, with crooked tap roots. The tap root of grapefruit was also crooked. The lateral roots develop at the expense of the tap roots, making a prodigious root system. A seven-year-old seedling had a tap root 120 cm long. The largest lateral root started 60 cm below the soil surface and extended for a distance of 8 meters at an average depth of 45 cm below the surface. Over 90 percent of the root system was confined to a layer 25-60 cm below the surface. Grapefruit had a much larger number of fibrous roots than sweet orange, and the roots were deeper beneath the surface, the majority below 38 cm. A nine-year-old navel tree on sour orange had the largest and uppermost lateral, which started 15 cm below the surface and descended immediately at an angle of 45° to 2.5 cm below the surface to a distance 3 M from the tree, when it rose to within 20 cm of the surface. It was then cut by cultivation equipment, grew downward 2.5 cm and horizontally 2.4 meters more. The longest tap root was approximately 3 meters, maybe the deepest recorded in California. Those trees on sour orange with few laterals were less productive than those which had numerous laterals near the surface.

Hume (1926) states that in Florida's Hammock soils, sour orange roots are produced abundantly and penetrate well into the soil. He felt that this was an advantage over sweet orange since the trees were not so readily affected by variations in soil moisture. The roots penetrate sufficiently deep to be more or less in contact with a permanent water supply. Hume also says that under these conditions, sour orange suffers less under prolonged drought under identical conditions than Rough lemon. With Rough lemon the main roots show a wide variation. In all cases the crown-roots extend a considerable distance from the trunk and a strong tap root is produced, but occasionally the large lateral roots lie close to the surface and most of the feeder roots are in the top 38 cm of soil. Hume also states that the root system produced by trifoliate orange is very good, as the roots penetrate well and fibrous roots are produced in abundance. He also cites the California experience of Mills (1902) that sweet orange is not deep rooted and that most of the roots are in the top 46 cm of soil. There is lack of evidence in Florida, but in nursery trees, [*"*Check*" appear here in typescript in the margin of the manuscript*] root development of trifoliate orange was equal to sour orange. The root system of grapefruit was well developed.

In Egypt, El Sawy (1932) found the root system of lime heavily branched with abundant fibrous roots. Those trees on citron, sweet lime, and sour orange were sparsely branched with less fibrous roots. The depth of penetration of citron or sweet lime was 41-46 cm, 61-71 cm on lime, and 112-168 cm on sour orange. As far as lateral extension, the citron had the least, followed by sweet lime and those on sour orange.

Brown and El Sawy (1936) observed in Egyptian orchards that the sour orange adapted to heavy soils and was not readily affected by variations in soil moisture. It provided good root anchorage, roots in loamy soils penetrating to a depth of 110-170 cm with a lateral spread of 4-10 M depending on the scion variety. They made no comment about the root system of sweet orange. The grapefruit and shaddock they felt were well adapted to heavy and moist soils, with their root systems well developed and evenly distributed. The Baladi lime (West Indian) was adapted to sandy soils, but not wet or heavy soils. The root system was richly branched and had more fibrous roots than any of the other stocks. The bulk of the roots in sandy soils penetrated an average depth of 70 cm and occasionally to 250 cm. Lateral roots extended to 7 M. The Rough lemon was adapted to sandy soils where sour orange failed to produce a satisfactory tree. Although it had a strong tap root which penetrated deeply into the soil, there were abundant lateral roots which were well and widely distributed and were nearer to the surface than sour orange. The Rough lemon had many feeder roots. The sweet lemon (lime) was also not recommended for heavy soils. Its root system was characterized by downward penetration and lateral expansion similar to that of the Baladi lime, but was sparsely branched and had less fibrous roots in the upper 30 cm of soil. There were no comments on the citron root system other than that it did very poorly on sandy soils.

In Israel, Oppenheimer (1936) examined the root systems of 19-month-old trees on sweet lime, sour orange, Rough lemon, citron, Baladi (sweet orange), Shamouti, sour orange, pummelo, and grapefruit. He says all *Citrus* root systems belong to the intensive type. The lemon-lime group are characterized by strong root branches whose horizontal spread does not fall short of their penetration in depth, and with a multitude of fine absorbing rootlets. Single tap roots are rarely found after transplanting. The surface layers of soil are well provided with roots, except the root system of sour lemon, which showed rather fine root branches and a tendency for deep penetration without strong crown root formation in the surface layers. With Rough lemon the lateral roots changed direction from the horizontal and turn downward. He agreed with Hume (1926) in praise of Rough lemon, "because of the great foraging power of its roots." With sweet orange, he observed a tendency to form a strong tap root system which showed good ramification and a considerable development of horizontally growing main roots. He did not agree with observations by Mills (1902) in California on this, but did agree with Hume's (1926) Florida observations, perhaps because of soil differences. Hume, in Florida, worked in super drained, very sandy soils, warm enough throughout the year for good root growth and root activity. The sour orange, grapefruit, and pummelo tend to form root systems of a conical shape with well developed penetrating central roots, and a monopodial character. None of the upper roots are strong, and most of the lateral roots descend obliquely. The abundance of fibrous roots on grapefruit produces more fibrous roots than sweet orange or sour orange.

In Florida's deep sandy soils, Savage, Cooper, and Piper (1945) examined six-year-old trees of Parson Brown on 15 rootstocks planted at a distance of 30-92 cm. However, some roots were lost in the excavation. Sour orange showed three or more well developed tap roots penetrating 90-125 cm deep. There were numerous small laterals in the upper foot and some of the laterals extended 150 cm from the trunk. The Bittersweet (sour) differed from sour orange in fewer laterals and very few fine fibrous roots. However, the tap roots penetrated slightly deeper than sour orange. With the sweet oranges, Pineapple and Parson Brown, the root systems were very similar. Both showed well developed central roots, usually two, penetrating about the same depth as sour orange, about 90-125 cm deep, with numerous small laterals the full length of the tap roots. The laterals in the upper 30 cm of soil were not as long as sour orange. There were abundant fibrous roots in the first 30 cm. Their data did not agree with what Mills (1902) observed in California's cooler and loamier soils, but rather with Hume's (1926) observations in Florida, that roots of sweet orange and sour orange are about equal in development, which Oppenheimer (1936) also reports in the sandy soils of Israel. Rough lemon had the most vigorous root system of all 15 stocks. It had exceptionally large lateral roots with a spread of 150 cm or more from the trunk. The central tap extended as deeply as sour orange, but the fibrous roots were not as abundant around the crown as sweet orange or sour orange. For Duncan and Bowen grapefruit they found an abundance of fibrous roots and many large vigorous laterals and two or more large penetrating tap roots extending 92 cm with a mass of fibrous roots the full extension. The abundance of fibrous roots agrees with observations by Mills (1902) and

Oppenheimer (1936). The trifoliate orange had deeply penetrating central roots and numerous laterals with abundant fibrous roots in the upper 31-46 cm of soil. The root system was similar to sour orange except for the smaller spread of the laterals. Cleopatra mandarin had a cone-shaped root system with well developed central roots penetrating 125 cm or more. There were long fine-textured lateral roots in the upper 61 cm of soil well supplied with fibrous roots. Its root system didn't differ much from sour orange except the tap root was straight, slightly longer, and less divided. The root system of Suen Kat was similar to Cleopatra. The root system of Morton Citrange had the tap root dividing into several which penetrated vertically and then fanned out, descending obliquely to about 91 cm. The laterals were similar to sour orange, with a good fibrous system. The Rusk citrange was similar in root structure to Morton except there were fewer fibrous roots. The sweet lime root system consisted of many slender laterals and a mass of fibrous roots. There were no tap roots. The root system resembled grapefruit in fibrous roots, but grapefruit had a pronounced tap root. The Cuban Shaddock had a root system almost identical to Rough lemon except it had more fibrous roots. The calamondin had a group of vigorous central roots (four or more) which penetrated deeply, in fact, more deeply than any of the other stocks observed. Yuzu displayed the smallest root system of all 15 stocks observed. It penetrated deeply, and there was a scarcity of laterals. Sweet orange cuttings had a shallow root system with many vigorous laterals which did not penetrate more than 61-91 cm. Savage, Cooper, and Piper (1945) thus concluded that Rough lemon and Cuban Shaddock had the most extensive root system, the calamondin the deepest, and sweet lime and grapefruit had the greatest amount of fibrous roots.

In [*date lacking*] [*"*Check*" appear here in typescript in the margin of the manuscript*], Ross (1956) reported that trifoliate orange produces a well-branched root system with an abundance of fibrous roots which are very sensitive to drying. Robinson (1940) grew ten scion varieties on Cleopatra mandarin and sour orange in Norfolk sand in Florida, and at nine years of age reported that Cleopatra produced a deep tap root with numerous fibrous roots superior to sour orange. In India, Burns and Kulkarni (1920) exposed roots of Santara (mandarin) and Mosambi (sweet orange) on Jamburi from five-year-old trees growing poorly. With the Santara trees 320 cm high, the lateral roots extended 42 M and average 2.5 M. The root spread was greatest parallel to the tree rows. With the Mosambi trees having a height of 2.1 M the diameter spread of the roots was 1.8 M. A 14-year-old tree of Santara had roots with a radius of 3 M with secondary roots of 4.9 M. The laterals were about 23 cm deep. He concluded Jamburi was surface rooting with a fair spread of laterals, but few deep penetrating roots under the tropical conditions of India.

In Ceylon (Sri Lanka), Gandhi (1939) examined the root systems of Mosambi trees (on Rough lemon) planted 5.5 x 5.5 M. The spread of the crown roots was 3.7 M, or less than 1.8 M between trees. Roots had spread 2.7-4.9 M from the crown and at four years the roots were intermingled. Grapefruit trees on Rough lemon at five years had a lateral spread of 4.9 M. Fifteen year-old Santara trees planted 4.6 x 4.6 M had roots which completely intermingled and extended trunk to trunk. The Santara trees on Rough lemon at 14 years had roots extending a radius of 3 M, some 4.9 M, and a similar situation occurred with Mosambi. He only studied the lateral spread of surface roots. He did not feel it necessary to ascertain the distribution of fibrous roots since he felt only the exposure of laterals to a depth of 10-20 cm was enough to give a general idea of the nature of the fibrous roots. Gandhi also stated that the depth of rooting, lateral spread of main and subsidiary roots and their branching, and quantity of fibrous roots are specific characters. These specific characters may vary with different species, but the location of the fibrous roots on the root system did not seem to be a specific character. He felt it appeared to be more a result of environment and cultural treatment.

Montenegro (1970) in Brazil found that sour orange seedlings had more superficial and less horizontal extensive root systems than Caipira sweet orange, and poorer feeder root systems as compared to the well-developed system of the Cravo tangerine. The root system of Caipira sweet orange was deep and had a vigorous feeder root system. The most vigorous root systems were Florida Rough lemon, sweet orange and Cravo tangerine. The least vigorous root systems were Rangpur lime, sweet lime, and trifoliate orange. Hamlin sweet orange scions strongly stimulated feeder root development in rootstocks. This effect was moderate with Pera and slight in Baianinha sweet orange. Root development was more vigorous in well-drained and aerated soil than in imperfectly drained, shallow layered soil. Exocortis and tristeza checked root development. Extensive root development was not necessarily associated with large tree crowns or high fruit yields. As rootstocks for the sweet orange varieties Hamlin, Pera, and Baianinha, Rangpur lime stock showed poorer feeder root development than Caipira, Pera, Cravo tangerine, or Florida Rough lemon. Vigor was medium on Sampson tangelo which is deep rooted like Florida Rough lemon. Trifoliate orange on clay soils produced fewer roots than Florida Rough lemon, Cravo tangerine, or Caipira orange. With Baianinha scions Caipira was more abundantly rooted than Rangpur lime, Brazilian Rough lemon, or sweet lime. Nucellar clones of Baianinha on Caipira had excellent root development superior to that of an old clone on Pera orange or Cleopatra mandarin. Seedlings of Caipira orange rooted more deeply than those of sour orange and Cravo tangerine, and in these instances the roots tended to be massed around the trunk base. Ten-year-old Hamlin oranges on either trifoliate orange or sweet lime had 90 per cent of the root system within 90 cm of the surface, but for all of the remaining ten-year-old combinations of scion and stocks the top 60 cm of soil contained 90 per cent of the roots. On light soils the roots of grafted and seedling trees of Baianinha extended down to 90 cm.

In Japan, Okuchi *et al.* (1962) excavated a single tree of Satsuma mandarin on trifoliate orange which was 22 years of age. Roots extended down to 120 cm so the distribution was similar to that observed by others. Most roots were within 1 M of the trunk. The horizontal and vertical distribution of the roots showed 93 per cent within 2 M of the trunk and 94 per cent within 60 cm. Most feeder roots were within 20 cm of the surface with only a few at deeper depths.

In Egypt, El Azzouni and Wali (1956) excavated the whole root system of 15-year-old Washington navels on Rough lemon, lime (West Indian) and sour orange. Roots were graded according to diameter and dry weights taken. There was some variability among trees on the same species. Roots of all stocks extended laterally outside the 5 M zone allocated. Sour orange extended laterally the most, with lime the lowest, and Rough lemon intermediate. The roots outside the 5 M radius were considered minor compared to the total root distribution. There was a high percentage of fibrous roots on all stocks. Woody roots .75 cm in diameter and greater extended 2.4 M from the trunk and beyond the 5 M radius, so greater extension was needed. Sour orange roots extended vertically 1.5 M, although Rough lemon and lime extended to 1.2 M with Rough lemon deeper than lime. Much of the root system of all three stocks was located in the 15-30 cm depth. There were considerable roots at .6 M, with lime having more roots in this zone than either Rough lemon or sour orange. Lime had the shallowest roots, Rough lemon intermediate, and sour orange the deepest. There were no direct orientation effects. Sour orange had the highest weight of total fibrous roots, with Rough lemon intermediate and lime the lowest. In contrast, the net weights of lime showed the highest percent of fibrous roots followed by Rough lemon and sour orange. All these stocks had fibrous roots located in the first .3 M and second .6 M, and with lime most were in the first .3 M, especially at 15 cm, even though the orchard was cultivated. Sour orange had the greatest root weight, followed by Rough lemon and lime, in that order. There were no tap roots on any of the stocks.

Ford (1954*a*) found Rough lemon roots penetrated to a depth of 4.3-5.2 M at 15 years of age in the warm (Reuther, 1973) deep well-drained Lakeland fine sand of Florida's central ridge. At 25 years, the total amount of feeder roots was greater at the 76-152 cm zone than the 0-25 cm zone. Fifty per cent of the feeder roots were below 76 cm, and 15 per cent below 2.7 M. At 18 years sour orange feeder roots only penetrated occasionally to a depth of 5.2 M in sandy soils. Trees on Rough lemon had more feeder roots below 76 cm than trees on sour orange. The feeder roots of grapefruit were confined to 2.1-2.4 M zones. Temple oranges on Cleopatra had feeder roots to 5.2 M at nine years of age. Sweet orange at 15 years had root penetration to 3.4 M and had the greatest total weight of feeder roots per unit volume of soil than any other rootstock observed. He reports Rough lemon feeder roots 7.6 M from the trunk. However, Ford (1971) reported Rough lemon roots had extended laterally a distance of 16.8 M. At Riverside, the author also observed the greatest lateral extension of roots on Rough lemon. One root extended parallel to the irrigation furrow a distance of over 9.1 M and was over 2.5 cm in diameter at the point at which it was severed during its removal.

Ford (1964*a*) reports that citrus trees in central Florida are very deep rooted. The root system of Rough lemon may penetrate to depths of 3 M at 6-8 years of age. Although 40 per cent of the feeder root system of a young five-year-old tree may be in the upper 25 cm of soil, by the time the trees are 20-30 years of age more than 50 per cent of the feeder root system may be below 76 cm in the soil, and of this amount 19 percent may be found below 2.7 M with roots extending down to 4.3-5 M. The unique character of Rough lemon under these conditions is the relatively high concentration of feeder roots at the 76-152 cm depths. On the poorly drained soils of the east coast of Florida, the results would be different. Results would also be different on the cooler and heavier soils of California. Frequent concentration in this zone may be greater than the total amount of roots in the upper 25 cm of soil. With sour orange the feeder roots have been found 3-4 M deep at nine years of age, which compares favorably with Rough lemon. Mature trees on sour orange usually have fewer feeder roots below 76 M than Rough lemon and differ from Rough lemon in having more feeder roots concentrated in the 0-25 cm zone and less in the 76-152 cm zone. Sweet orange differs from Rough lemon and sour orange in that the sweet orange has the greatest concentration of feeder roots of any stock used commercially. The roots of the sweet orange do not penetrate as deep or as far horizontally as Rough lemon. The high concentration of roots in rather limited zones may account for why growers in sandy soils claim sweet orange must be irrigated more frequently than Rough lemon. Ford also reports that 30-year-old trees on grapefruit roots had a shallow root development. Roots were found only to 2-3 M making it the shallowest root system of any stock observed. He also says that Cleopatra is deep rooted. Temple oranges on Cleopatra at nine years of age had roots to 5.2 M.

In regard to Webber's (1948) comments regarding citrus root systems, the author is taking the liberty of interspersing his own comments since Webber did not live to the termination and removal of many of his rootstock trials in 1960. At the time of the conclusion of these experiments, the root system of each tree (over 2000) was carefully analyzed by Kirkpatrick and Bitters (unpublished), in which the roots of every tree and combination were counted, sized, and measured. Also, during the tristeza era in Southern California, when thousands of trees were pushed and pulled, it provided an opportunity to observe numerous root systems under diverse soil and environmental conditions. At the time of Webber's demise (1944), sour orange was still the world's most popular rootstock and the most widely used rootstock in California. Webber points out that the sour orange has commonly been considered to be best adapted to growth on low, moist, and fairly heavy soils. It first became established in Florida on such soils. On the very light sandy soils of the so-called "ridge" section of central Florida, it has been a failure. In California, especially with lemons (for which it is no longer used), it was equally successful on light sandy soils such as in the Upland area. In rootstock experiments it gave better results on a fairly light sandy soil at Riverside than a much heavier loam soil at Fillmore. His explanation to these different reactions was the difference in climatic and soil conditions as they reacted on the deep rooted sour orange. In California, where alkali in sub-soils and high water table is sometimes a problem, such as in the Imperial Valley, a deep-rooted tree like sour orange may be seriously injured. The condition is more likely to occur on low heavy soils where drainage is poor. Aeration may be a problem in high water tables and root asphyxiation may occur, or damage from high salt content. As the lower roots die back, they may be attacked by soil organisms like Phytophthora and cause further damage. A shallower-rooted tree would sustain little or no damage.

The sour orange develops one or more tap roots which can grow to considerable depths, but lateral root development is more limited than in Rough lemon, sweet orange, or grapefruit. The tap root of sour orange cut back at transplanting from the nursery commonly branches and forms a small group of tap roots. Halma (1934) found one mature Eureka lemon grove in which the average number of main roots per tree was fifteen for 64 trees, of which 65 per cent were typical tap roots, whereas sweet orange was devoid of tap roots. Deep tap root penetration on deep soils renders the sour orange, to some degree, resistant to the effects of drought. Hume (1926) states that both nursery and grove trees on sour orange suffer much less in periods of protracted drought under identical conditions than Rough lemon, but Evans (1922) states in Dade County, Florida, orchard trees on grapefruit and sour orange may be actually dying of drought when adjacent trees on Rough lemon are satisfactory. Hume's statement would not apply, perhaps, to results on the deep, sandy "ridge" soils of Florida which were planted mostly after 1926.

Webber further states the sweet orange does not develop a well differential tap root and is usually moderately shallow rooted. It does, however, have an abundant system of lateral roots. The author's observations in California would agree. Mills (1902) states the sweet orange is a surface growing stock which has few or no penetrating roots, which does not agree with the observations of Ford (1954*a*, 1964*a*).

Webber makes no comment on mandarin root systems. However, when the old rootstock plantings at Riverside were pulled, the author found the most extensive and massive root systems of all stocks observed with Washington navel, Valencia, grapefruit, and Eureka and Lisbon lemons to be on Cleopatra mandarin. It penetrated nearly as deeply as sour orange, had extensive laterals, but moderate fibrous roots on the sandy loam soil at Riverside which is underlain by a caliche hard pan at 1 M or more in depth. Dancy, Clementine, and Oneco were similar in structure to Cleopatra, but to a slightly lesser extent. Even the tractor driver removing the trees commented that the trees on Cleo were the most difficult to remove.

Webber also made no statement regarding the pummelos. With all scion varieties at Riverside the root system of the pummelos was similar to that of sour orange, with deep penetrating multiple tap roots, a moderate lateral root system extending somewhat obliquely as in sour orange, and a scarcity of fibrous roots. On Rough lemon rootstock, he states it develops a very wide spreading abundant system of lateral roots and commonly exhibits no marked tap root. The trees in these experiments did have abundant spreading laterals, profuse fibrous roots, but no tap roots. The root systems were not nearly as extensive as sweet orange, Cleopatra mandarin and several other stocks, and may account for the smaller tree size on the Rough lemon stocks.

Webber also made no comment regarding lime rootstocks. In the root-stock experiments at Riverside, the root system of sweet lime was similar to, but inferior to, Rough lemon. There were no tap roots, the laterals did not extend as far, but there were abundant fibrous roots. In other California experiments, the West Indian Lime had a root system similar to that described by El Azzouni and Wali (1956), no tap root, extensive surface laterals with limited extension, and profuse fibrous roots. The Rangpur lime had a somewhat similar root system but did not duplicate the mandarin rootstocks in character. The citron also had no tap root, no extensive surface laterals and only fair amounts of fibrous roots. Many of these trees were “leaners”, further indicating that they had a weak root system.

Relative to trifoliate orange, Webber remarks that it develops a well-branched root system with very abundant fibrous roots, but that the roots did not extend laterally as far as Rough lemon or sweet orange. The author’s observations on many trees indicate the complete absence of deep laterals, very shallow penetration, a very sharp angle of diversion from the trunk area and a moderate amount of fibrous roots. Most of the laterals were flattened in proximity to the trunk area with no surface laterals and many fibrous roots.

No references were made to any of the citranges, although Morton, Savage, Rush, Coleman and Cunningham were in the plantings and Troyer and Carrizo were in later plantings. Most of the citranges have a poorly developed tap root system which only penetrates to a depth of about 1 M. They have, however, many laterals which emerge at an oblique angle and descend downward and may penetrate deeper than the tap roots. Fibrous roots are less extensive than the sweet orange parent, and in the surface layers less than the trifoliate orange parent. The root systems of Troyer, Carrizo, Savage and Morton were more extensive than the others observed and agrees well with Savage, Cooper, and Piper (1945).

No reference was made to Sampson tangelo. As expected from its parentage, its root system was extensive, but not as extensive as either mandarin or grapefruit. The tap root system was not well developed but the surface and subsurface laterals were prolific, and fibrous roots were moderate. Yuzu was very deep rooted with good surface laterals, but lacking in fibrous roots. The author would agree with Webber’s description of Calamondin, which has very large penetrating tap roots, at least several extending straight down to 150-180 cm or more. There were few laterals, only near the surface, and a scarcity of fibrous roots. Of 25 rootstocks Webber observed, he felt Calamondin exhibited the most marked tap root system, followed by *C. webberii*, and sour orange next. The author’s observations would agree with this except, the shaddocks would also have to be included.

The root systems of *C. macrophylla* and *C. pennivesiculata* are very similar to the lemon-lime group, that is no pronounced tap roots. Extensive trees on *Severinia buxifolia* were the smallest of any observed and it was surprising that the roots could support and anchor the tree. There was no tap root *per se*, but extensive surface laterals, most of which were less that 5 cm in diameter and did not extend more than 150-180 cm from the tree trunk, and very few fibrous roots. The root systems of cuttings varied tremendously with the scion cultivar. Those of navel were the poorest, consisting of only 3-5 very large surface laterals with little penetration and few fibrous roots. Those of grapefruit cuttings were intermediate. The Valencia cuttings, however, were very similar to sweet orange rootstocks except they didn't penetrate as deeply. There were lots of surface laterals and lower tier laterals and extensive fibrous root development.

Factors Affecting Citrus Root Development

Huberty (1948) states that the dominant factors in determining root distribution of plants appeared to be irrigation and soil types and subsoils. However, in an irrigation experiment at the Citrus Experiment Station which provided for irrigation on a two, four, and six-weeks' schedule, no noticeable difference was apparent in the amount, or the pattern, of the roots as affected by the various irrigation treatments. A marked difference was shown by the type of rootstock. Smith, Kinnison, and Carns (1931) in Arizona report the effect of variable frequency of irrigation treatments on the root development of young Marsh grapefruit trees on sour orange rootstock in the light sandy soils of the Yuma Mesa. In these experiments, irrigation intervals of one, two, three, four, five, and six to nine weeks were followed during the summer irrigation season for three years. The weekly irrigation schedule followed on Plot I kept the surface soil moist and at a lower range of temperature than in the other plots, and permitted an extensive root development the first year in the top 15 cm of soil. The root development in the top 15 cm of Plot II, irrigated every two weeks, was quite pronounced, but in the remaining plots it was appreciably less. This related condition prevailed for several years and then indicated a tendency toward relatively shallow root development irrespective of soil-moisture conditions. The effect of increasing the interval between irrigations seemed to limit the total root structure rather than to force development into the lower soil depths where favorable moisture conditions existed. Huberty (1948) also points out that part of the root system of a 25-year-old Washington Navel orange tree on sweet orange root was exposed by careful digging. This tree was planted on a contour row in a sandy loam soil exceeding 150 cm in depth. The longest root found was growing along the tree row in soil which was not cultivated and to which irrigation water was not directly applied. The root terminated 9.1 M from the tree trunk and was 11.3 M long. At no place was the root more than 46 cm below the ground surface, and at the free end was only 15 cm below the surface.

In the imperfectly drained east coastal soils of Florida, Ford (1954*b*) reported that stabilizing the water table at a lower level increased the total rooting area and the newly developed roots survived without periodic destruction. Lowering the water table from 76-178 cm doubled the quantity of feeder roots in four years and increased the size of the tree.

Cahoon, Harding, and Miller (1956) found that the higher the tree yields, the more feeder roots found in the irrigated row middles. In several high-producing orchards the amount of roots found between trees actually exceeded those found under the trees. Low-producing orchards had fewer feeder roots in the row middles as well as under the trees. Cahoon, Huberty, and Garber (1961) report on a differential furrow irrigation treatment applied to a Washington Navel orange orchard from 1934-1957 on sweet orange stock. The treatments were frequent versus infrequent. In 1957 root samples were taken to a depth of 122 cm. Trees irrigated on a frequent schedule produced fewer deep roots than the trees irrigated on an infrequent interval. The difference was more evident at the 61-92 cm levels. Samish (1957) in Israel reported essentially the same thing. Cahoon and Stolzy (1959) in California used a neutron moderation method to estimate root distribution as affected by irrigation and rootstocks. They encountered troublesome problems with soil moisture variability, soil profiles, etc.

Ford (l964*b*) found poor root growth in the leached zone of certain acid soils of the imperfectly drained Florida flatwoods. In laboratory tests poor root growth was not corrected by the application of adequate water and nutrients. In laboratory tests the Rough lemon produced the best feeder and lateral roots, even better than sour orange. Damage to the roots was more severe at low pH 5.0. Roots of Cleopatra were severely damaged at high and low pH 5.0-6.5. Ford also states that the relatively poor feeder root growth of trifoliate orange together with the root damage that occurred at pH 5.0 when flooded suggests this stock should be carefully evaluated. On the other hand, the satisfactory tolerance of Rangpur lime to flooding warrants further study. Ford (1964*a*, 1964*b*) says the citrus root system is capable of rapid and deep growth in sandy soils but will not grow into or exist long in a soil saturated with water. When the water table is within 60 cm of the surface, roots are confined to a shallow zone. Fluctuating water tables have a pronounced affect on the root system. He compared roots from trees in orchards with 1.8 M deep drain lines to an adjacent undrained orchard. In the undrained orchard the highest per cent of roots were at 0-50 cm, less at 25-50 cm, and almost none below 50 cm. In the drained orchard there was good rooting to 50 in. and some rooting even to 180 cm, but less as the distance from the chain line increased. Stabilizing the water table at a lower level increased the total rooting area and newly developed roots survived. Lowering the water table from 75 cm to 180 cm doubled the quantity of feeder roots in four years and increased the size of the trees. The feeder root concentration in the deep rooting zone 75-180 cm was greater than in the 0-25 cm level. In Israel, Cossman (1939) established a close correlation between the vigour of stocks on sandy soil and the osmotic pressure of their root cells. The slow-growing group represented by pummelo, grapefruit, and sour orange have remarkably low figures for their osmotic pressure. The roots of this group are easily outclassed by the retentive forces of the soil particles whenever the wilting range is approached.

In Texas, Adriance (1947) stresses the importance of the tap root system of sour orange, but points out that the major portion of the root system was between 46-61 cm. He emphasizes the importance of environment, natural habitat of species, aeration, water table, salt content and stratified soils. Adriance and Hampton (1949) examined the root systems of trees on sour orange grown on different soil types and subjected to different cultural practices. A poor-stunted tree grown on a very dense and compact soil had a spread of lateral roots 1.8-2.1 M. There were few roots 1.2-2.5 cm in diameter in the upper 21 cm of soil, a minimum of fibrous roots down to 61 cm, and no roots below that zone. A medium sized tree grown on a compacted soil and underlain with caliche at 125 cm showed roots were small but up to 2.5 cm in size and were well distributed although they did not penetrate deeply. A large tree grown on a good textured soil to a depth of 152 cm had roots down to 152 cm and below. Another tree in a tilled orchard which was disked to a depth of 10 in. had good roots around the tree, but there was little lateral spread beyond that distance. A tree under nontillage had roots with a lateral spread of 5.5-6.1 M.

In California, Crider (1927) found that citrus roots were found to be distributed largely according to the character and the previous cultivation treatment of the soil. In the case of a 25-year-old tree there were practically no roots below 1.2 M due to a tenacious subsoil. A 30-year-old tree on a dry sandy soil showed good root development to a depth of 2.7 M. In a well-cultivated and fertilized orchard, with young trees 3-6 years old, 50 per cent of the roots were in the first 46 cm of soil. On the other hand older indifferently handled trees showed greater root accumulation in the 30-60 cm and 60-90 cm layers. Young (1948) stresses the importance of soil texture, drainage, aeration, and moisture relationship to citrus root development. In Florida, Ford (l959) observed Hamlin and Valencia oranges on Cleopatra and Rough lemon at 15-21 years of age growing on a red sandy clay some 46 cm-4.8 M below the soil surface. Trees on the Cleopatra were 46-92 cm taller than the trees on Rough lemon where the roots penetrated into the clay. The height of the trees on Rough lemon decreased as the clay was closer to the surface. A restriction in root growth imposed by the clay did not consistently increase feeder root concentration above the clay. Root growth ceased when the clay percentage was above 28 per cent. Feeder root concentration of 15-year-old Hamlins and Valencia on Cleopatra growing in deep sandy soil was greater than Rough lemon, even though the trees were smaller than the same scions on Rough lemon.

At Riverside, much of the area occupied by the citrus rootstock trials initiated by Webber was underlain with impenetrable hardpan. At one location where the hardpan was approximately 1 M from the surface, some of the deep-tap-rooted trees such as sour orange had their tap roots growing down to the hardpan and then fusing together in a solid plate like a pedestal (Figure 62-1 and 62-2) and then the roots diverged at a lateral angle. In the Azusa-Covina area of California where many of the soils are alluvial sandy loams, especially adjacent to washes which were subject to flooding and were underlain with sand and gravel substrata. In such soils where the alluvium was deep, the roots of sour orange penetrated to a depth of 2 M or more with few laterals. However, as the trees in the orchard approached the stream bed the sour orange roots penetrated only to a depth of 60 cm or less with no tap roots, but a well developed system of surface laterals (Figure 63).

Fertilizers and nutrition also play a big part in citrus root development. In Florida's deep sandy soils, Ford, Reuther, and Smith (1957) found nitrogen was the primary element influencing root development in two fertilizer experiments after six years of differential treatment. The high nitrogen plots had 37 per cent less feeder roots than the low nitrogen plots to a depth of 1.5 M. Neither potassium or magnesium had any appreciable effect on root development. In the second plot there were 38 per cent less feeder roots at 13-89 cm in the high nitrogen regime as compared to low nitrogen levels. They felt a direct salt concentration [*"Check" appear here in typescript in the margin of the manuscript*] was responsible for the effects. In California, Cahoon *et al.* (1959) examined the effects of various types of nitrogen fertilizer on root density and distribution as related to water infiltration in a long-term fertilizer experiment on a sandy loam soil. They found that various nitrogen treatments, particularly the long-term application of sodium nitrate, and ammonium sulfate reduced root concentrations in the first 10 cm of soil.

In tropical Trinidad Gregory (1935) found the root systems of Marsh grapefruit on sour orange were more vigorous and extensive on manured trees than unmanured trees. The manured trees had several lateral roots which exceeded the average spread of the branches and extended 106 cm from the trunk on 3-year-old trees. Most were shorter, and feeder roots occurred 8-46 cm from the trunk. The unmanured trees had shorter roots and the main feeding roots were only 8-31 cm from the trunk. In Florida's deep sandy soils, Spencer (1958) found that phosphate applications markedly reduced the concentration of feeder roots, especially in the surface 30 cm of soil. Reductions in root growth were not noted in the deeper soil zones even at the highest phosphate rates. Similar observations were made by Smith (1956) and Ford (1957).

Smith and Specht (1952) suggested an increase of iron chlorosis in Florida was mainly caused by an accumulation of copper in the soil with consequent root damage. Since copper accumulates primarily in the top soil they suggested trees became chlorotic because of root damage in that area. Chelated iron applied to seedlings in soil solution did not overcome the stunted root system associated with high copper levels. Ford (1954*a*) had shown that in Florida 70 per cent of the feeder root system of healthy trees growing in deep sandy soils are located below 25 cm. Ford found that feeder root damage in orange trees affected with severe iron deficiency was not confined to the topsoil. Feeder root damage like copper toxicity was found to a depth of 1.5 M in groves located near lakes and swamps. Soil pH in the 0-25 cm zone was below 1.5 M with the subsoil at pH 3.9-4.4. All the groves had a high concentration of copper in the topsoil. The application of FeEDTA chelate to chlorotic trees which showed extreme root damage to a depth of 1.5 M resulted in pronounced new growth of roots in the subsoil. The increase of root growth was proportionately greater with an increase in depth so that often there were more new roots in the 75-150 cm zone than the 25-75 cm zone. Where iron chelate resulted in new leaf and shoot growth there was a corresponding increase in feeder root growth which occurred mostly below the 25 cm depth. If feeder roots were found in the 0-25 cm zone under chlorotic trees, treatment resulted in an increase of the number of feeder roots on the laterals. If there were no lateral roots in the surface 25 cm, then no new feeder roots were present after treatment. Changes in soil pH greatly influenced the distribution of feeder roots throughout the entire root profile.

Ford (1964*a*) says that in general, root concentration is highest when nutrition elements are low but not deficient. At high levels of applications of fertilizers the concentration of roots is reduced for all major elements. The correlation did not apply to the micro-elements. A deficiency of iron severely reduced the root system and an excess of copper and manganese prevented growth of the feeder roots due to toxicity in certain soil horizons. He suggested that from the standpoint of the root system the lowest level of nutrients consistent with high yield and healthy trees was the best. The effect of excessive accumulations of micro nutrients like Cu, Zn, and Mn on mycorrhiza and in turn, on root development, has yet to be fully evaluated.

The cultural practices within an orchard can materially affect root systems. In Ceylon (Sri Lanka), Gandhi (1939) cites a difference in citrus root distribution between irrigated areas and rainfall areas. However, when he grew grapefruit trees on Rough lemon with various degrees of cover crop (*Calopogonium mucunoides*) the citrus roots would not compete with the cover crop. They either turned back into open areas or penetrated deeper. If the roots extended to the cover crop they grew under it, but not through it. Those trees without cover crop extended roots laterally 2 to 3 times the spread of the branches. Where cover crops were used the roots only extended to the periphery of the branches. A nine-year-old grapefruit tree with a cover crop of *Indigofera* and Ecaphylla [*could not identify this plant*] also had lateral roots extending a little beyond the periphery of the crown. They did not appear to appreciably mingle with roots of other trees only 4.3 M away. His observations clearly indicate citrus roots are not able to maintain the same growth rate in association with permanent cover as without it, and that for free development of their roots they require the soil beyond the drip of the tree crown to be free of competition for water by other roots.

Figure 64 by Wallace and Nauriyal (1958) [*figure could not be included due to copyright restrictions*] shows citrus rootlet distribution as influenced by cultivation. The tilled orchard had few roots at the 0-15 cm level and most were in the 60-150 cm. By contrast, under nontillage there were 7 times as many roots in the 0-15 cm and the highest concentration was at the 15-30 cm zone. Deep soil was essential for making furrows, basins, or block-and-ridge systems for water. Such tillage severed most of the surface laterals and caused severe damage. Figure 65 shows such a root system with the laterals cut at several locations, and Figure 66 [*Image could not be located*] shows such a severed root which then regenerates a multitude of short stubby roots, with no single root gaining dominance. Water and nutrients are most available in the upper soil zones, which is rendered unavailable by tillage.

Diseased trees have reduced root systems. Ford (l952*b*) reports that declining grapefruit trees had 43% less roots than healthy trees. Oranges on Rough lemon at 7 years of age replanted on spreading decline soil (infected with the burrowing nematode, *Radopholus similis*) (Baines, Van Gundy, and DuCharme, 1978) had 18 per cent more feeder roots in the upper 25 cm of soil than good trees the same age. However, the decline trees had no roots below 75 cm. Ford (l953*a*) says that mature citrus trees affected by the spreading decline nematodes had 40 per cent fewer feeder roots than healthy trees. Decline trees had more feeder roots in the upper 25 cm of soil but almost none below 75-105 cm. Roots examined in affected groves showed significant disintegration at the 50-64 cm level with a rapid increase in deterioration with increase in depth. Practically all roots of decline trees at 50-105 cm were dark and discolored. Trees replanted in spreading decline affected soil had no lateral roots or feeder roots below 75 cm.

Montenegro (1970) found poor root systems under trees affected with exocortis or tristeza. The sour orange, because of its tendency to develop deep tap roots, was used extensively in the West Indies as a rootstock for limes. Such trees were reported by growers to withstand hurricane injury better than lime on its own roots. Fennah (1937) in a study of the root systems of budded trees at St. Lucia Island in the Caribbean found that sour orange seedlings in the nursery all had tap roots. However, out of 24 orchard trees examined at three years of age only three had tap roots and that of 110 trees at five years of age only three had tap roots, and the root system was horizontal. Fennah explained this circumstance as due mainly to damage by the citrus weevil (*Diaprepes* spp.) and to injury at transplanting.

Kaufmann, Boswell, and Lewis (1972), in a spacing trial of Washington navels on Troyer citrange in California, studied root distribution at different spacings. They found that the distribution of the roots varied with the distance from the tree and the availability of soil water (the irrigation furrows). The trees at a 2.7 x 4.7 M spacing at eight years of age had utilized the full rooting area and this was leading to a reduced tree performance. In Florida, Ford (1964*a*) observed that the root system of sour orange was influenced more by freeze injury of the scion than the root system of Rough lemon, and that the root system of sour orange recovered more slowly. In California, Biely, Wallace, and Kimball report pruning citrus trees affected root distribution. In a period of five months following skeletonization (severe pruning) there was a great reduction in feeder roots at all depths. Essentially all the feeder roots had disappeared. One year later the amount of rootlets under skeletonized trees was greater in number than before the trees were severely pruned.

In a Florida rootstock experiment, Castle and Krezdorn (1975) report that the depth of rooting was correlated with tree height; the tallest trees had the deepest root systems. Feeder root weight and tree height were not correlated. The tallest scion trees were on Rough lemon, Palestine sweet lime and Cleopatra mandarin. The shortest scion trees were on Rusk citrange and various trifoliate orange selections. Scion trees on Carrizo and Troyer citranges, sour orange and sweet orange were intermediate. The depth of rooting varied from 465 cm for Rough lemon to 377 cm on trifoliate orange and 366 cm on Rough lemon to 206 cm on Rusk citrange. Rootstocks had a pronounced effect on total feeder root weight. Deep-rooted trees on Rough lemon and sweet lime had more than 50 per cent of their feeder roots below 75 cm. Intermediate-sized trees were about the same as the tall trees above and below the 75 cm level. Exceptions were Cleopatra, Rusk citrange, and Rubidoux trifoliate which had over 60% of their roots above 75 cm. Rough lemon was the only rootstock with roots below 457 cm.

Reports on drought resistance are somewhat variable. Webber (1948) says sour orange is tolerant. Hume (1926) confirms this and states Rough lemon is more susceptible. Evans (1922) states Rough lemon is tolerant and grapefruit and sour orange are more susceptible. Brown (1924) indicates the Egyptian lime is tolerant. Ford (1964*a*) reports sweet orange to require more frequent irrigations than Rough lemon. Bhattacharya and Dutta (1956) indicate the Soh-myndong (Standard) to have drought resistance. Various visitors to the Citrus Research Center have indicated that the Palestine Sweet Lime and the Rangpur lime have drought resistance. All of this may vary with soil type, temperatures, etc.

Hilgeman *et al.* (1966) compared Rough lemon, Rangpur lime, Ocklawaha sour orange, Sacaton citrumelo, Troyer citrange, Koethen sweet orange, arid Wilking mandarin as rootstocks for Lisbon lemon in a sandy soil near Yuma, Arizona, and a sandy loam near Phoenix. They found that young trees on sour orange and Troyer citrange developed greater moisture stress between irrigations than trees on Rough lemon and Rangpur lime. The growth of the fruit was restricted at the differential irrigation levels. They suggested the root growth on the Rough lemon was more rapid than on sour orange stock and hence a larger soil volume was available to provide water to the trees on Rough lemon than those on sour orange.

Gardner and Horanic (1967) in Florida's humid climate compared the transpiration of young trees on four rootstocks by weighing container-grown trees at frequent intervals. The rate of transpiration of Hamlin orange tops was lowest on Rough lemon, highest on sweet orange and intermediate on Cleopatra mandarin and sour orange, although the actual amount of water transpired was essentially the same for all four rootstocks. The transpiration rates were inversely proportional to the leaf areas of the scion variety tops developed by these rootstocks, indicating the tops carried the greatest leaf area on Rough lemon and had the least resistance to transpiration. The effect of the rootstocks on transpiration rates apparently resulted from differences in leaf resistance. Horanic and Gardner (1959), following a prolonged dry period in Florida during September 1958, found a marked difference in wilting of Parson Brown and Valencia oranges in a rootstock experiment on a Lakeland fine sand. Marked differences between rootstocks were evident. Sour orange, Rough lemon, and Cleopatra mandarin were outstanding in their survival resistance to drought as compared to trees on grapefruit, sweet orange, and Rusk citrange. Unbudded Parson Brown seedlings in the planting also showed severe wilting. They felt the differences in apparent drought resistance were attributable to the rootstock effect rather than to a greater or less soil moisture depletion by trees of different size.

Ongun and Wallace (l958*b*), using the water weight loss in plants grown in containers in a greenhouse, studied the effect of both rootstocks and root temperature on the transpiration rate of Washington Navel orange scions grafted on rooted cuttings of a number of rootstock varieties. They reported that of the rootstocks used, the transpiration rate was highest on Rough lemon and lowest on sour orange and that while root temperatures influenced transpiration, not all the rootstocks were affected to the same extent. It descending order the combinations were rated best on Rough lemon, then *Poncirus trifoliata*, Troyer citrange, grapefruit, sweet orange, Cleopatra mandarin and sour orange. Mendel (1951) in Israel agrees that trees on Rough lemon transpire at a faster rate and, although a large tree, shows considerable drought resistance. He remarks of the remarkable drought resistance of trees on Rough lemon in spite of the high transpiration rate. Trees on sour orange had a strong tendency toward lower transpiration losses than trees budded on sweet lime.

O'Byrne (1939) lists Rough lemon as most drought resistant followed in descending order by sweet orange, sour orange and grapefruit. Crocker, Bell, and Bartholic (1974) using a modified Scholander pressure bomb found it was sensitive enough to detect significant differences in relative leaf water stress on Orlando tangelo trees on several rootstocks. The greatest stress was on trifoliate orange and lowest on Rough lemon. In descending order the trees ranked Rough lemon, Palestine sweet lime, sour orange, Carrizo citrange, and trifoliate orange.

Perhaps the largest contingent of trees observed for drought resistance was made in Brazil by Moreira *et al.* (1965) on nucellar Bara and Valencia Late orange, Dancy tangerine and Eureka lemon budded on 77 tristeza-tolerant rootstocks which were grown under nonirrigated conditions in Brazil. They categorized the drought resistance into three groups: low, fair and good. Those in the 'low' rootstock category were: Kinnow mandarin, Hamlin orange, Florida sweet seedling, Parson Brown orange, Cleopatra mandarin, Seminole tangelo, Kara mandarin, Clementine tangerine, Oneco tangerine, Minneola tangelo, Orlando tangelo, Pineapple orange, Valencia late orange, Nobilis #10642, King of Siam, Swatow tangerine #14054, Swatow tangerine #10032*,* Murcott Honey orange, Tavares limequat, Cowgill marcott, Sunshine tangelo, mandarin #10630, Tresca grapefruit, mandarin #114412, Caipira sweet orange, Navel orange, Williams tangelo, Suwannee tangelo, San Jacinto tangelo, *Poncirus trifoliata*, Webber tangelo, Calushu, Umatilla tangor, Mediterranean sweet orange, Ruby blood orange, range, *Citrus taiwanica*, Lue Gim Gong orange, Jaffa orange, Cravo tangerine, Weshart tangerine, Shamouti orange, tangelo 18-H-6, and Lamb's summer orange.

Those classed as 'fair' in drought resistance were: Rusk citrange, Dancy tangerine, Troyer citrange, Satsumelo 10-V-3, Sampson tangelo, sweet lemon #1158, Sun chu sha kat mandarin, Paak ling mung mandarin, Temple tangor, Suen kat mandarin, Savage citrange, Florida Rough lemon, Lima de Persia, Uvalde citrange, Satsuma mandarin, Kunembo mandarin, and Limeira Rough lemon.

Those classed as 'good' in drought resistance were: Rangpur lime, Sunki mandarin, Morton citrange, Citrumelo #4475 (Swingle), Swatow tangerine #10031, Mandarin #117477, Ling mung mandarin, Chao Chou Tien Chieh mandarin, Citrumelo #4482, and Kalpi lime.

If one ignores the early reports from Florida on the drought resistance of sour orange which seemed to be a special circumstance, it would appear that those rootstocks which have the greatest amounts of fibrous roots appear to be the most drought tolerant irrespective of the tap root system, and that conversely those rootstocks lacking quantities of fibrous roots regardless of the depth of penetration are more susceptible to drought.

Undoubtedly, the good drought resistance of Rough lemon rootstock in Florida is the deep root penetration into the warm sandy subsoil of the “ridge” area. These soils are very deep and [*text incomplete*] drained in the poorly drained soils in eastern Florida the drought resistance of Rough lemon is not so good.

In California during the summer months, there are periods of high temperatures and low humidity accompanied by hot, dry, desiccating winds. Under these extreme conditions leaves of trees may suffer severely from mesophyll collapse. After one such occasion in Coachella Valley, several of the author’s rootstock plantings were rated in 1960 for severity of mesophyll collapse (unpublished data). Leaf damage was very severe on Brazilian sour orange, Bessie sweet orange, Batangas mandarin, Cleopatra mandarin, Suen Kat mandarin, #653 tangor, Carrizo citrange, Savage citrange, Troyer citrange, Uvalde citrange, Calamondin, and Shekwasha. It was much less on stocks of #343 grapefruit, Ponkan mandarin, Sunshine tangelo, *Citrus macrophylla*, *C. pennivesiculata*, Rangpur lime and Rough lemon. This correlates very well with observations on the extent of fibrous roots for the various stocks.

One of the most striking effects on root system development is that exerted by the scion variety. The remarkable degree of change in size of stock or scion produced in some combinations of citrus was first pointed out by Brown (1920) (Figure 67 [*Image could not be located*]). In his experiments in India, the Malta (orange) made fine vigorous growth on the Rough lemon, medium growth on the sweet lime, and less growth on the sour orange and the citron. The Santara (mandarin) made the best growth on the sweet lime, a fairly satisfactory growth on the sour orange, but was markedly dwarfed and unsatisfactory on the Rough lemon and the citron. With the Santara the most prolific root system was on sour orange followed by sweet lime, citron and Rough lemon. With Malta orange only the root system of Rough lemon was good, the other root systems being extremely stunted. The tap root system of the sour orange is clearly shown with both scions and the lateral system of sweet lime with the Santara and that of Rough lemon with Malta. However, Singh and Singh (1942) indicate that Brown misidentified the Rough lemon and that it was in reality the Kharna Khatta. Regardless, the point is well illustrated.

In Florida, Ford (1952*a*) shows a comparison of the root systems of 29-year-old trees of grapefruit and orange on Rough lemon (Figure 68 [*Image could not be located*]) [*image could not be included due to copyright restrictions*] growing adjacent on the same soil type. The distribution of the roots in the different soil zones is markedly different.

The author has previously mentioned that when the old rootstock and scion experiments at the Citrus Research Center, Riverside, were removed in 1960, the root system of each tree was examined and the roots were counted, sized, and measured. In general, the pronounced effect of scion on rootstock development was not as evident as Brown (1920). However, in one experimental planting of 28 lemon strains on Seville sour orange there were differences equally as outstanding as noted by Brown (1920). These trees were all adjacent, there were 20 trees of each combination (five tree plots), and the trees were 20 years old at the time they were pulled. Diagrams of the root systems were reconstructed by Kirkpatrick and Bitters (unpublished) from the data and are shown in Figure 69 [*Image could not be located*]. The root systems fell into three very distinct categories reflective of the lemon scions budded upon them. The differences are difficult to explain in clones so genetically alike as these lemon strains, in trees the same age, the same soil type, and the same cultural practices. There were of course some differences in vigor of the scions as between the Eureka, Villafranca, and Lisbon types, and also some differences as far as phloem necrosis in the scion or the rootstock and the presence or absence of disorders like shellbark, and the fact that some scions carried psorosis and exocortis, which should not have had much effect on the particular combination.

In the author's opinion, a very important asset for citrus rootstocks to have is the ability for rapid root regeneration when roots have been damaged or destroyed by unfavorable circumstances. Unfavorable circumstances would include injury from Phytophthora, and damage from excessive irrigation, or high water table, etc. Once root damage has occurred and the unfavorable circumstances are removed, or cease to exist, then it is essential that new roots be formed soon if the vitality of the tree is to be retained. While the author has no scientific data to bear this out, field observations over a period of 40 years have indicated there are considerable differences between rootstocks in this regard. For example, roots of sweet orange and Cleopatra mandarin do not recover well from damage whereas roots of Rough lemon and Troyer citrange do—even though Troyer roots are very sensitive to overwatering.

Very little research has been done on the rooting ability of the various citrus species and hybrids, as well as the citrus relatives. Erickson and Bitters (1953) reported on the use of various growth regulators on the rooting of some of the citrus relatives. Percentage of rooting varied with the particular growth regulator and the concentration. Cuttings of *Atalantia citroides* responded best to a 0.2% solution of IBA: Cuttings of *Clausena lansium* to 0.05% solution of 2,4,5-T; cuttings of *Microcitrus virgata* almost equally as well to 0.2 and 0.4% NAA and .05 and 0.10% 2,4-D; cuttings of *Murraya exotica* (*paniculata*) to 0.5 to 0.10% 2,4-D; and *Severinia buxifolia* responded best to both 0.2 to 0.4% NAA and 0.05 to 0.10% 2,4-D. Checks of Eureka lemon (*Citrus limon*) rooted exceptionally high without treatment, but otherwise responded well to treatment with NAA and IBA. In later experiments (unpublished), it has been extremely difficult to root some of the *Citrus* relatives such as *Balsamocitrus*, *Aeglopsis*, *Afraegle*, etc. Most of the *Citrus* species and hybrids respond well to standard rooting techniques with success rates of over 90 per cent very common. Most mandarin varieties, however, root with some difficulty, which might be due in part to the very narrow stem diameter of the cuttings.

Of all the *Citrus* species, the citron (*C. medica*) roots the most easily. This characteristic may be explained by the presence of preformed root primordia in the stems (Carpenter, 1961). Carpenter also pointed out that this phenomenon was an inherited character and was commonly found in citron hybrids. A similar situation may also be found in closely related cultivars in the citron lemon-lime group. Among seedlings derived from open-pollinated flowers at Indio, California, the 'Iran' lemon, 'Rangpur' lime, 'Mexican' lime and 'Indio' lemon had some preformed root primordia. Occasionally, under field conditions, where young trees have their trunks covered with tree wraps to prevent sunburn or resist rodents, if humid conditions prevail, one may find roots sprouting on the trunk or rootstock of a susceptible combination (Figure 70 [*Image could not be located*]). The early stages of this phenomenon could easily be mistaken for a pathological abnormality if one is not familiar with this occurrence.

Very little research work has been done with *Citrus* roots since around 1960. Several recent developments may change this and provide new tools for obtaining answers to certain problems. Until recently, no one had succeeded in culturing citrus roots, much less subculturing them. At the Citrus Research Center, Riverside, Said (1978) succeeded in culturing roots of the citron (*C. medica*) *in vitro*, and what is more, was successful in continuous passage through subcultures *in vitro*. This feat had never been accomplished before. The ease of rooting with the citron may have been a factor because

Said was not successful in subculturing roots of other *Citrus* species. Perhaps more time and effort was needed. If *Citrus* roots could be subcultured and grown under controlled conditions *in vitro*, they could provide valuable information on root physiology. Recently Menge (Burnham,1984 at the Citrus Research Center, Riverside, devised observation boxes for studying root growth under orchard conditions. His dimly lit underground box which he calls a "rhizotron" is used for studying the living roots of mature trees. The rhizotron is equipped with special temperature, moisture and oxygen sensing devices. Recently, these studies have been expanded to a multidiscipline orchard known as the McKellar orchard near Visalia, California, as a part of the Integrated Pest Management Program. A better understanding of root growth periodicity and critical temperature levels for new rootstock cultivars not previously studied could provide a better understanding of specific rootstock performance.

ALLELOPATHY

Allelopathy is the retarding influence of one plant upon the growth of another due to the secretion of toxic substances by the roots of the first plant in the succession. In some instances the toxic substances produced are harmful to the subsequent growth of plants with a wide genetic variation, but in other cases only closely related species and hybrids, including clonal progeny of the plant producing the toxic substance, are affected. Molisch (1937) defined allelopathy as the direct or indirect interaction between plants, including microorganisms, through the production of chemical compounds that escape into the environment. For more general information on allelopathy, consult Rice (1974, 1979). An excellent treatise on the types and reactions of organic chemicals in soils may be found in Goring and Hamaker (1972).

Allelopathy does occur in citrus orchards. In California in the early 1950's, there was rather rapid expansion of new citrus acreage, partly due to the inroads of tristeza and replacement of old low-production orchards. It soon became evident that there was indeed a replant problem—the difficulty of obtaining satisfactory growth on young trees in an area where previous citrus trees had grown. In California, the replant problem was proven to be principally due to the presence of the citrus nematode, and soil fumigation seemed to correct the problem (Baines, Van Gundy, and DuCharme, 1978).

However, there was always the suggestion, but no completely concrete evidence, that allelopathy could play a part in the replant problem of citrus orchards. Thus, Martin and Batchelor (1952) suggested that certain phytotoxins were produced by microbial action from citrus plant residues. Martin and Ervin (1958) also explained growth reduction in plants to possibly be due to production of toxins either directly by plant roots or through microbial decomposition of the roots. The studies of Martin and Ervin included the influence of comparison cropping, organic materials, and crop rotation on growth of orange seedlings in old citrus soils. They found a reduction in growth of orange citrus seedlings (apparently both sweet and sour orange) could be produced readily in some noncitrus soils or accentuated in some old citrus soils by prior growing of orange citrus seedlings in that soil in the greenhouse. In the noncitrus soil, no citrus-root nematodes or *Phytophthora* species were found after cropping. Inasmuch as organic materials and companion crops generally exerted very little influence on growth of citrus seedlings in old citrus soil, Martin and Ervin decided to try the approach of crop rotation. They chose alfalfa and Rhodes grass as the noncitrus crop. After one year's cropping, they obtained a marked increase in growth in subsequent citrus seedlings, but in no instance did the growth equal that obtained in fumigated old citrus soil. Perhaps a period of longer than a year was necessary. However, the importance of organic matter was established. It has been postulated that the application of organic materials to the soil may favor various organisms which are capable of breaking down the toxic materials present in the soil. The rate of decomposition of organic materials used in planting mixes (and soils) and effects on soil properties and plant growth is discussed by Martin, Branson, and Jarrell (1978).

Dr. J. P. Martin was a close friend and colleague. In view of the improvement in growth of citrus seedlings via the crop rotation procedure, the author suggested to him that rootstock rotation also ought to be investigated. This suggestion was made because in the 1950's orchards in Southern California on sour orange rootstock were being devastated by tristeza. The susceptibility of sweet orange to gummosis and its poor performance as a replant were well known at that time. The pressures brought on the citrus industry of California to make a choice of new rootstocks meant that more information was needed in the performance of alternate citrus rootstock cultivars such as Rough lemon, Cleopatra mandarin, Sampson tangelo, the trifoliate orange (*Poncirus*), and the bigeneric hybrid Troyer citrange (*C. sinensis* x *P. trifoliata*). Would the genus *Poncirus* or its hybrid, Troyer citrange, be genetically different enough from previous croppings of *Citrus* that they would not be affected by their toxic residues, or vice versa? Subsequently, Martin and Bitters (1962) conducted a series of experiments with various rootstocks and the replant problem. In the first study, 'Corona' sweet orange, 'Standard' sour orange, 'Sampson' tangelo, 'Cleopatra' mandarin, 'Troyer' citrange and 'Pink' shaddock seedlings were grown in two old citrus soils in the greenhouse. Relative growth of Troyer citrange was best, followed by Standard sour orange, Corona sweet orange, Sampson tangelo, Cleopatra mandarin, while the Pink shaddock seedlings grew very poorly. For another test, a noncitrus soil (a Yolo loamy walnut soil) was cropped twice to seedlings of Corona sweet orange, Standard sour orange, Troyer citrange, Cleopatra mandarin, and Rangpur lime. The third crop consisted of each species or hybrid cropped after itself and following all other seedlings. Growth of all seedlings was greatly reduced by the previous cropping. Rangpur lime reduced growth of subsequent plantings the most and Cleopatra the least. Growth of the Cleopatra was reduced most drastically by previous plantings of all the varieties. The test was repeated using a Hanford sandy loam noncitrus soil and substituting Rubidoux trifoliate orange in place of Corona sweet orange. Previous croppings to trifoliate orange caused the least reduction in growth of a third crop, and sour orange and Rangpur lime the greatest. The trifoliate orange probably had the smallest root system. Relative growth of the various seedlings in the old citrus soils was in the following order; Rubidoux trifoliate orange > Troyer citrange > Standard sour orange = Rangpur lime > Cleopatra mandarin.

In yet another experiment, seedlings of Alemow, Volkamer lemon and Standard sour orange were grown on an old citrus soil, and one created in the greenhouse by growing six different citrus rootstock seedlings (Troyer citrange, Rough lemon, Jochimsen grapefruit, Corona sweet, Cleopatra mandarin, and Standard sour orange) budded to Washington navel orange. The previous croppings caused a highly significant growth retardation of all three kinds of test seedlings. There was a 34 percent reduction for Volkamer lemon, a 38 percent reduction for sour orange and a 60 percent reduction for Alemow. The previous cropping of a navel orange scion on Troyer citrange root caused a significantly greater growth reduction than did the cropping to the same scion on the five other rootstock types. This is pointed out because the navel scion increased the incidence of *Fusarium solani*. The use of a navel scion in other observations mentioned elsewhere has also increased the incidence of gummosis and the population of the citrus nematode.

In yet another aspect of these experiments, seedlings of Standard sour orange, Cleopatra mandarin, and Troyer citrange, and budded trees of navel orange on Standard sour orange and Cleopatra mandarin were planted on four old citrus soils, including Yolo, Hanford, and Romana, which are typical good citrus soils in California. Growth reduction was 16 percent on the Troyer seedlings, 42 percent on the sour orange seedlings, 55 percent on the Cleopatra seedlings, 44 percent on the navel/Cleopatra combination, and 48 percent on the navel/sour combination. The final experiment consisted of seedlings of four rootstock cultivars, namely sour orange, Cleopatra mandarin, Troyer citrange, and trifoliate orange, and those rootstocks budded to navel orange. They were grown in an unclassified virgin soil from the nearby San Bernardino mountains. Growth reduction of the second crop varied from 5-92 percent. With the exception of Cleopatra mandarin, the addition of the navel orange scion increased the growth retarding effect of the first crop on the second. The combination of navel orange on Troyer citrange root caused the greatest reduction of the second crop and Rubidoux trifoliate orange seedlings the least. Relative growth of Rubidoux trifoliate orange seedlings and navel orange on the trifoliate orange seedlings was best, and that of the Cleopatra mandarin seedlings and the navel orange trees on Cleopatra rootstock was poorest. The author will reemphasize that the citrus nematode was not present. Martin and Bitters made no attempt to extract and identify any toxic substances from these pot cultures.

In South Africa, Burger and Small (1983) did some very intensive research on allelopathy in citrus orchards. Based on the fact that citrus growing in South Africa was basically a monoculture on Rough lemon rootstock, they made extracts from orchard soils in which citrus trees had been grown for up to 30 years in various citrus areas of the country. The extracted samples were tested for toxicity to Rough lemon roots using a bio-assay method with very young seedlings. Of 24 phenolic compounds which are known to occur in citrus or in decomposing organic matter, they concluded that homovanillic acid, a relatively rare phenolic acid in higher plants, was the major toxin present in the citrus soil extracts. However, phioretic acid, o-cournaric acid and coumarin also cause some reduced growth. A comparison of the phytotoxicity of fresh roots, and partly decomposed root and soil from a 30-year-old citrus orchard sampled at different depths, and an adjacent virgin soil, showed that only the extract from the virgin soil did not show any significant reduction of the seedlings in the bio-assay procedure. There was little effect from the fresh root extracts. However, no growth occurred with the same extract fraction of partly decomposed root residues. This observation, state Burger and Small, supports the supposition that phytotoxins are found during the decomposition of citrus roots. They also investigated the relationship between soil depth and the accumulation of the phytotoxic compounds. From an orchard at the Sundays River Research Station (in southeast South Africa), they collected soil samples at four depths: 0-25, 25-50, 50-75, and 75-100 cm. Their studies showed that the extract of the 0-25 cm sample caused the greatest growth reduction and the 25-50 cm sample the least reduction, but with gradually increasing toxicity at increasing depths. They felt that phytotoxic substances might accumulate in certain soil due to poor aeration and the absorbent properties of certain soil particles. No extracts were made from other than soils of Rough lemon orchards and no phytotoxic bio-assays were run other than on Rough lemon roots.

In addition to the bio-assay studies reported by Burger and Small (1983), extensive replant studies are reported by Burger (1981). However, in these later studies, it is not clear cut as to what effects are caused by allelopathy and those caused by nematodes, or both. Even in some of the fumigation experiments the fumigation was not adequate, or effective enough, to kill all the nematodes, so the experiments were confounded by variable nematode populations. It did appear that deep plowing to a depth of 60 cm was helpful in either case. The response of the rootstock seedlings subjected to the treatments is not clearly delineated.

It is somewhat peculiar that so little attention has been directed to allelopathy in the citrus growing areas of the world. There is no reason to believe the problem exists only in California and South Africa, although the environmental conditions are very similar. The toxic substances involved are apparently biodegradable and do not last long in the soil as compared to a nematode infestation (without fumigation). The effect of the toxic substances is thus one of retardation rather than a permanent effect. In the author's many trips to Japan, I occasionally visited old Satsuma orchards which had been cultivated by one family for many generations. When I would inquire about a replant problem, the owners would respond with "Do you see any?" The trees were often of variable age, but all appeared to be healthy and productive. One must remember, however, that the principle rootstock in Japan is the trifoliate orange. This rootstock cultivar inherently has considerable resistance to the citrus nematode. Also, the studies of Martin and Bitters (1962) showed that growth retardation following trifoliate orange was the least of the seedlings studied. Burger (1981) reports a similar effect in South Africa. Furthermore, Burger found that Rough lemon root residues caused a highly significant reduction in shoot growth and internode length. According to Monselise (1947), a reduction of internode length in the shoot is an indication of the inhibition of gibberellic acid activity in the shoots. In Burger's studies, neither the presence of nematode, nor trifoliate orange root residues, had any effect on shoot growth and internode length.

MYCORRHIZAE

Martin (1972) reported that the inhibition of P, Cu, and Zn absorption in citrus follows soil applications of fumigants, fungicides, heat and other treatments which kill soil organisms. This condition most commonly has occurred in greenhouses and nursery operations following heat or steam treatment of soils or the use of soil fumigants. The condition was never predictable and was often spotty. Martin further stated that when citrus seeds or young citrus seedlings were planted in the treated soil, one to several progressively poorer growth flushes occurred. The newer leaves remain smaller and turn a pale green to yellowish color as described by Martin, Baines, and Page (1963) and Martin *et al.* (1953). Depending on the soil type, the plants may develop moderate to severe deficiency symptoms of Cu, Zn and necrosis of leaf edges. Root growth is severely retarded, but the root appearance is healthy. The plants are stunted. The deficiency symptoms may last from a few weeks to a year and eventually the plants recover and resume normal healthy growth. Phosphorus levels were low in affected plants. About 1970, the California State Department of Agriculture adopted a requirement that nursery trees and other plants for sale or distribution be free of specified root parasites and noxious weeds. This action, plus the tristeza quarantine, necessitated fumigation of citrus seed bed and nursery sites. Rather high dosages of fumigants (such as methyl bromide) were used to kill nematodes, parasitic fungi, and in some cases, noxious weeds. Hindered by these restrictions, California nurserymen could no longer afford to be nomads—the practice of planting one nursery site and then moving onto new ground after the trees were grown. Most of the nurserymen thus selected and developed a permanent site. After the first nursery, fumigation treatments were necessary. In a number of citrus seed bed and nursery sites, phytotoxic problems were encountered. Initially, Martin, Baines, and Page (1963) postulated that the apparent toxicity might be caused by an organic compound synthesized by a dominant soil organism, and that beneficial organisms capable of destroying the compound were killed by the soil fumigation treatment. Wilde (1968) was one of the first researchers to point out that in view of the close relationship of certain mycorrhizal fungi to the phosphorus nutrition of certain tree seedlings, that soil fumigants, heat, or steaming kills the beneficial fungi as well as the harmful one and therefore interferes with the ability of those seedlings to absorb phosphorus.

The first reported incidence of the post-fumigation problem in a field nursery probably occurred on the sandy soils of central Florida reported by Tucker and Anderson (1972). They were perhaps the first to apply the term “seedling stunting” to the problem. Seedling rootstocks affected included sour orange, Carrizo citrange, Cleopatra mandarin, and to a lesser extent, Rough lemon. The latter observation does not agree with other observations.

The problem was easily corrected by phosphate application. Kleinschmidt and Gerdemann (1972), in field data from Illinois, indicated that Rough lemon seedlings were also most mycorrhizal dependent, and Cleopatra mandarin, Troyer citrange, and sour orange were progressively less dependent. Greenhouse data by Schenck and Tucker (1974) on sandy soil further suggested that although the mycorrhizal dependency was similar for the citrus rootstocks they tested, Rough lemon was the most mycorrhizal dependent and sour orange and Cleopatra mandarin were less mycorrhizal dependent.

The problem first appeared in the early 1970's in a large citrus nursery on a sandy soil near Thermal, California (Newcomb, 1975). The seed bed following fumigation was a disaster. The seeds germinated and grew normally for a short time (until the seed nutrients were exhausted), but when the seedlings reached a height of 7-10 cm, they were variably stunted in clusters within very short distances in the seed bed, between seedling varieties. Specialists from the Citrus Research Center, Riverside, were called in and preliminary guesses ranged from fumigant residues in the soil, poor seed lots, excess fertilizer, etc.—although there was no symptom evidence of any such suggestion. Leaf samples from the stunted seedlings when analyzed revealed a phosphorus deficiency as well as a few other micro-nutrient deficiencies, especially copper. An application of 1200 pounds of phosphorus per acre improved growth considerably. However, Rough lemon and Troyer citrange seedlings only attained 80-90 percent of normal growth while seedlings of sweet orange and sour orange only attained 40-50 percent of normal size in spite of phosphorus levels being adequate. Root samples from affected plants and healthy plants were sent to J. W. Gerdemann of the University of Illinois at someone's suggestion. Dr. Gerdemann determined that the stunted seedlings had non-mycorrhizal roots and the healthy seedlings had roots with mycorrhizae. The first attempt at field inoculation was done at the Thermal nursery on *Citrus amblycarpa* seedlings by Harold Lembright of Dow Chemical Company with inoculum supplied by Dr. Gerdemann. The plants responded almost instantly. The response suggested the possibility of inoculating citrus seed with the fungus. Work by Dr. Gerdemann and J. A. Menge with inoculated seed of sour orange was successful. More about this later. Newcomb (1975) was also able to improve growth essentially to normal by bringing soil from adjacent healthy nursery trees and spreading it on the retarded seedling areas.

Menge, Johnson, and Platt (1978) grew six citrus seedling cultivars with and without the mycorrhizal fungus *Glomus fasciculatus* under three fertilizer regimes, all of which were without phosphorus. Of the six citrus cultivars, the mycorrhizal dependency of Rough lemon and Brazil sour orange were greater than Alemow (*C. macrophylla*), Troyer citrange, Bessie sweet orange, and trifoliate orange. Most importantly, the order of mycorrhizal dependency was different for all three fertilizer regimes. The greatest mycorrhizal dependency occurred with the least fertilizer. This may explain why field problems were greatest on sandy soils—and why sandy soils were used in the greenhouse experiments. Incidentally, Dr. Menge was not associated with the Citrus Research Center until the summer of 1974, which explains his delay in getting involved in mycorrhizal problems.

Kleinschmidt and Gerdemann (1972) emphasize that heavy fertilization of a citrus nursery (W-N) in California did not produce citrus seedling growth that was entirely satisfactory. The 1972 fertilizer practice of the W-N nursery on a sandy soil was to supply two metric tons of chicken manure, 2.5% (N) and 3.5 (P_2O_5), per acre 6-8 weeks prior to planting. This application did improve the growth of the citrus seedlings, but the more susceptible varieties produced only about 25 percent normal growth. The W-N nursery did obtain an excellent growth response following inoculation with *Endogone mosseae*, a VAN (vesicular-arbuscular-mycorrhiza fungus). Seed and seedlings of citrus cultivars were supplied to these researchers by the W-N nursery.

Nemec (1978) grew seedlings of six citrus rootstock cultivars in a sandy soil in a greenhouse. The rootstock seedlings were Rough lemon, Rangpur lime, sweet orange, sour orange, Cleopatra mandarin, and Carrizo citrange, all of which were inoculated with the VAN fungi *Glomus etunicatum*, *Glomus mosseae* and *Glomus fasciculatum*. Some treatments were fertilized with phosphorus and others were without phosphorus. The combined top growth of all six rootstock seedlings was increased with the addition of VAN fungi and no phosphorus. However, the combined growth with VAN and phosphorus was slightly more. The rootstock seedlings decreased in dependency on VAN in the following order: sour orange, Cleopatra mandarin, sweet orange, Rough lemon, Rangpur lime and Carrizo citrange. Root-shoot ratios indicate that rootstock mycorrhizal dependency decreases as their capacity for root production increases.

Emphasizing the importance of previous work, Timmer and Leyden (1980) state the interactions of copper and phosphorus in the fumigation-mycorrhizal syndrome are important. Copper deficiency has been frequently observed in citrus seedlings following the application of phosphate fertilizer. (This may be why Troyer citrange is so sensitive to copper deficiency.) According to Timmer and Leyden, the application of phosphorus induces copper deficiency by stimulating growth of non-mycorrhizal seedlings until copper becomes limiting nutritionally. However, phosphorus-induced copper deficiency appears to be due to phosphorus inhibition of mycorrhizal development of seedlings inoculated with *Glomus fasciculatus*.

Rhodes (1981) stresses the fact that mycorrhizae are recognized as being significantly beneficial to host-plant relationships, particularly where root systems are restricted and nutrient systems are low—although he makes no special reference to citrus.

Mehraveran (1977) (unseen) also discusses the mycorrhizal dependency of six citrus cultivars (will try and obtain microfilm).

The role that the VAN fungi play in the health of the host plant is not fully clear. Plants with mycorrhizae and a given phosphorus level are healthier than non-mycorrhizal plants with an equal phosphorus level. The type of mycorrhizae is important; the soil type, area of origin, effects on nematodes, *Phytophthora*, photosynthetic activity, and hydraulics are all factors to consider. Thus, Menge *et al.* (1982) found that in greenhouse experiments the addition of *Glomus fasciculatus* significantly increased the growth of Troyer citrange seedlings in 20 of 26 methyl bromide-fumigated soils from Southern California. Of the six soils in which the mycorrhizal fungus provided no growth increase, two were greenhouse soils (mixed), three were nursery soils, and one was a field soil. Presence of the fungus increased foliar phosphorus, potassium, and copper and decreased foliar magnesium and sodium concentrations in the leaves of the Troyer citrange in the majority of the citrus soils. They present an interesting table on the mycorrhizal dependency of Troyer on *Glomus fasciculatus* on the 26 soils. While much of the work has been done with sandy soils, the whole soil-mycorrhizal complex is extremely important.

Obviously there are different species of the mycorrhizal fungus and one wonders if they are equally effective and if their response varies in a different soil environment. To determine this, Graham, Linderman and Menge (1982) tested six VAN isolates. They found that isolates of *Glomus fasciculatus* was most efficient, and *Glomus macrocarpum* the least effective. Growth enhancement was significantly greater for *Glomus* isolates from California than from Florida. It is also stressed that growth enhancement for VAN fungi may vary with the soil type.

Johnson (1984) reports on the effects of phosphorus nutrition on mycorrhizal colonization, photosynthesis, growth, and nutrient composition in sour orange seedlings. The sour orange seedlings were inoculated with the VAN fungus *Glomus intraradices* and fertilized with weekly applications of phosphorus. The photosynthetic rates correlated with a high phosphorus content in the leaf tissue of the central plants, but Johnson could find no correlation for the VAN-infected seedlings. He suggests that factors in addition to improved phosphorus nutrition influence the photosynthetic rate of

VAN plants. The conclusions of Edriss, Davis and Burger (1984) were somewhat similar. Using sour orange seedlings and inoculating them with the mycorrhizal fungus *Gigaspora heterogama*, they found that the cytokinin production was greater than that of the check non-mycorrhizal plants despite the fact that there were similar dry weights and phosphorus concentrations in the leaves. The enhancement of the cytokinin production seemed to be associated with the mycorrhizal infection rather than increased phosphorus uptake.

The effect of VAN inoculations on nematode populations was first investigated by O'Bannon *et al.* (1979) in greenhouse studies in Florida. They found that when Rough lemon seedlings were inoculated with the citrus nematode, *Tylenchulus semipenetrans* and then transplanted into soil infected with VAN *Glomus mosseae*, that the presence of the fungus increased seedling growth. The seedling suppression by the citrus nematode alone was greater than the checks or the VAN inoculated. They made no studies on other nematodes such as the burrowing nematode *Radopholus similis*. Similarly, Hussey and Roncadori (1982) report that nematode suppression of vegetative growth or yield are partly offset by the presence of a VAN fungus. Using Rough lemon seedlings they found that the presence of the mycorrhizal fungus lessened the nematodes' attraction to the citrus roots, hindered penetration, and the subsequent development and reproduction of the citrus nematode was suppressed. They do not specify why, except that a healthier plant is a more resistant plant. To some extent, this same hypothesis exists with the VAN fungus relationship with *Phytophthora*. Davis and Menge (1980) working with Pineapple sweet orange seedlings, present evidence that suggested that there was some tolerance to *Phytophthora parasitica* in seedlings infected with *Glomus fasciculatus*. They also felt this effect was caused by the ability of mycorrhizal roots to absorb more phosphorus and possibly other nutrients than non-mycorrhizal roots, as evidenced by root health and greater phosphorus uptake. Again, a healthier plant is a more resistant plant. They did not report on any studies with *Phytophthora citrophthora*. Davis and Menge (1981) again suggest that VAN fungi have a variable influence on the tolerance of seedlings of Pineapple sweet orange and Troyer citrange to *Phytophthora parasitica*.

There are a number of papers on the effects of VAN fungi and water relationships of host citrus seedlings. The first report perhaps was that of Levy and Krikun (1980). These two Israeli researchers working with Rough lemon seedlings studied recovery from water stress on similar-sized VAN infected seedlings and non-mycorrhizal seedlings. They found the VAN-infected seedlings affected stomatal conductance, photosynthesis and proline accumulation but not leaf water potential. They suggest that most of the effect of mycorrhizal association is on stomatal regulation rather than on root resistance. Syvertsen (1981) studied the hydraulic conductivity of four commercial citrus rootstocks. The hydraulic conductivity was estimated using a special pressure chamber technique. He found that Carrizo citrange and Rough lemon had the highest root conductivity, whereas Cleopatra mandarin and sour orange had the least. Further hydraulic studies were conducted by Graham and Syvertsen (1984). They used seedlings of Carrizo citrange and sour orange grown in a low phosphorus sandy soil and either inoculated with *Glomus intraradices* or fertilized with phosphorus. The mycorrhizal-infected seedlings had sufficient levels of leaf phosphorus, but the non-mycorrhizal seedlings were phosphorus deficient. The root-shoot ratio of both rootstocks was reduced by the mycorrhizal colonization, but root hydraulic conductivity per unit root length of mycorrhizal Carrizo and sour orange was more than twice that of non-mycorrhizal seedlings. The mycorrhizal plants had higher transpiration rates, apparently increased by the conductivity of the roots. The authors felt the response was due to the mycorrhizal enhancement of phosphorus nutrition. In further studies, Graham and Syvertsen (1985) grew seedlings of five citrus rootstocks in a low phosphorus sandy soil. The seedlings were incorporated into three treatments: (1) inoculated with *Glomus intraradices*, (2) non-inoculated, but fertilized with phosphorus, and (3) non-inoculated and no phosphorus added. The order of the mycorrhizal dependency (M.P.) of the five root-stocks is as follows: sour orange = Cleopatra mandarin > Swingle citrumelo > Carrizo citrange > trifoliate orange. The less dependent rootstocks, i.e., trifoliate orange and Carrizo citrange, had greater leaf phosphorus, finer roots, and slower growth rates than sour orange and Cleopatra mandarin. Rootstocks with a lower mycorrhizal dependency also generally had greater hydraulic conductivity of the roots, greater transpiration and carbon dioxide assimilation rates. In additional but similar studies, Syvertsen and Graham (1985) amplify their work again with seedlings of Carrizo citrange, trifoliate orange, sour orange, Swingle citrumelo, and Cleopatra mandarin. Whole plant transpiration and maximum rates of net gas exchange or carbon dioxide and water vapor from single leaves were positively correlated with the hydraulic conductivity of the seedlings. Leaf nitrogen and phosphorus content and shoot-root ratio were also positively correlated with root conductivity. The differences in soil water depletion and plant water relations of trifoliate orange and Carrizo citrange during drought and recovery cycle is related to their root conductivity. They stress that the capability of root systems to conduct water and mineral elements is a very important factor in plant growth and physiological activity.

The possibilities of seed inoculation or field inoculation was first mentioned by Newcomb (1975). Hattingh and Gerdemann (1975) inoculated sour orange seed, successfully developing a special technique. They coated the seed with a mycorrhizal inoculum in a 1% solution of methyl cellulose. Menge, Lembright and Johnson (1977) indicated that commercial production of mycorrhizal inoculum for use in fumigated or sterilized soil was being attempted in several locations in the United States. They felt the only current way to produce suitable quantities of mycorrhizal inoculum was on roots of susceptible host plants. Contamination by other pathogenic organisms can be a problem. Maybe better methods are available. The most common method for inoculating citrus in the field and in the greenhouse has been to mix the mycorrhizal inoculum with the soil prior to planting or transplanting. Menge *et al.* (1982) felt banding, layering and root inoculation were more efficient than seed inoculation. Root fragments can also be an important source of inoculation. Graham and Fardelmann (1986) found that root pieces stored up to one year under moist conditions did not lose the colonization potential with *Glomus epigaeum*. However, drying reduced this potential to nearly zero after nine months. *Glomus intraradices* was found sporulating in citrus roots found in orchard soil. They propose that dead root fragments account for a high percentage of the propagules in the citrus soil. The propagation of mycorrhizae cannot be too difficult. For a number of years a citrus nurseryman in California offered mycorrhizae for sale for inoculative purposes. This service is no longer available either because of propagation problems or little demand by the citrus industry. The knowledge of the necessity of the mycorrhizae in the seed bed or the transplant stage is the important thing. The mycorrhizae will gradually re-infect a fumigated soil. The nurseryman could leave the fumigated site fallow for a year or plant host cover crops of cereals and grasses or legumes prior to planting a seedbed or transplanting. Furthermore, field grown nursery trees are gradually diminishing. Container growing is so much more efficient and economical, and container trees can be grown in a shorter period of time. There is also less transplant shock. When the author visited South Africa in 1982, there were only three field grown nurseries left and they ceased with that planting. South Africa is essentially 100% in container growing. Spain and Australia are now heavily into container growing, with more citrus producing areas following suit. If the container planting mix is properly planned and prepared, there will no longer be this problem.

For further information on this problem, a nice review of the total VAN potential benefits and interactions is presented by Graham (1986). While the article is a review, it nicely presents the views and facts in pathology, horticulture, and physiology. A book on the subject is currently being written by J. A. Menge of the Department of Plant Pathology, Citrus Research Center, Riverside.

ROOTSTOCK IDENTIFICATION

Rootstock identification is at best uncertain, difficult, and at times, quite time consuming. Perhaps many growers do not particularly care what rootstock their orchard is budded on, especially if there are no orchard problems. Other growers simply do not know what stock their orchard is budded on. Sales slips are lost and the grower forgets or becomes confused. Often times an orchard ownership may change hands several times and the records are lost. Even citrus nurserymen make errors in keeping accurate records on their rootstock-scion combinations for sale. Thus, it is frequently desirable to identify the rootstocks of trees when orchards are sold or a threatening disease like tristeza comes along. Unfortunately, there is not always a satisfactory method of identification. At times, the date of planting may be helpful. Thus in California, Troyer and Carrizo citranges and *C. macrophylla* were not planted prior to 1950, and the same is true of Milam in Florida.

Leaf Characters

Perhaps the quickest, but not necessarily the surest, method of identifying a rootstock is by examination of sprouts from the stock. See leaf characteristics of most major rootstock varieties in Figure 71-1, 71-2 and 71-3. If good cultural practices are followed, rootstock sprouts are routinely removed and one seldom finds a fruiting sucker which might aid in the identification. Someone thoroughly familiar with *Citrus* species, their hybrids and cultivars can frequently identify different ones by the character of the foliage or the odor of the crushed leaves (Bitters, 1948; Beñatena, 1953). Frequently, however, no sprouts are formed on the stock and several years might be required to induce them to develop.

Stock-Scion Configuration

A fairly correct diagnosis of the stock species may often be made by observing the stionic reaction (a portmanteau word involving the combination of stock and scion) at the budunion as pointed out by Webber (1926*b*), Bitters (1948), Beñatena (1953), and others. Extreme reactions in different combinations may somewhat overlap, however, so that with individual trees on mixed stocks, errors will frequently be made. For budunion characteristics, see the discussion of stock reactions. The use of such visual aids has not been much needed until recently in Spain, where nearly all the trees are budded on sour orange and a few on trifoliate orange. The same may be said for Italy, where again until recently everything was budded on sour orange or a few younger trees on the Volkamer lemon. Japan's citrus acreage is principally characterized with most trees on trifoliate orange, with some on Yuzu and a few on natsudaidai. The situation becomes much more complicated in California, Arizona, Texas, and Florida, where many more rootstocks are or have been used, such as sweet orange, sour orange, Cleopatra mandarin, Sampson tangelo, grapefruit, various selections of Rough lemon, trifoliate orange, Troyer Carrizo and C32 and C35 citranges and a few lesser stocks like Cuban shaddock, Ichang pummelo, Sacaton and Swingle citrumelo, etc. The situation will become even more complex as more and more hybrids are introduced as new rootstocks.

Anatomical Characters

Differences in cellular structure have infrequently but effectively been used to distinguish a limited number of stock species. Thus, Penzig (1887) found a striking difference in the cellular structure of the pith of twigs of trifoliate orange and sour orange, and this may probably also be true of the roots. Swingle (1909) suggested this method of distinguishing between these two species when used in Satsuma production in the U.S. Gulf states. Longitudinal sections of the pith of young stems of the trifoliate orange exhibit an irregular arrangement of thin-walled cells (Figure 72, Webber, 1948, pp. 149, 150, 151) [*labeled as*] Fig. 66A, while similar sections of sour orange stems show only uniform thin-walled cells arranged in regular series and an entire absence of the crossplates of thick-walled cells ([*labeled as*] Fig. 66 *B*).

Wolf (1912) extended this method to distinguish Yuzu, which was found to have only thin-walled pith cells similar to those of the sour orange, but irregularly arranged ([*labeled as*] Fig. 66 *C*). Thus, it differs from the sour orange, in which the cells are arranged in regular series or chains, and from the trifoliate, in which there are crossplates of thick-walled cells ([*labeled as*] Fig. 67).

Wolf also studied characteristic differences observable in cross-sections of one-year-old roots (about 4 mm in diameter) of the same three species ([*labeled as*] Fig. 68). The trifoliate orange is easily distinguished from the sour orange and the Yuzu by the large vessels in the wood, these being much larger and more numerous than similar vessels in the other two species, and by the more numerous groups of bast fibers in the bark, which form three or four broken concentric rings. In the Yuzu, only a few scattered groups of bast fibers are present in the bark, whereas in the sour orange the groups of bast fibers are numerous and close together in the inner row, with only a few scattered groups farther out, a condition intermediate between that of Yuzu and the trifoliate orange, but clearly differentiating the sour.

In the differentiation of trifoliate stock from the Yuzu, Wolf also found that the Yuzu roots, when bruised, emitted a strong penetrating odor, disagreeable to many, and that the odor of the trifoliate is fainter and milder. The author also noticed some differences in the color of roots and their morphological appearance.

In Israel, Cossman (1939) also studied the anatomy of citrus roots, including the root structure of sweet lime, Rough lemon, sour lemon, citron, ‘Baladi’ sweet orange, ‘Shamouti’ sweet orange, sour orange, grapefruit and shaddock. Cossman felt that characters which might be of taxonomic importance were the mode of lignification of the pith, the configuration of the protoxylem strands, suberization in the endodermis, and the thickening of the walls of the epiblema (the piliferous layer or epidermis of the young root). Later, Hayward and Long (1942) described in detail the anatomy of the seedling and roots of the Valencia orange.

In Israel, Green, Vardi, and Galun (1986) studied the plastomes of various citrus species and several citrus relatives. They found a resemblance between the plastomes of cultivars of lemon, orange, sour orange, grapefruit and pummelo. The plastomes of other citrus species, such as mandarin and citron, differed from each other as well as the plastomes of the above citrus species. Furthermore, within the citrus relatives examined, the plastomes of the trifoliate orange and *Microcitrus* spp. were distinct from each other as well as from the citrus cultivars tested. They felt the result of their study constituted a useful tool for the identification of plastomes in hybrid (inter-cultivar) plants of *Citrus* developed from protoplast fusion, i.e., somatic hybridization.

Some excellent work on the anatomy of *Citrus* has been published by Schneider (1968). However, most of this is developmental anatomy. He has also published crucially important papers on the seasonal production of xylem and phloem in the sweet orange tree trunk (1952*b*) and the ontogeny of lemon tree bark (1955), the relationship of the phloem to certain destructive diseases such as the Buckskin disease of peach and cherry (1945) to tristeza (1959), and the incompatibilities and decline of lemons (Schneider *et al.*, 1978). Schneider *et al.* (1978) were extremely helpful in the early detection and diagnosis of these pathological and physiological problems. However, for some reason, Schneider ignored the structure of the xylem as it might differ between citrus species and how it might aid in identification.

Some excellent work has been done on the structure of wood as an aid to identification with forest trees, both conifers and deciduous. One might consult Jane (1970) and [*text incomplete*] (Otis, 1931). The importance of knowledge of wood structure cannot be emphasized more than the convincing and convicting evidence provided by a wood expert in the trial of the kidnapper of the Charles Lindbergh baby in the early 1930's. The expert from the regional U.S. Forest Products Laboratory at Madison, Wisconsin, successfully established that the wood in the ladder used by the kidnapper came from the attic of the kidnapper's home, from which several pieces of wood were missing. The wood in the ladder matched perfectly with wood remaining in the attic.

Wagnon, Dobbins, and Breece (1959) used foliar gland characters in the identification of peach and nectarine varieties. It is possible that the nature, size, number, and arrangement of oil glands in *Citrus* leaves may also be useful in identification. Hirano (1931), and Gianotti (1945) reported on the numbers and variation in stomata in *Citrus* and some related genera. This technique also might be of some benefit.

Nothing has been done recently with anatomical structure as an aid to rootstock identification or taxonomic relationships. Clearly this method will become more complicated as more hybrids involving bigeneric and even trigeneric crosses are made. Furthermore, a microscope, good laboratory, technique, and a thorough knowledge of plant anatomy are required.

Chemical Identification

The first attempt to identify rootstocks by colorimetric chemical reactions was apparently that made by Henricksen (1928), who based his method on the presence of varying quantities and kinds of glucosides containing phenol in all citrus roots. He used extracts from root pieces and, with ferric chloride as an indicator, found that the different color reactions or precipitations obtained were more or less characteristic for the four species he worked with, namely sour orange, grapefruit, sweet orange, and Rough lemon. Color density was greatest on sour orange and lightest with Rough lemon. Some confusion existed between sweet orange and Rough lemon. One, of course, needs known standard samples for comparisons.

Halma and Haas (1929*a*, 1929*b*) developed a similar but more extensive method of identifying citrus species by employing colorimetric chemical tests with samples of dried bark since most of the reactive agent seemed to be concentrated there. A number of tests were used in these experiments, but the one that gave most consistent results was the Almen test developed by Cohn (1903) for carbolic or salicylic acid, which is practically the same as Millon's reagent for albumens and phenols. Their experiments also indicated that three other reagents in various forms, molybdic acid, titanium chloride, and ferric chloride, were of value when identification was doubtful. The results obtained by these investigators was sufficiently uniform within commonly accepted limits of the species to lead Halma and Haas (1929*b*) to “suggest the possibility that these colorimetric differences may be useful in citrus classification.”

In a later paper, Halma (1934) described the preparation and use of the Almen test as it had been modified since its first use by Halma and Haas (1929*a*). The tests were only carried out with lemon, Rough lemon, grapefruit, sweet orange, and sour orange.

Marloth (1936), in South Africa, made extensive studies and experiments on the use of the four colorimetric reagents in identifying *Citrus* species, working mainly by the methods suggested by Halma and Haas (1929*a*). Both groups were able to distinguish between the commercial lemon and Rough lemon, and Marloth (1936) was able to separate grapefruit and pummelo.

As the inroads of tristeza in Brazil became more prevalent and the relationship of rootstock-scion combinations became more evident, Bacchi (1943) also used these colorimetric tests to distinguish rootstocks. He attempted to identify 15 species, hybrids, and cultivars and found that the reactions obtained were somewhat different from those described by Halma and Haas (1929*a*) and Marloth (1936). The differences between sweet orange and sour orange were quite apparent, but the situation becomes more complex with other species and varieties. Bacchi (1943) therefore proposed the separation of rootstock species and varieties into four groups: (1) sour orange, (2) sweet orange, (3) lemon, and (4) “all the others.”

When tristeza began to threaten California orchards and a variety of rootstocks appeared to be involved, Masters (1948) made a review of laboratory tests for the determination of *Citrus* rootstock varieties. He refined the technique somewhat and was more specific in his color chart, which is perhaps the best available; it is reproduced here for the benefit of those who wish to conduct such colorimetric tests (Figure 73 [*figure could not be included due to copyright restrictions*]). Masters was the first person to point out that there is a difference in color reaction between above-ground and underground samples, and for these reasons an addendum is attached. Masters also proposed the use of ultraviolet light and fluorescence as an additional aid. Some of the differences between above-ground and below-ground samples may be pointed out, such as: above-ground sour orange extracts are clear with the ferric chloride test, below-ground samples may become cloudy; sweet orange extracts show poor fluorescence above-ground and good fluorescence below-ground. Some of the differences in bark sample location may account for the discrepancies between previous investigators. Certainly it makes a difference as to how much the bark sample is scraped or washed to remove soil particles. The presence of contaminants such as fertilizer, pest control residues, fungicides, and other chemical agents may also make a difference in the color reactions. Of course, the importance of having knowns to compare unknowns with is critical to the tests.

Furr and Reece (1946) also used a modification of the rootstock color tests for the identification of hybrid and nucellar citrus seedlings with a reasonable degree of success. Similar tests were also used by Nishiura, Matsushima and Okudai (1957) to identify species and also distinguish hybrids from nucellar seedlings. Nakamura and Nakayama (1941) and Krishnamurthy, Singh and Deo (1960) also used the tests for studying phylogenetic relationships of the citrus species. Although these chemical tests were somewhat primitive by today’s standards, remarkable results were obtained by someone with care and experience.

As chemical techniques and procedures improved, so have the diagnostic aids. Selle (1954*a*, 1954*b*) proposed a method of clearly identifying sour orange rootstock from other stocks by paper chromatography. Essentially the method consisted of taking a piece of rootstock bark, placing it upon a sheet of filter paper and hitting it with a hammer. Or, he used a bark extract made with a solution of ethyl alcohol-normal butyl alcohol-acetic acid and water, and placed drops of the extract on filter paper. The spots were allowed to dry, sprayed with a dilute solution of ninhydrin and again allowed to dry. The spots were examined with a long wave ultraviolet lamp (3600 Angstroms) and a characteristic flame pattern was observed for fluorescence. The hammer technique gave the most striking results.

Selle (1958) also developed a spot chromatographic method. Root sections were taken and the bark removed, cut into very small pieces, placed in a bottle, and treated with 2,2-dimethoxypropane. After standing for 30 minutes, single drops were placed on filter paper and the spots observed as they dried. Complete identification of all the rootstocks was not obtained by using dimethoxypropane alone, and he got better differentiation by adding anhydrous aluminum chloride to the solution. He was thus able to identify sour orange, sweet orange, grapefruit, tangelo, mandarin, Rough lemon, trifoliate orange and Troyer citrange. The memory of the past is not always too reliable, but the author is quite certain that in conversation with Selle, he indicated he could also tell with the root bark what the scion variety was budded on it. Unfortunately, with Selle's sudden death, perhaps this information was lost.

Pieringer, Edwards, and Wolford (1964) and Kesterson *et al.* (1964) studied the application of gas-liquid chromatography to the citrus leaf oils for the identification of kinds of *Citrus*. Kesterson and his coworkers included eleven kinds of citrus and their data demonstrated that the oil composition for the different species is quite variable. They list the most prevalent and distinguishing features for each type oil in order of importance for sour orange, grapefruit, tangelo, mandarin, sweet orange and Rough lemon. They state that, "The percent of composition within species is shown to be sufficiently different to distinguish one variety from another." Limits of normal deviation, tree variability, and seasonal variations are all factors which may affect leaf oil properties and they feel additional work will establish these limits.

Pieringer, Edwards and Wolford (1964) studied the leaf oils of eight different citrus varieties and two sources of sour orange as subjected to four methods of instrumental analyses. These were: infrared and ultraviolet spectrophotometry, gas chromatography, and measurement of refractive indices. Some methods were more effective than others in separating closely related cultivars. They felt gas chromatography more successfully differentiated the varieties, whereas infrared and ultraviolet spectrophotometry appeared to be limited to the identification of *Citrus* species. The value of the refractive index was not fully determined. Burger (1981), on page 109 of this thesis, obtained chromatograms with high pressure liquid chromatography (HPLC) of the phenolic present in the rootstocks he worked with. Using this method, he could distinguish between Troyer and Carrizo citranges, which most other researchers could not do. This chromatograph is reproduced in Figure 74 [*Image could not be located*]

The use of, or combination of, other diagnostic aids may also prove valuable. Thus, Albach and Redman (1969) used the composition of flavones in citrus fruits as an aid in citrus classification, but these compounds might be a factor in bark identification as well. Dreyer (1966, 1967) used citrus fruit bitter principles for chemotaxonomy in the *Rutaceae*.

Esen and Soost (1974) found that based on the occurrence or absence of browning in young shoot extracts, *Citrus* taxa can be classified into two phenotypes: browning and nonbrowning. The ability to cause browning in shoot extracts has been shown to be due to a single gene (Br), which controls the production of a substrate of polyphenol oxidase. Esen and Soost (1974) suggest the technique might not only be useful as a genetic marker, but also as a taxonomic criterion, when used with other procedures.

Another very helpful chemical technique to aid in citrus identification, particularly in distinguishing between nucellar and zygotic seedlings, is the use of isozymes. This procedure is based on the horizontal starch gel electrophoresis of heterozygous loci found in leaf extracts of the cultivars to be analyzed, whether known cultivars or new hybrid progenies. Perhaps the first researchers to use the method as a practical approach in *Citrus* were Ueno (1976), Ueno and Nishiura (l976*a*), and Ueno and Nishiura (l976*b*). Ueno and Nishiura (1976*a*) were very successful in identifying hybrid and nucellar seedlings in progeny obtained from a breeding program extending over a 10 year period at the Fruit Tree Research Station at Okitsu, Japan. The progeny of the crosses were categorized by analysis of the leaf enzymes using peroxidase isozyme electrophoresis. Ueno (1976) extended this technique to confirm the identity of *Citrus* species and varieties in the collection at the Okitsu Station. Ueno and Nishiura (1976*b*) used the same procedure to study the graft hybrids, Kobayashi mikan (natsudaidai + satsuma), Kinkoji-unshiu (kinkoji + satsuma), and Takagi-mikan (hiua koji + satsuma). They were able to establish that the Kobayashi mikan and the Kinkoji unshiu were tree graft hybrids, but that the Takagi-mikan was not. Torres, Soost, and Diedenhofen (1978) were the first to report clearly the allozyme systems in *Citrus*. They reported 19 co-dominant identifiable alleles distributed among four loci controlling three enzymes. These three gene enzyme systems were glutamate oxaloacetate transaminase (GOT), phosphoglucose isomerase (PCI), and phosphoglucose mutase (PGM). Using this technique, Soost, Williams, and Torres (1980) were clearly able to distinguish between zygotic and nucellar five-month-old citrus seedlings. The seedlings were from a cross using King mandarin as the female parent and Parson's Special mandarin as the pollen parent. Of the 128 seedlings obtained from the cross, and using the two genetically defined markers (PGI and PGM), they found 18 to be nucellar and 110 to be zygotic. Fortunately, all of these seedlings were planted in the orchard for further observations. (As many readers know, the Parson's Special mandarin is the best available indicator plant for the viroid cachexia. It is possible that some of these hybrids might respond even better as indicators. As of March, 1988, these trees are fruiting and will be pointed out as potential indicators to a pathologist working with cachexia. (However, this was not the purpose of the experiment.)

The work of Soost and Torres (1982) extends and amplifies the work of Torres, Soost and Diedenhofen (1978). Three additional gene-enzyme systems, malate dehydrogenase (MDH), hexose kinase (HK) and isocitrate dehydrogenase (IDH), were determined and used for possible identification of cultivars in the subgenus *Eucitrus*. Additional taxa were analyzed for glutamate oxaloacetate transaminase (GOT), phosphoglucose isomerase (PCI) and phosphoglucose mutase (PGM). Examples of the use of the three latter enzyme systems are presented in the paper as well as considerable references to the numerous cultivars in the Citrus Variety Collection at the Citrus Research Center, Riverside. Torres, Soost, and Mau-Lastovicka (1982) emphasize that isozymes of *Citrus* provide molecular tags to determine the genetic origin of citrus seedlings. A very large proportion of all possible seedlings, either from selfing or crossing, can now be distinguished with a great deal of certainty as to their genetic origin.

Citrus leaf extracts were analyzed by starch gel electrophoresis for the previously mentioned enzymes of hexokinase (HK), isocitrate dehydrogenase (IDH), leucine aminopeptidase (LAP), malate dehydrogenase (MDH) and malic enzyme (ME).

The isozyme technique is wonderful for distinguishing between nucellar and zygotic seedlings, but for other uses it does have limitations. Sometimes it may accurately identify the genetic makeup of many cultivars, in others, not. However, in some cases it is extremely helpful in that although it cannot tell one of the parentage of a cultivar, it can tell one what it is not. Sibs out of the same cross cannot be identified from each other. Orange cultivars cannot be accurately identified, or with little confidence. Carrizo and Troyer citrange have not been definitely identified. Eureka, Lisbon, and Villafranca lemon strains cannot be distinguished, etc.

Many of the various chemical tests are rather complicated and not only need special supplies and equipment, but also trained technicians. If such tests are necessary, the grower should obtain the services of a professional laboratory with experience in these techniques. Furthermore, these tests are not practical for use by the nurserymen who grow thousands of trees or hundreds of thousands of trees. One should use rootstocks which are highly nucellar, such as Troyer and Carrizo citrange, Rough lemon, sweet orange, etc. Using rootstocks like Sacaton citrumelo and *Citrus taiwanica*, which only have about a 50% nucellar rate, can provide nothing but trouble. The nurseryman cannot possibly effectively discard all the zygotes and hence, tree variation and poor performance in the orchard is to be affected.

THE ROOTSTOCKS' SPECIES, VARIETIES AND HYBRIDS

Much of the general information about specific rootstock cultivar performance which follows is well documented. However, personal observations and experiences of the author over a period of 40 years are introduced because they have also contributed greatly. There may be some California bias as a result—results that in some cases may be fairly specific to California, but notwithstanding, the general characteristics of individual rootstock cultivar performance are basically as described unless specifically indicated to the contrary. The taxonomic system followed is mostly that of Swingle (1943), but, for the purpose of clarity, at times the system of Tanaka (1969) is often referred to. A rootstock cultivar must be adequately identified so that readers know exactly the cultivar being referred to with its vernacular name(s). Some readers may not agree with some of the author's identifications, but he will try and support decisions with more specific references.

The Sweet Oranges (*C. sinensis* [L.] Osbeck) as Rootstocks

The sweet orange, *Citrus sinensis*, achieved prominence only in California (Webber, 1948). In Southern California during the period from 1900-1950 it was probably the principal rootstock in use, except on heavy soils and the sandy soils of the Coachella Valley. Since 1950, its use as a rootstock has steadily declined so that by about

1970 it was seldom planted, but is in certain situations. As a rootstock, its performance in California was very satisfactory, with all major commercial scions performing comparable to those same scion trees on sour orange or better. Such trees were superior in performance to trees on Rough lemon, grapefruit, Cleopatra mandarin, trifoliate orange, etc., see Webber (1948), Wutscher (1979), and Castle (1984). Sweet orange was used to a very limited extent in Florida and Australia. It was well tested in South Africa by Marloth (1957, 1958), but never achieved acceptance. The sweet orange consists of a homogeneous group of cultivars, one of the most uniform of the citrus species. Maximum variability may exist between the Valencia and the navel, the red- pigmented "blood" oranges (anthocyanin), the pink pigmented varieties (lycopene), the blond oranges, the acidless oranges, and the seedy varieties that have been used for rootstocks. They are commonly and collectively referred to in California as 'sweets,' 'seedy sweets,' or 'Mediterranean sweets.' According to origin, they may be 'Blackman', 'Koethen', 'Hinckley', 'East Highland', 'Olivelands', etc. In Florida, seedy varieties like 'Pineapple,' 'Parson Brown,' 'Homosassa,' and 'Florida common' were some of the sources used.

The sweet orange varieties grow readily from seed, but the seeds are easily injured by drying out and must be handled carefully ([*reference information lacking*]). All sweet orange varieties are highly nucellar ([*reference information lacking*]), and require a minimum amount of rogueing in the seed beds and nursery seedlings to remove the variants. The seedlings grow more slowly, when young, than those of the sour orange, and produce low-branching bushy trunks (Figure 75 [*Image could not be located*]) which may require more shaping in the nursery prior to budding than seedlings of Rough lemon, Troyer citrange, Cleopatra mandarin and others. The scion buds, after insertion, grow rapidly and produce large budlings with most scions —but not as large as on Rough lemon, Rangpur lime, Alemow, etc. The sweet orange may be grown from cuttings more easily than the sour orange, but not as easily as cuttings of the Rough lemon.

As a rootstock, the sweet orange in California is only medium in cold resistance, more hardy than Rough lemon, but maybe not as good as sour orange. When mature trees are frozen to the ground, as in a Florida freeze, it sprouts readily from the base of the trunk. The rootstock buds well to all the common scion varieties.

The sweet orange usually gives normal bud unions with all varieties of sweet orange, mandarin, grapefruit, lemon and lime. That is to say the stock and scion are usually nearly equal in size, particularly with young trees. With older trees, there may be a tendency for a slight bulge at the union and the stock may be slightly smaller than the scion, but not to the degree attained on sour orange stock. This is generally true with grapefruit and lemon scions. In some instances, Eureka lemon trees on sweet orange may show a slight budunion overgrowth. For illustrations of these budunions, see Figure 76 [*Image could not be located*].

The sweet orange grows fairly well on some heavy soils, but is best adapted to growth on rich sandy loams. Trees on sweet orange do not do well on very sandy soils such as in the Coachella Valley of California, nor extremely heavy or calcareous soils such as Porterville or Ducor adobes. On heavier soils that are poorly drained, the trees may develop severe iron chlorosis symptoms, and this is also true on the calcareous soils. Embleton, *et al*. (1973) and Wutscher (1974) found that trees on sweet orange root may have higher leaf levels of nitrogen, phosphorous and copper than trees on other rootstocks.

The trees of sweet orange rootstock do not commonly develop a well differentiated tap root like the sour orange rootstock and is usually moderately shallow rooted, rarely penetrating to the depth that sour orange rootstocks do, although an occasional lateral may do so. The sweet orange does, however, develop an abundant system of lateral roots which generally penetrate deeper than those of Rough lemon in California soils. Illustrations of these root systems may be found in the section on roots. Navel orange cuttings produced only a few very large surface laterals which have little penetration. On the other hand, Valencia orange cuttings produce a more abundant root system similar to those obtained on sweet orange seedlings. There would appear to be no disadvantage in using Valencia orange cuttings for orchard trees in areas where sweet orange could satisfactorily be used as a rootstock.

Trees on sweet orange rootstock are large and vigorous, producing standard sizes in combination with all commercial citrus varieties in California. In most areas of California, the sweet orange trees are larger than those on sour orange rootstock, but are smaller than trees on Sampson tangelo or Troyer citrange. Also, in California, they have, on the better soils, produced larger trees than those on Rough lemon, but in the sandy soils of Florida they are generally smaller.

Yields on sweet orange rootstock are good, generally among the higher echelon with all scion varieties except with navel oranges, where trees on sour orange, Troyer citrange, or the non-commercial Morton citrange out-yielded them. Rios Castaño, Torres, and Camacho (1968) report that orange trees on sweet orange rootstock in Columbia were low in production, but offer no explanation. The sweet orange combinations are not as precocious in bearing as trees on trifoliate orange or Alemow, but the trees under favorable situations are long-lived and bear well into the advanced age of 50-60 years or longer. One orchard at the Citrus Experiment Station, Riverside must be 80 years and is still productive, although tree size is getting out of hand. There have been few loses from gummosis in the old orchard, but some trees have declined from psorosis.

In California, fruits on the sweet orange stocks mature at the normal season for the variety; they are thin skinned, juicy, and of high quality, and hold up well in all physical and chemical characters to the extreme end of the long harvesting season. Percent juice, soluble solids and citric acid content of the fruits are essentially identical to those obtained on sour orange—with all varieties and in all areas of California (Sinclair and Bartholomew, 1944). Wutscher (1978), however, reports that the acid content of fruit on sweet orange rootstock in Texas was higher than that of fruit on sour orange. This is not true in California. Fruits on sweet orange rootstock are thus intermediate in quality, being superior to those grown on Rough lemon, sweet lime, or Alemow. They are, however, of poorer quality than those grown on trifoliate orange or Troyer and Savage citranges. Granulation of the fruit is generally not a serious problem as compared to other stocks. Fruit sizes on sweet orange tend to run somewhat smaller than average (Bitters, 1961). In California, they are larger than on Cleopatra mandarin, but smaller than those grown on Rough lemon, sour orange, or Troyer citrange.

Seedlings of sweet orange are resistant to verrucosis (sour orange scab) according to Klotz (1978). Again, this is not a problem in California, but in nurseries or grown trees it can be a problem in areas with more humid climates. Sweet orange is also resistant to mal secco (Klotz, 1973), but this disease is not known to exist in the United States. It is a severe problem in some Mediterranean countries. Psorosis, or scaly bark, can be more serious on sweet orange than the resistant sour orange (Klotz, 1978), since if both the scion and the stock are affected, the rate and degree of decline of the trees may be greater. Lemon trees on sweet orange do not express shell bark (Wallace, 1978) with the severity that they do on sour orange or Rough lemon. The sweet orange does not appear to be affected by exocortis, cachexia, xyloporosis, or woody gall (Wallace, 1978). Trees on sweet orange rootstock in Florida are not threatened by blight (young tree decline, YTD) according to Lawrence and Bridges (1974).

The reaction of sweet orange rootstocks to tristeza inoculations has generally been negative (Bitters and Parker, 1953). However, in my Baldwin Park experiments in California, there was some light stunting as a result of the inoculations. A seedling cultivar of 'Bessie' sweet reacted severely enough to be classed as susceptible. The mother tree source did not. Trees on 'Koethen' sweet were also somewhat stunted and borderline in their reaction. In Brazil, trees on 'Caipira' sweet orange are also adversely affected.

Sweet orange is susceptible to the citrus nematode (Baines, Bitters and Clarke, 1960; Baines, Van Gundy and DuCharme, 1978; and O'Bannon and Hutchison, 1974). In fact, it is one of the most susceptible rootstocks. Certain selections of sweet orange like the 'Ridge Pineapple' and the 'Sanguine Grosse Ronde' have shown some resistance to the burrowing nematode (Ford and Feder, 1962; Baines, Van Gundy and DuCharme, 1978).

Not only are sweet orange trees very susceptible to nematodes, they are very susceptible to gummosis (Klotz, 1978). This is true even though the trees are budded high, planted high, and the best cultural practices are used. This is probably the greatest disadvantage that sweet orange has. It is remarkable, considering the susceptibility of sweet orange, that so many seedling orchards survived for a half a century or more, in the early history of California and Florida plantings. Surviving affected trees often bear scars of the infection by this disease. Sweet orange trees are as susceptible as trees on Rough lemon, often worse, but not nearly as tolerant as sour orange, Alemow, or Troyer citrange. It is interesting that at the Citrus Experiment Station, Riverside, and in some of my other rootstock plots, that although the sweet oranges in the original plantings were remarkably free of gummosis, that in replant situations, even though the soil was fumigated and good cultural practices used, it is almost impossible to successfully re-establish trees on sweet orange root (Bitters, 1973). It should be pointed out, however, that the soil fumigation is generally for eliminating the citrus nematode. The fumigant rate to kill nematodes is lower than the dosage to act as a fungicide. Because of roots the higher dosages are generally not used. Sweet orange has very poor root generation capacity and once infected, usually succumbs to the attack.

Klotz and Fawcett (1930) reported that the 'Indian River' variety, an ambiguous name, from Florida was somewhat more resistant to gummosis than other sweet orange varieties tested in the variety collection at Riverside, or in existing rootstock trials also at the Citrus Experiment Station. However, the tests were not replicated and the gummosis differences were small. The difference was not enough to attract any grower interest and consequently, it was never used as a commercial rootstock. The gummosis resistance of 'Precoce de Valence' reported by Olson, *et al.* (1962) in Texas would also warrant further investigation. When the author came to Riverside in the mid-l940's, there were still many seedling orange orchards in Riverside and adjacent areas. The first sweet oranges were planted in Riverside in 1871. One of these, the 'Koethen,' was probably planted prior to 1880, and was selected by H. B. Frost in the early 1900's, and later incorporated into the 1927 rootstock trials by H. J. Webber and reported on elsewhere in this text. The 'Koethen' turned out to be one of the better performing sweet orange cultivars and is still grown commercially, especially in Southern California. Seedling orange trees were first planted in San Bernardino County in 1857. One of these, the old Cram tree, at East Highlands is shown on page 36 of Volume I of The Citrus Industry, with Dr. H. J. Webber standing beside it. It was widely used in the San Bernardino area. Nearby was the 'Hinekby' orchard at Bryn Mawr. It also was used commercially. In Ventura County, the 'Olivelands' sweet from the Limoneira Company has also been widely used as a rootstock in that area and its other seedling orange cultivars have also been used, and their performance has been good. The Limoneira Company has continued to use the 'Olivelands' sweet as its principal rootstock for lemons. They state "we know sweet orange, its performance and limitations. We feel that with good cultural practices, inspection, and sanitary procedures we can control gummosis. There is nothing we can do about the phloem necrosis of the Eurekas on *C. macrophylla*, the sudden incompatibilities of Eureka on 'Troyer', on 'Swingle' citrumelo, or #1452 citrumelo, and the bud-union overgrowth and compression girdling on 'Cleopatra' mandarin. Much of the success of an orchard depends on its longevity and orchards which have to be replaced every decade or several decades cannot be considered successful."

There was always interest in a "good-performing" sweet orange. About 1950 the author introduced the 'Kona' from the Kona district of the island of Hawaii on the basis the trees were quite old and grew quite well in an area characterized by 250 cm of rainfall. Its performance in California districts was mediocre. In 1940, H. S. Fawcett introduced sweet orange seeds from the Santa Ana Mission in North Argentina. The author incorporated these in later rootstock trials and the performance has been good. The author visited many sweet orange seedling orchards in Southern California, which persisted well into the 1950's. The very striking thing in most of these orchards was the freedom of the trees from gummosis which certainly was not a factor in their ultimate removal.

In an effort to develop cold hardy edible citrus to extend its commercial growing range, Swingle hybridized the navel orange with trifoliate orange, and the 'Troyer' and 'Carrizo' citranges are part of the result. The 'Washington' navel, aside from producing no or few seeds, has nothing to recommend it as a rootstock. More recently, Cameron and Soost (1986) hybridized the 'Ruby' blood orange with a trifoliate orange from which resulted the 'C-32' and 'C-35' citranges. However, the 'Ruby' blood has never been used as a rootstock and has nothing to recommend it. Dr. Cameron's defense was that they thought the 'Ruby' produced more hybrids than some of the other sweet oranges. However, that seems a poor excuse, when a few more pollinations or the use of developing tissue culture techniques may have increased the number of zygotic embryos obtained. One wonders how much better 'Troyer', 'Carrizo', 'C-32', and 'C-35' citranges might have been if the sweet orange female parent would have been a more desirable and proven rootstock type. If new citranges are to be developed for rootstocks, then certainly the plant breeders should consider using the 'Argentina' sweet, or the 'Olivelands' sweet, as the female parent.

One of the disadvantages of some of the commercial citranges is their exceptional vigor, which doesn't fit in with today's interest in close spacing. However, the 'Fuya Menuda' cultivar is a genetic dwarf. Hybridized with a dwarfing strain of trifoliate orange, it is possible that more dwarfing hybrid citranges might be obtained. Positive identification or verification of the 'Fuya Menuda' is essential. Unfortunately the specimen in the Citrus Variety Collection at Riverside is not true to type and hopefully has not been distributed in seed or budwood requests.

None of the sweet oranges tested have ever shown any resistance to the citrus nematodes. However, the 'Ridge Pineapple' and the 'Sanguine Grosse Ronde' show resistance to the burrowing nematode (Ford and Feder, 1962). Perhaps they should be hybridized with select strains of trifoliate orange to produce hybrids possibly resistant to both the citrus and burrowing nematode. Also, the California strain of 'Carrizo' citrange which shows resistance to the burrowing nematode might be hybridized with the above sweet orange cultivar to provide improved resistance to this destructive soil organism.

The Sour Orange (*C. aurantium* L.) and Probable Hybrids

The sour orange, *C. aurantium*, was once the world's most widely used citrus rootstock. It was intensively used in the United Sates (California, Arizona, Texas and Florida), all of the Mediterranean area, including the Near East, all of South America, Cuba, Central America, and to a limited extent in Australia and New Zealand. It was never successful in the Orient, Java and South Africa due to a virus disease called tristeza (Wallace, 1978). Because of the rapid spread of this disease around the world, the acreage on this stock has continued to dwindle. It is still an important rootstock in the United States in Arizona, Texas and Florida. It is still used in the Mediterranean area, but the occurrence of tristeza in Spain and Israel threatens adjacent countries as well as the Near East, and other rootstocks are rapidly being employed. The stock is still used in Cuba, the western half of South America (Chile, Peru, etc.), in Central America and a few other scattered areas. As a rootstock the sour orange possesses many fine qualities and it has been a major disaster to the citrus areas which have been decimated by the tristeza virus. A sour orange rootstock fully tolerant to the tristeza virus would still be a tremendous asset to the growers and the plant breeders.

All of the standard sour orange varieties are very seedy, producing large plump seeds, which are moderately to highly nucellar, not being as high as sweet orange, Rough lemon, 'Troyer' citrange, 'Cleopatra' mandarin, etc. This is not always true of the so-called aberrant types like 'Chinotto' or putative hybrids like the 'Nansho daidai' which will be discussed later. A minimum of rogueing is therefore required in the citrus seed bed or nursery and container growing. The seeds are also more resistant to drying out than seeds of many other citrus species like Rough lemon and trifoliate orange. The seedlings are fairly vigorous growers, not as much so as Rough lemon, Alemow, or 'Troyer' citrange, but more so than sweet orange or grapefruit. The seedlings develop mainly a strong single trunk which requires less shaping in the nursery than sweet or grapefruit, but more than 'Troyer' citrange and Rough lemon (Figure 77 [*Image could not be located*]). This growth habit has facilitated easy budding, and the seedlings bud well to all common scion varieties. The sour orange may be grown quite easily from cuttings, but they are more difficult to root than cuttings of Rough lemon and sweet orange. Due to its seediness and the uniformity of its seedlings, there is no need for the cuttings. Seedlings are perhaps more resistant than other rootstocks commonly used with the exception of the trifoliate orange and some of its hybrids like 'Troyer', 'Carrizo', 'C-32', 'C-35', 'Swingle' citrumelo, etc. When frozen back, the seedlings readily sprout from the base of the trunk and a sprout can easily be trained to a new leader. Sour orange seedlings are very susceptible to citrus scab (verrucosis), which sometimes causes serious injury to nursery seedlings in humid climates (Klotz, 1978).

The budunions of the common sour orange variety are nearly normal with scions of sweet orange, mandarin, and grapefruit varieties, but rather commonly show a strong scion overgrowth with most varieties of lemons (especially Eurekas, some Lisbons), limes, and citrons. This lack of congeniality was called "miriñaque" with lemon in Spain (Gonzalez-Sicilia, 1968). With most scion varieties there is a slight bulge at the union, with the stock tending to be smaller than the scion. Grapefruit scions tend to overgrow the stock to a greater degree, but this is slight compared to the reaction with lemons and citron (see figures in budunion section). Certain strains of Lisbon lemons such as the 'Keen,' 'Monroe,' 'Bradbury,' etc. on sour orange show a more congenial reaction. Although certain scions on sour orange show the stock undergrowth, the author wishes to state that at one time almost all the cultivars in the entire citrus variety collection at the Citrus Experiment Station, Riverside, were budded on sour orange rootstock, and that few incompatibilities occurred. Many of these combinations were planted in 1917 and it was only the eminent threat of tristeza approaching the Riverside area which instigated repropagation of the collection on tristeza-tolerant rootstocks in the 1950's.

Although the sour orange is no longer used as a rootstock for lemons in California, it should be pointed out that essentially the entire lemon industries of Spain, Italy, Greece and other Mediterranean countries were successfully established on sour orange rootstocks. In one lemon strain experiment at the Citrus Experiment Station, Riverside, the planting consisted of 28 lemon strains (both Eurekas and Lisbons) on Seville sour stock. When this planting was discontinued after years, the degree of budunion overgrowth varied widely among the combinations (Figure 78 [*Image could not be located*]).

The sour orange has commonly been considered to be best adapted to growth on moist, fairly fertile soils, and heavy soils such as adobes. It was on the hummock soils of Florida that the wild natural groves of sour orange became established and on which it proved to be the most successful rootstock. On the very light, excessively drained soils of the so-called "ridge" section of central and peninsular Florida it has been a mediocre rootstock, being slow to reach good production. It has been very successful in the heavy soils of Northern and Central California (San Joaquin Valley) and also in the light sandy and rocky soils of the Upland area (Los Angeles basin) and Fillmore (eastern Ventura County) as well as the sandy soils of the Coachella Valley. It has not done well in the very sandy soils of the Yuma mesa at Yuma, Arizona, but was the principal rootstock in the Phoenix area. In areas in which sweet orange rootstock would not tolerate the soils conditions, the sour orange has been very successful. The old adage in California of using sour orange on the heavy soils and sweet orange on the lighter soils has proven to be quite true. In the heavier soils where soil-moisture relationships have been conducive to iron chlorosis in scion leaves, this problem has been much more severe on scions on sweet orange stock than on sour. Wutscher (1979) indicates it is highly tolerant to calcareous soils.

The sour oranges generally develop a deep penetrating tap root system which, if unrestricted by soil profiles, grows to a considerable depth. In California, lateral root development is more limited than in Rough lemon, sweet orange or grapefruit (see section on roots). Rarely is a single taproot found. The tap root which is cut back at the time of removal from the nursery usually touches and forms a small group of several equi-sized tap roots. The lateral roots come off obliquely to the central axis. Where soil strata of different textures exist, the tap roots may penetrate to the sandy, clay, or rocky impervious strata and then shunt horizontally along the lens (strata). Sometimes these tap roots may fuse together into a broad plate, or pedestal, from which smaller laterals may protrude (Figure 79). There is not an abundance of lateral roots under most conditions in California. The drought tolerance of sour orange is somewhat dubious, but it would appear to be less than that of the shallower, but more extensively rooted rootstocks like Rough lemon, Rangpur lime, and ‘Gajanimma’ under California conditions (see discussion on drought resistance). The author is aware of the deep rooting of Rough lemon in Florida (Savage, Cooper, and Piper, 1945; Gardner and Horanic, 1961; Ford, 1964*a*) but this is discussed in detail in the section on roots. In California, where all orchards are irrigated, and many characterized by hardpans, sandy strata, clay strata, etc., there has been little chance to observe this, and the deep sands of central Florida are an unusual situation that doesn’t generally occur elsewhere.

In California, where salinity in subsoils and underground waters is frequently a problem, a deep-rooted plant like the sour orange may be seriously injured. The tap roots may die back from the salty water, or lack of aeration, and gummosis may attack the injured roots and extend upward into the subsurface root system. This condition is most likely to occur on low, heavy soils where drainage is poor and less likely on light sandy soils which permit the free passage of irrigation water and thorough drainage. In Florida, on the contrary, the accumulation of salinity in injurious concentration is of rare occurrence.

The same lemon strain experiment at Riverside in which the scions modified the budunion conformity also affected the configuration of the root system. Root systems varied all the way from vestigial tap roots with strong laterals to strong tap roots and extensive laterals and surface roots (unpublished data, Kirkpatrick and Bitters, 1960). In this experiment were 28 different lemon scions, with five tree plots and four replications on 20 trees per combination, a total of 560 trees examined and measured. These differences were between lemons, so variations in root configuration between lemons, oranges, grapefruits and mandarins can vary.

Extensive rootstock trials conducted by the Citrus Experiment Station at Riverside have provided the opportunity to compare the performance of sour orange with other rootstocks for a period of 34 years. Initially reported on up to 1940 by Batchelor and Rounds (1948), data on this experiment is reported by the author in this monograph up to 1960, at which time the planting was discontinued due to the effects of tristeza on certain rootstock combinations, especially those on sour orange. In this rootstock planting, the trees on sour orange were smaller in size than trees on sweet orange, Cleopatra mandarins and Sampson tangelo. The trees on sour might be considered as substandard in size. These effects are mentioned by Webber (1948) and [*text incomplete; possibly also Batchelor and Rounds (1948)—RK*]. Tree size on 'African' sour was smaller than on 'Brazilian' and 'Rubidoux' sours. Trees on the "bittersweets" are sometimes smaller than the trees on the 'Standard' sour, particularly navel orange trees. The 'African' sour was inferior to the others in many categories. For example, Satsuma trials budded upon it died, although the growth of the Satsumas was fairly satisfactory on other sour orange types, eliminating the possibility of tristeza effects. The failure of Satsuma on sour orange was generally attributed to the presence of tristeza in the Satsuma scion in other citrus areas. Nucellar Satsuma on sour orange has given a fine performance.

Fruit yield on sour orange rootstocks has been quite satisfactory (Webber, 1948; [*additional reference information lacking*]). Although the scion trees were smaller on sour orange, these smaller trees yielded as much fruit as the larger trees on sweet orange in the case of the navel and grapefruit scion. With the navel oranges, the yields on sour orange were nearly 20 percent greater than on the sweet orange rootstocks. In fact, the navel yield on sour orange was greater than all the other rootstocks in the experiment except the 'Morton' citrange (see section on yields). The adaptability of a specific scion to a specific rootstock is thus pointed out.

Fruit sizes on sour orange are medium to large. With navels, Valencias and grapefruit, the fruit sizes were larger than on sweet orange, 'Cleopatra' mandarin and comparable to those on Rough lemon (Bitters and Batchelor, 1951; Wutscher, 1979). Fruit quality on sour orange is about standard to excellent (Sinclair and Bartholomew, 1944; Bitters, 1961; Wutscher, 1979). Fruit quality is equal to that on sweet orange and better than that on Rough lemon or 'Palestine' sweet lime, but not as good as on trifoliate orange or 'Savage' citrange (see section on fruit quality). Fruit from trees on sour orange tend to have a higher ascorbic acid content than fruits from many other rootstocks (Harding, Winston, and Fisher, 1940; Blondel, 1974; Cooper and Lime, 1960). Wutscher (1979) reports the citric acid content is higher than on sweet orange in Texas, but results in California do not agree (Bitters, 1961; Sinclair and Bartholomew, 1944). The fruits on sour orange rootstock are smooth, thin skinned, juicy, excellent in quality, and hold up well without appreciable deterioration after maturity during the long harvest season in California.

The sour oranges are highly tolerant to gummosis, much more so than sweet orange, Rough lemon, grapefruit, and most mandarins (Klotz, 1978; Klotz and Calavan, 1969). If the stock is infected, it has a greater ability to recover than sweet orange, for example. Frequently, the scion variety becomes infected first, particularly if it has been budded too low or planted too low, and the infection spreads downward to the sour orange. Under conditions of high water tables, the disease may start on immersed tap roots as they are weakened by lack of aeration, and the infection progresses upward, perhaps never becoming viable above ground and only detectable after the trees have declined and are pulled out. However, Hutchinson *et al.* (1972) and Hutchinson and Grimm (1972), have shown than under certain conditions, it is not as resistant as believed.

Sour oranges are not affected by woody gall, exocortis, or cachexia, but of course are symptomless carriers (Wallace, 1978). Shellbark of lemons which affects the scion variety (Wallace, 1978) is worse on sour orange than on any other rootstock except Rough lemon. Trees on sour orange are susceptible to the fungus disease mal secco, a disease which appears to be limited as yet to the Mediterranean area (Klotz, 1973, 1978). The sour orange is still used as a rootstock in new plantings in Florida because it is more hardy than Rough lemon and has a lower incidence of blight (young tree decline) which severely affects trees on Rough lemon rootstock (Wutscher, 1979; [*additional reference information lacking; Possibilities in approx. timeframe of wriiting:* 1. *Young, R.H., L.G. Albrigo, D.P.H. Tucker, and G. Williams. 1980. Incidence of citrus blight on Carrizo citrange and some other rootstocks. Proc. Fla. State hort. Soc. 93:14-17and/or* 2. *Young, R.H., L.G. Albrigo, M. Cohen, and W.S. Castle. 1984. Blight: rates of blight incidence in trees on Carrizo citrange and other rootstocks. Citrus Industry Magazine. February (volume number not known) 20,23,27,30—RK*]). Apparently the hazard of blight in Florida is deemed greater than the fear of tristeza. The sour oranges are susceptible to the citrus nematode and the burrowing nematode (Baines, Bitters and Clarke, 1960; Baines, Van Gundy and DuCharme, 1978; Hutchison and O'Bannon, 1972). However, Baines, Van Gundy and DuCharme (1978) indicate that one selection of sour orange from California shows a high resistance to the citrus nematode.

The tristeza aspects of the various rootstock-scion combinations are well discussed by Wallace (1978) and Bitters and Parker (1953) and elsewhere in this text. It must not be forgotten that there are many varieties and forms of the sour orange. Nearly thirty from different sources around the world were tested by the author at Baldwin Park, California (Bitters and Parker, 1953). Most of these were of the 'Seville' sour. None of those tested at Baldwin Park, or later on at South Coast Field Station in Southern California were tolerant to the disease. None have been found by other researchers working on tristeza tolerant rootstocks. The 'Zadaidai', 'Herale' and 'Gadadehi' appear to be typical sour oranges, although there are some differences in degree of tolerance. The "bittersweets" are another group of sours. They produce smaller trees, have budunions which are smooth, or the stock slightly overgrows the scion. In addition, the colorimetric bark tests of Halma and Haas, 1929*a*, 1929*b*) are not typical and are not the same on the group as for the 'Seville' sours. The bittersweets tested at Baldwin Park for tristeza tolerance generally declined faster and more severely than the 'Seville' sour. The incidence of collapse was high. The aberrant type 'Bouquet' was equally as susceptible as the 'Sevilles'. The 'Chinotto' is not as highly nucellar as the other types, however, it was equally as susceptible and the trees showed no signs of dwarfing. The 'Abers', a narrow-leafed variant sour orange, has not been listed for tristeza tolerance, and neither has the 'Willow leaf' which is *C. aurantium* var. Salicifolia and is quite different from the 'Abers'. The 'daidai', characterized by the fleshy calyx, was also susceptible. The Japanese 'Kabusu' was not tested.

There is an interesting situation that occurred with individual trees of the sweet orange-sour orange combinations inoculated both at Baldwin Park and at South Coast Field Station. At Baldwin Park, some individual inoculated trees of sweet on sour were still alive and healthy ten years after the inoculations (they did have tristeza). The author mentioned this to Dr. J. M. Wallace, Plant Pathologist at Riverside, and he indicated he had noticed the same thing in some of his Baldwin Park experiments. We both felt sooner or later symptoms would show, but at the age of 13 years when the Baldwin Park plantings were abandoned in 1960, the trees were still healthy. The tristeza scion rootstock testing was continued at South Coast Field Station, Tustin, California, with plantings in 1964 followed by plantings in 1966, 1968, 1969, 1971 and 1973. In these plantings, the author always placed trees of a sweet-sour combination to serve as checks and establish that the tristeza inoculum introduced (which was always the same source) was hot (active). While most of the inoculated trees showed symptoms in 12-18 months, and some of the uninoculated checks equally as fast, again some individual trees did not show any symptoms. Twenty years later (1985), some still haven't shown any symptoms. One might think some tolerant hybrids are involved. However, the symptomless trees were checked by the isozyme method and they test typical sours, not hybrids. Perhaps these should be propagated and fruited to see if this reaction is real and if the progeny show any tolerance to tristeza.

Orange scions on sour orange appear to be most susceptible to tristeza, followed by mandarin scions. When tristeza infected the old Citrus Variety Collection at Riverside, which was on sour orange, most of the orange cultivars were in advanced stages of decline before the first mandarin combinations began to express symptoms. Grapefruit scions are much slower in expressing symptoms. Young grapefruit trees on sour orange are fairly susceptible to tristeza and decline readily when inoculated, but generally do not collapse. With mature grapefruit trees under field conditions in California, the decline is very slow. None of the taxa within the sour orange group have shown any indication of stem pitting from the presence of tristeza. However, grapefruit trees on sour orange, in the absence of tristeza, do have a tendency for inverse pitting to occur in the sour orange immediately below the bud union.

Probable Hybrids

Perhaps the best known of these is the ‘Natsudaidai’ or ‘Summer daidai’ of Japan. It is *C. natsudaidai* and is grown commercially as a grapefruit substitute. In the tristeza trials at South Coast Field Station in California, Bitters (1968) found it to be tolerant to tristeza with Valencia orange scions. The trees were vigorous, but the trees were shy bearers, a characteristic known in Japan where it is occasionally used as a root. The author never included it in any horticultural evaluation trials and it has never been used commercially except for the few trees in Japan. The ‘kikudaidai’, or ‘chrysanthemum daidai’, because of the natural ridging of the fruit, is *C. canaliculata*. In the South Coast Field Station experiments (Bitters, 1972), it was susceptible to tristeza. For further evaluation, it was placed in a lemon rootstock evaluation trial by the author at Lindcove Field Station, Tulare County, in 1977. It has shown no merit as a rootstock there for lemons, oranges or tangelos. The most tested of these probable hybrids is the ‘Nansho daidai’ of Japan. It is classified as *C. taiwanica*. Salibe (1974) states that it is tolerant to tristeza in Brazil. This cultivar was included in the rootstocks tested for tristeza at Baldwin Park, California (Bitters and Parker, 1953). The combinations were rated susceptible since the inoculated trees are quite stunted, but somewhat questionably so. A picture of these trees at 13 years of age is shown in Figure 80. The inoculated tree is on the right, uninoculated on the left. This combination illustrates an average response, not the best, but the poorest (12 inoculated trees, 12 uninoculated). In Florida, Garnsey ([*date lacking; reference could not be identified*]) reported that the nansho daidai was susceptible to the T_3 strain of tristeza. This is the author’s proof. Where is the evidence of those who say it is resistant? Because of its somewhat questionable tolerance to tristeza, it was incorporated into a number of rootstock evaluation trials in California, Arizona, Florida, Texas and Brazil. In Brazil, Moreira *et al.* (1965) report that yields and fruit quality of both grapefruit and Valencia orange were poor. In Texas, Wutscher and Shull (1973); Wutscher, Maxwell, and Shull (1975); and Wutscher and Dube (1977) report that the yield of early orange varieties and tangelo on *C. taiwanica* was similar to trees on sour orange, but that the fruit quality was also low (Wutscher and Shull, l976*a*, 1976*b*). In California, the author planted rootstock trials containing the stock with lemons, navels, Valencia oranges, and Marsh grapefruit in Tulare, Ventura, Riverside and Orange counties. Like the Brazil experience, yields and fruit quality were poor. In fact, in the South Coast Field Station plantings in Orange County, California, the granulation of the fruit on *C. taiwanica* was so severe the fruit was harvested in advance of the normal harvest period and actually dumped. None of the other 24 rootstocks in the trial had this problem. These trees are now 28 years old, and still show no general decline from tristeza. The only good experimental result on this stock was in a rootstock planting at Yuma, Arizona, on a very sandy soil. In this planting, Rodney and Harris (1973) found the highest yields on this stock. Trees on *C. taiwanica* are quite cold hardy. A personal communication from Harold Ormsby of the Yuma, Arizona, area indicated they were the most cold tolerant of any trees he'd grown in the Yuma area. This cultivar has nothing to recommend it for rootstock use. It is highly variable from seed. The fact that it produces so many hybrids has made it attractive to some plant breeders, but it should not be.

The 'Karna Khatta' is probably another sour orange hybrid and is classed as *C. karna*. In the Baldwin Park experiments, Bitters and Parker (1953) found it tolerant to tristeza. The trees were vigorous, but somewhat shy bearers and quite susceptible to gummosis. These characteristics have been noted in India where it has occasionally been used as a rootstock.

Wutscher (1979) suggests that the 'yama-mikan' or 'mountain mandarin' classified by Tanaka (1969) as *C. intermedia*, may also be a sour orange hybrid. This might be a questionable issue. The question has nothing to do with the results reported. The question deals with Wutscher's statement that the 'yama-mikan' is a sour orange hybrid. The name suggests that one parent of this hybrid might be mandarin, the other parent is debatable. However, Tanaka (1969) places this cultivar with pummelo hybrids and perhaps with no evidence to the contrary, that is what it should be considered as. It is occasionally used as a rootstock in Japan (Swingle and Reece, 1967), and the author did see a few trees budded on it in his many trips to Japan. Wutscher, Maxwell, and Dube (1976) reported that mandarin hybrids budded on sour orange performed better than on yama-mikan. In the South Coast Field Station tristeza experiments, Bitters (1972) found Valencia oranges on this stock were susceptible to tristeza. It was never placed in any other rootstock trials in California.

The smooth flat Seville or Australian sour orange is, according to Hodgson (1967), probably a hybrid. It has not been used as a rootstock in Australia, according to Bowman (1956), but according to Grimm and Garnsey (1969), there has been some interest in Smooth Seville in Florida because it has some tolerance to gummosis as well as some tristeza tolerance. In Texas, Wutscher, Maxwell, and Shull (1975) found that yield and fruit quality of grapefruit on this rootstock was poor. The author doesn't know for sure whether the smooth Flat Seville is the same as the Mildura sour (Appleby) of Australia. The latter is not a typical sour, and while it was reported to have some tristeza resistance, this fact has been disproven.

Another cultivar which is a possible sour orange hybrid is *C. obovoidea*, sometimes known as the 'marumero' orange, but best known in Japan as 'kinkoji'. In Japan, it has been used as an indicator plant for seedling yellow tristeza, but in the author's tristeza trials at South Coast Field Station (Bitters,1972), when inoculated with normal strains of tristeza, it shows good tolerance. Along with other tolerant or less-tolerant stocks that did well at South Coast Field Station, the author transferred seed to the Lindcove Field Station in Tulare County to place in long term rotation trials. Rootstock plantings of Limoneira 8A Lisbon containing trees on *C. obovoidea*, *C. miaray*, *C. canaliculata*, *C. neo-aurantium*, *C. shunkokan*, and other stocks, and Parent Navel, Olinda Valencia, and Minneola tangelo scions on *C. miaray*, *C. obovoidea*, *C. neo-aurantium* and *C. shunkokan*, as well as other stocks, were planted out in replicated plots by the author in 1977. Upon the author's retirement in 1982, the rootstock work was assigned to Dr. M. L. Roose of the Department of Botany and Plant Sciences, University of California, Riverside. Roose, in 1985, published a preliminary progress report on these rootstock plantings (Roose *et al.* 1985), and a summary report in 1989 (Roose *et al.* 1989). This is ten years from the planting date and provides about seven years of yield data. In his report, Roose eliminates the possible further testing of *C. miaray*, *C. canaliculata*, *C. neo-aurantium*, *C. shunkokan*, and *C. obovoidea* and some others as having no value as rootstocks. Perhaps he's right in most instances, but each of the rootstocks placed in those trials was included because of a purpose—they were not pulled out of a hat. While the grower is interested in such a progress report, the grower also wants to know what those trees will be doing at 20 years, 30 years, and even 50 years. A ten-year decision with no other experience is not adequate. Let me cite several points in partial defense of *C. obovoidea*. Some extra trees of the various rootstocks contained in the Lindcove plantings were distributed from that nursery by C. D. McCarty (now retired, but then with University of California Cooperative Extension) to some cooperating growers in Tulare, Ventura and Riverside counties and planted in 1977. In August, 1988, the author had a communication from R. M. Burns of Ventura (who was the former Farm Advisor with the University of California Agricultural Extension for that area), in which he states that with Valencia orange planted in 1977 (and now 11 years old), that the rating of the trees on the six rootstocks included found that the trees on *C. obovoidea* were the best. In 1987, I received a letter from a grower-friend (P. N. F. Niven) of the Amanzi Estates near Uitenhage in the Sunday's River area of South Africa. In this communication, Mr. Niven asks the question "What can you tell me about *C. obovoidea*? It looks rather interesting." A good long hard look should be taken at *C. obovoidea*. If it doesn't have the qualities to make it as a rootstock per se, then perhaps it would be worth hybridizing.

Among other possible sour orange hybrids looked at by the author was the 'konejime', or *Citrus neo-aurantium*. This cultivar is also called 'Tosu' and 'Takosu'. It was tolerant to tristeza in the author's 1969 plantings at South Coast Field Station (Bitters, McCarty and Cole, 1974*a*). It should also be looked at in depth. The 'Rokugatsu' or 'Tanakas', *C. rokugatsu*, was very susceptible to tristeza (Bitters, 1972). The 'otachibana', Tanaka's *C. otachibana*, was also very susceptible to tristeza (Bitters, 1972). *C. miaray* was also susceptible to tristeza (Bitters, McCarty and Cole, 1974*a*), but was placed in a lemon rootstock trial by the author at Lindcove Field Station in 1972. Its performance there has been poor (Roose *et al.*, 1985). *C. maderspatana* or 'vadlapudi', sometimes 'kitchili', was susceptible to tristeza (Bitters, 1972). In 1971 plantings at South Coast Field Station (Bitters, unpublished data), the 'Natsudaidai', or *C. natsudaidai*, was tolerant to tristeza. The trees were vigorous, but shy bearers, a fact known in Japan. The author never placed them in any other rootstock trials. In the Baldwin Park plantings (Bitters and Parker, 1953), the 'karna khatta', or *C. kharna*, was also tolerant to tristeza. The trees were vigorous, but very susceptible to gummosis, a trait known in India and Pakistan. The author never tested it further. The 'gabbuchinee' has been tested in Pakistan and India, but has been of no commercial importance.

The 'leather-head' sour orange described by Swingle (1943, p. 407-408) is probably as he indicates, a sour orange hybrid. Reports from China have indicated this cultivar is tolerant to tristeza. In China, this variety is called Pi-do-geng. C. A. Roistacher, Plant Pathologist at the Citrus Research Center, Riverside, visited China in 1981 and l986. He found mature trees of this variety heavily stem-pitted by tristeza. A planting made by Roistacher (personal communication) at the Citrus Research Center comparing Valencia trees on the leather-head sour with Valencias on a standard sour orange, and inoculated with several sources of tristeza, show quite a contrast (Figure 81 [*Image could not be located*]). There were different reactions to the different sources of tristeza inoculum. The sour orange, of course, was very susceptible to all sources of the virus. Trees on the leather-head sour were very compact and dark green three years after the inoculation, although the sour orange counterparts were in severe decline. Unfortunately, Roistacher left no checks. To the author, the trees on the leather-head sour appear stunted and lacking in general vigor. In other words, there is a slight tristeza reaction, which may differ with different sources of the tristeza virus and perhaps the environment. This hybrid also should be hybridized. Some of the 'citradias', hybrids between sour orange and trifoliate orange, were tested at Baldwin Park, California (Bitters and Parker, 1953), but the results were extremely variable. Additional hybrids of this combination are needed.

In 1980, C. D. McCarty, Horticultural Technologist at the Agricultural Cooperative Extension, Citrus Research Center, made numerous crosses between sweet orange and sour orange in the Citrus Variety Collection at Riverside. His objective was to obtain hybrids which might be tolerant to both tristeza and gummosis. Seeds produced from these crosses were germinated at the University Lindcove Field Station in Tulare County and grown for approximately one year. In 1982, the seedlings were tested by isozyme procedures and the difficult-to-identify nucellars discarded. The hybrid seedlings are being field grown at the Lindcove Field Station and, when they come into fruiting will be tested by Dr. M. L. Roose of the Department of Botany and Plant Sciences for their disease resistance and ultimate horticultural characteristics as rootstocks. New possibilities may also arise from recombinations of species, or genera, from graft hybrids or somatic hybrids.

The Grapefruits

The grapefruits, *C. paradisi* Macf., like the shaddocks with which they are closely related, have not gained general acceptance as rootstocks. In California they were mostly used as a lemon rootstock, but are seldom used now. In many countries, the grapefruit is called pomelo, a name which can be very confusing since it is pronounced almost the same as pummelo, which is *C. grandis*. Most of the cultivars tried were understandably seedy varieties and sometimes they were confused with the small seedy shaddocks like the 'Tresca' and 'Pernambuco'. Others, like the 'Triumph' and 'Imperial', are not typical grapefruit, but are obviously hybrids of some type. Most grapefruit of the 'Duncan' type are very seedy, the seeds of which are very large and easily injured by drying out. In seedbeds, the young plants are very likely to give trouble by gumming and by blooming prematurely, frequently setting fruits when only 15-30 cm high. Grapefruit sometimes grows vigorously in the nursery, but, like the sweet orange, it is inclined to branch rather low and therefore requires considerable shaping and pruning prior to budding (Figure 82 [*Image could not be located*]). Otherwise, it is easy to bud, handles well in the nursery, and is easily budded with all commercial scion varieties. Different varieties of grapefruit give variable results, partly because of their confusion with variant varieties and partly because of the significant proportion of zygotic seedlings produced. Most varieties used in the United States were moderately nucellar and thus reproduced moderately true-to-type, requiring the elimination of 20 to 30 percent of small off-type seedlings in the nursery. Seedlings in the nursery show a tendency to develop mottle-leaf, but this does not appear to be a problem with budded trees. The inability of seedlings to be able to absorb a nutrient like zinc, whereas there is no problem when budded to scion varieties, has been reported by Chapman (1968).

Grapefruit develops an excellent root system and although deeply rooted, spreads more widely than that of sweet or sour orange (see section on roots). It is apparently best adapted to growth in heavy or loamy soils and is poorly adapted to light sandy soils. Most *Citrus* varieties on grapefruit stocks show an overgrowth of the stock at the bud union similar to that of shaddock. In some cases, this is like a shoulder extending out from the bud union, in others it is smooth at the union and flares outward and downward as it approaches the ground line, sometimes referred to as an 'elephant's foot' (see Figure 83). The union is, however, cylindrical and shows no tendency for fluting or ridging. The bark is usually slightly thicker than the scion. With some selections, there is a slight bud union overgrowth with lemon scions (see Figure 84-1 and 84-2).

At the Citrus Research Center, Riverside, 1927 rootstock plantings of trees on grapefruit root developed into normal-sized trees and, at 34 years of age, were comparable in size to adjacent trees on sweet orange stock and larger than on sour stock with all scion varieties (Batchelor and Rounds, 1948; see rootstock section). In spite of their large size, such trees were characterized by surprisingly low yields, which in some cases was only 70 percent of their sweet orange counterpart. The tendency for low yields has also been noted in Florida by Hume (1957) and Ziegler and Wolfe (1961). Fruit size tended to be larger than on sweet orange stock and comparable to that on sour orange or Rough lemon stocks (Bitters and Batchelor, 1951). The larger fruit size might possibly be associated with the fewer numbers of fruit per tree. Fruit quality was good, equal to that on sweet orange stock and frequently slightly superior (Sinclair and Bartholomew, 1944; Bitters, 1961).

Grapefruit rootstocks are probably slightly more resistance to *Phytophthora* than trees on sweet orange or Rough lemon, but are not as resistant as sour orange (Klotz, 1978). That is one of the reasons California growers used it, although Wutscher (1979) indicates susceptibility to foot rot was one of the reasons it was discontinued in Florida. California lemon growers also used it because they felt it was more resistant to foot rot than sweet orange or Rough lemon, and that lemon trees budded on it were not as susceptible to shell bark as those on some orange and Rough lemon. Also, phloem necrosis of the lemon scion was less than on sour. They show no resistance to the citrus nematode or the burrowing nematode (Baines, Van Gundy and DuCharme, 1978). Numerous cultivars tested for their resistance to tristeza were variable in their response, some varieties being almost as susceptible as the sour orange, others less, but none were tolerant (Bitters and Parker, 1953). Under field conditions, trees declined from natural infection by tristeza at a much slower rate than those on sour orange, erroneously causing some growers in California to assume the combinations were tolerant to the disease. Under California conditions, the stock does not generally stem-pit from tristeza, or only mildly so.

In experimental trials conducted by the Citrus Experiment Station, Riverside, the 'Duncan' variety did not perform very well. This was the original 'Duncan' variety introduced from Florida in the early 1900's. Recently, all seedy varieties of grapefruit in Florida were lumped as 'Duncans'. Unfortunately, the original 'Duncan' source in the Citrus Variety Collection at Riverside was eliminated and a seedling of it, of doubtful authenticity, substituted. The original 'Duncan' may now be lost. Of all the varieties tested at Riverside, the C.E.S. No. 343 (an unnamed cultivar introduced from Florida in the early 1900's) gave the best performance, but even it did not compare with the sweet orange or the sour orange (Batchelor and Rounds, 1948; also see section on yields). The

C.E.S. No. 343 never gained commercial acceptance. In the eastern Los Angeles basin the 'Jochimsen' and the 'Hall' were grown. In Ventura County, the 'Camulos' was principally grown, and in Santa Barbara County, it was the 'Stow'. Trees budded on grapefruit stock are less cold resistant in California than those on sour or sweet orange. Although both orange and lemon trees were budded commercially on grapefruit stock, but primarily lemons, results were not outstanding and the stock was never very popular. Because of tristeza, orange trees are no longer propagated on this stock in the U.S. Lemon trees on grapefruit stock can only be purchased through special orders to California nurserymen.

Grapefruit cuttings, like shaddock marcots, have performed about equal to the budded trees. The trees were more spreading and shorter than those grown on seedling stock (Figure 85 [*Image could not be located*]). The root system, like those of the Valencia and the navel, was less penetrating than those of the seedlings, with a strong shallow lateral system. It is conceivable that in some areas commercial grapefruit orchards under the right conditions could be propagated from cuttings or grown as seedlings and eliminate any budunion problems. In areas where freezes are a major hazard, as in Texas, this could eliminate the practice of mounding to regenerate trees frozen to the budunion or groundline.

Several hybrids of the grapefruit have been tried as rootstocks and show some interesting results. Among these are the 'Sampson' tangelo, 'Williams' tangelo, 'Siamelo' and the citrumelo. The tangelo will be discussed with the mandarins, and citrumelos with the trifoliate hybrids.

The Poorman's orange is neither an orange nor a grapefruit, although it is used commercially as a grapefruit substitute. Sometimes it is referred to as 'Morrison's' grapefruit or 'New Zealand' grapefruit (Hodgson, 1967, p. 550). It is monoembryonic and passes along a genetic scaly bark to its progeny. Like the grapefruit, when budded to Valencia orange it was susceptible to tristeza (Bitters and Parker, 1953).

The Israeli Poorman is not a Poorman's orange but something else, perhaps a seedling selection from Poorman ([*reference information lacking*]). It is nucellar and does not show the flakey bark of Poorman. It has given fairly promising results in rootstock trials in Israel (Mendel, 1971), but its tristeza tolerance is no longer in doubt and it proved susceptible in trials at South Coast Field Station in l97__ (Bitters, unpublished data). The Natsudaidai of Japan, or Japanese summer orange (not to be confused with Hyuganatsu), is not an orange, or a grapefruit, although it too is commercially used as a grapefruit substitute in Japan where it is the second-most important variety. However, it is used to a very limited extent in Japan as a rootstock for the Satsuma. The trees on it are vigorous and do not compare with the more productive trees on trifoliate orange, but the fruit quality is inferior. In California at South Coast Field Station, orange trees budded upon it are tolerant to tristeza, show no stem pitting and are moderately vigorous. However, they are shy bearers (Bitters, unpublished data).

The Pummelos or Shaddocks

The pummelos or shaddocks, *C. grandis* [L.] Osbeck (sometimes known as *C. maxima* and *C. decumana*), are often confused with the grapefruit, particularly some of the smaller fruited varieties. The pummelos are referred to in some areas as pumplemousse, zabon, buntan, bankan, etc. They differ from most other potential rootstocks in one major character, however, in that all varieties of pummelo are monoembryonic and produce no nucellar seedlings. In spite of this, most of their progeny are remarkably uniform in the nursery row and require a minimum of rogueing. When budded to major scion varieties, the scions are remarkably vigorous and uniform in size, even up to an age of 34 years (in 1960), with surprising uniform performance at the Citrus Experiment Station, Riverside (Batchelor and Rounds, 1948; also see section on yields). Some of the better eating commercial varieties like the 'Alemoen', 'Thong Dee', 'Kao Phuang' and 'Kao Panne' have been among the most uniform. From the author's experience, variability is not the major factor in their failure to obtain commercial rootstock acceptance .

Pummelo fruits, if not parthenocarpic, generally produce an abundance of large seeds, although under certain conditions they may be nearly seedless. Many are self-incompatible and require pollenizers to set seed (Soost, 1964). The seeds germinate readily and produce vigorous seedlings which are somewhat bushy in character, like the grapefruit, and require considerable training prior to budding. Numerous pummelo varieties have been successfully budded with most of the major commercial citrus varieties in California experiments and observed in various plantings for periods of from 13 to 34 years of age. The reported failure of Satsuma mandarin on pummelo cited by Webber (1948) was undoubtedly due to the presence of the tristeza virus in the Satsuma scion. All varieties of pummelos budded with orange scions and inoculated with tristeza by the author (Bitters and Parker, 1953), were extremely susceptible to the disease. The reaction of pummelo to tristeza is very similar to sour orange in this respect with many of the young inoculated trees collapsing and dying within a few years. Trees affected with tristeza do not show stem pitting in the stock. This then (tristeza susceptibility), is the greatest drawback to the use of pummelo as a rootstock, not its variability.

In California, especially in rootstock trials at the Citrus Experiment Station, oranges, grapefruit and lemons budded on pummelo stocks make large sized trees about equal to those on sweet orange stock. Like grapefruit stocks, yields tend to be somewhat low in proportion to the size of the trees. Like grapefruit, fruit sizes tend to be larger than on stocks like sweet orange and Cleopatra mandarin and more comparable to that on Rough lemon stock (Bitters and Batchelor, 1951). Fruit quality is comparable to that on sweet orange or sour orange stock (Bitters, 1961).

The budunion of trees budded on pummelo is good, and like grapefruit stock, shows an overgrowth of the stock. This may be either a slight shoulder effect or a tendency to slope outward and downward from the union in a slightly pyramidal shape (Figure 86). There is no distinctive character to the bark, except that it tends to be considerably thicker than the scion bark, much thicker than grapefruit. In some instances, the bark may be very thick and extremely rough, like that of an oak tree (Figure 87). Lemon budunion overgrowth does not appear to be a serious problem with the stock in California in the limited plantings observed.

The root system of the pummelos is a strong, deeply penetrating tap root system with strong laterals. There are many fibrous roots, with the feeder roots tending to be coarser in texture than feeder roots of most other species (Kirkpatrick and Bitters, unpublished data; see section on root systems). It shows no tolerance to the citrus nematode or the burrowing nematode (Baines, Van Gundy and DuCharme, 1978). Pummelos, however, do have a high resistance to *Phytophthora* (Klotz, 1978). No problems with gummosis were experienced in any of the author's plantings. In Thailand, where pummelos are extensively grown, they are propagated principally as marcots and grown on soil beds a few feet above the water table and are relatively short-lived. It is probable that few other stocks would tolerate these conditions as long as the pummelo.

In the Philippines, trees grafted on pummelo roots reportedly showed more mottle-leaf disease (zinc deficiency) than on other rootstocks observed (Lee, 1921). In California rootstock trials, it was not observed that zinc deficiency was any more of a problem than on the other rootstocks. In one lemon rootstock trial in Ventura, California, where boron and salt were both somewhat of a problem, the Alemoen shaddock did not show the boron tolerance of *C. macrophylla* or *C. pennivesiculata*, but of 40 rootstocks, gave essentially the best total performance after 25 years. In Thailand, it is grown under conditions where brackish water would be a problem for many other stocks, but in Thailand salinity, not boron, is the problem.

Some varieties of pummelos are not very vigorous when grafted on other rootstocks, nor as cuttings, at Riverside. Whether this is due to some unrecognized virus disease, or is of a genetic nature, is not known. Certain hybrids of the pummelo at Riverside have been extremely vigorous, as for example sibs of shaddock X St. Michael sweet orange. One of these hybrids provided fairly interesting rootstock results, but proved to be very susceptible to tristeza (Bitters and Parker, 1953).

The pummelos therefore, have never gained commercial acceptance as rootstocks and probably never will in a tristeza area. Usage would best be confined to lemons and in areas where salinity and gummosis may be critical factors. Hybrids of pummelos with other promising rootstock cultivars should be considered. The citrumelos are hybrids of grapefruit (not pummelos) and trifoliate orange.

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APPENDIX I

Tables

TABLE 1

COMPARATIVE YIELDS OBTAINED BY SEGREGATING STOCK SEEDLINGS AND BUDLINGS (AFTER ELIMINATION OF VARIANTS) INTO LARGE AND SMALL GRADES*

Grade	Diameter of Trunk (cm)	Number of Trees	Per cent of total population	Total average yield per tree (pounds)	Gain in yield per tree over second grade	
					Pounds	Per cent
Seedlings:						
Firsts (large)	2.1 or more	237	68.5	294.4	56.2	23.6
Seconds (small)	2 or less	109	31.5	238.2	--	--
Budlings:						
Firsts (large)	1.8 or more	242	69.9	290.8	47.2	19.4
Seconds (small)	1.7 or less	104	30.1	243.7	--	--

*Total population, 346; mean total yield per tree for five-year period, 227.19 lbs. After Webber (1948).

TABLE 2

COMPARATIVE YIELDS AND TREE SIZE OBTAINED BY SEGREGATING BUDLINGS OF VARIOUS STOCK-SCION COMBINATIONS INTO SIZE CATEGORIES

Size Category	Scion	Rootstock	Final Tree size-1960 ACS, cm^2	Ave. Accum. Yield per tree, kg.
Large	Washington navel	Homosassa Sweet	443	76
Small	Washington navel	Homosassa Sweet	409	53
Large	Washington navel	Brazilian Sour	391	87
Small	Washington navel	Brazilian Sour	343	90
Large	Washington navel	Cunningham Citrange	240	39
Small	Washington navel	Cunningham Citrange	214	26
Large	Washington navel	Savage Citrange	282	33
Medium	Washington navel	Savage Citrange	333	34
Small	Washington navel	Savage Citrange	364	34
Large	Washington navel	Standard Sour	388	65
Small	Washington navel	Standard Sour	378	71
Large	Washington navel	Morton Citrange	293	90
Small	Washington navel	Morton Citrange	287	82

TABLE 3

THE EFFECT OF HEIGHT OF BUD INSERTION FOR GRAPEFRUIT ON SOUR ORANGE ROOTSTOCK, PLANTED - 1932

Height of budding (cm)	Ave. No. Fruit per tree per year 1934 - 44	Ave. weight fruit per tree per year (kg)	Girth - cm 1945	
			stock	scion
5	305	189	98	89
13	282	186	89	82
25	276	213	83	82
38	272	216	76	79
51	287	193	74	77
64	275	212	72	77

After Murray (1951)

TABLE 4

EFFECT OF HEIGHT OF BUD INSERTION FOR JAFFA ORANGE ON SOUR ORANGE ROOT, PLANTED - 1932

Height of Budding (cm)	Ave. No. Fruit per tree per year 1934-45	Ave. weight fruit per tree per year (kg)	Girth - cm 1945	
			stock	scion
5	129	75	72	61
13	110	83	73	61
25	107	87	63	57
38	103	99	63	59
51	103	94	63	57
64	95	60	58	54

After Murray (1951)

TABLE 5

EFFECT OF BUDDING EUREKA AND LISBON LEMONS ON ROUGH LEMON ROOTSTOCK AT SIX DIFFERENT HEIGHTS, RIVERSIDE, 1960*

Height of Budding (cm)	Top Volume M^3	
	Eureka	Lisbon
30	73.5	60.3
45	79.8	71.7
60	98	23.5
90	99.6	24.7
120	54	37.9*
150	83.4*	33

* Replaced in 1940.

TABLE 6

INFLUENCE OF HEIGHT OF BUDDING OF 'CAMPBEL' NUCELLAR VALENCIA ON CLEOPATRA MANDARIN AND TROYER CITRANGE ROOTSTOCKS BUDDED AT SIX DIFFERENT HEIGHTS, SOUTH COAST FIELD STATION, 1976

Height of Budding (cm)	Campbell' Valencia on Cleopatra		Campbell' Valencia on Troyer	
	Ave. Yield kgs per tree 1972-76	Tree vol. M^3 1976	Ave. Yield kgs per tree 1972-76	Tree vol. M^3 1976
5	84	38.5	82	34.3
15	87	37	92	33.9
30	95	38.3	74	38.3
45	86	31	62	37.9
60	76	33.8	58	36.4
90	67	31.3	73	29.6

TABLE 7

EFFECT OF HEIGHT OF BUDDING ON YIELD AND NUTRIENT CONCENTRATION IN SCION LEAVES OF ORANGE GROWN AT SOUTH COAST FIELD STATION ON CLEOPATRA MANDARIN AND TROYER CITRANGE ROOTSTOCK*

Budding		Nutrient Concentration in Oven-dried Leaves											
ht (cm)	Yield (kg/tree)	N (%)	P (%)	K (%)	Ca (%)	Mg (%)	Na (%)	Cl (%)	Zn (ppm)	Mn (ppm)	Cu (ppm)	B (ppm)	Fe (ppm)
5	69.5ab	2.44b	0.131BC	9.90C	5.39bc	0.297C	0.042bc	0.070b	181C	90	5.2b	68BC	78
15	73.6a	2.40c	0.132BC	0.93BC	5.32c	0.292C	0.039bc	0.0678bc	186BC	89	4.8bc	68BC	81
30	70.8ab	2.41bc	0.133BC	0.89C	5.61b	0.305BC	0.038c	0.0647c	183BC	88	4.7c	68C82	
45	60.2abc	2.43bc	0.136B	0.99B	5.45bc	0.297C	0.042bc	0.0673c	191BC	91	4.9bc	71C	83
60	54.3c	2.40bc	0.132BC	0.99B	5.45bc	0.296C	0.043b	0.063c	206BC	93	5.1bc	66B	85
90	58.8bc	2.43bc	0.127C	0.98BC	5.54b	0.318B	0.041bc	0.063c	2.3B	94	5.2bc	71C	82
Coef. Of correlation (r)	-.803**	NS	0.931***y	0.749**	NS	0.719**	NS	-0.818**	0.947**	NS	NS	NS	NS
CV	53%	2%2	5%	11%	7%	8%	17%	18%	17%	17%	17%	9%	15%

* Each value is a mean of 28 individual determinations. Mean separation 5% level (lower case) or 1% level (upper case).

y This value is expressed as R.

After Labanauskas et al. (1976).

TABLE 8

EFFECT OF HEIGHT OF 'TROYER' CITRANGE INTERSTOCK INSERTION ON YIELD AND CANOPY VOLUME OF 'VALENCIA' ORANGE ON 'CLEOPATRA' MANDARIN ROOTSTOCK

Height of interstock insertion cm	Avg. Yield--kg/tree 1972-1980	Canopy Volume m^3 1980
5	94.2	46.5
15	101	49.4
30	99.9	48
45	77.4	45.9
Avg.	93.1	47.5
Val/Cleo-15	100.1	53.4
Val/Cleo/Cleo	67.1	34

TABLE 9

EFFECT OF HEIGHT OF 'CLEOPATRA' MANDARIN INTERSTOCK INSERTION ON YIELD AND CANOPY VOLUME OF 'VALENCIA' ORANGE ON TROYER' CITRANGE ROOTSTOCK

Height of interstock insertion cm	Avg. Yield--kg/tree 1972-1980	Canopy Volume m^3 1980
5	63.3	47.4
15	67.3	39.2
30	74.2	42.1
45	68.3	38.7
Avg.	68.3	41.8
Val/Troy-15	112.5	50.9
Val/Troy/Troy	54.7	37.3

TABLE 10

EFFECT OF LENGTH OF 'TROYER' CITRANGE INTERSTOCK INSERTION ON YIELD AND CANOPY VOLUME OF 'VALENCIA' ORANGE ON 'CLEOPATRA' MANDARIN ROTSTOCK

Length of interstock insertion cm	Avg. Yield--kg/tree 1972-1980	Canopy Volume m^3 1980
5	106.5	49
15	96.2	51.7
30	81.1	45.5
45	97	47.4
60	95.7	43.5
Avg.	95.3	47.4
Val/Cleo-15	100.1	53.4
Val/Cleo/Cleo	67.1	34

TABLE 11

EFFECT OF LENGTH OF 'CLEOPATRA' MANDARIN INTERSTOCK INSERTION ON YIELD AND CANOPY VOLUME OF 'VALENCIA' ORANGE ON 'TROYER' CITRANGE ROOTSTOCK

Length of interstock insertion cm	Avg. yield--kg/tree 1972-1980	Canopy volume m^3 1980
5	50.1	34
15	79.5	34.3
30	59.3	32.9
45	71.9	35.9
60	59.5	34.3
Avg.	64.1	34.3
Val/Troy-15	112.5	50.9
Val/Troy/Troy	54.7	37.3

TABLE 12

CITRUS TOPWORKING COMPATIBILITY*

Scion/Rootstock	Topworked to: Sweet orange	Eureka lemon	Lisbon lemon	Grapefruit	Mandarin	Tangelo
Sweet Orange/Sweet orange	--	OK (a)	OK (a)	OK	OK	OK
/citrange	--	OK (a,b)	OK (a)	OK	OK	OK
/trifoliate	--	OK (a,b)	OK (a)	OK	OK	OK
/Rough lemon	--	OK (a)	OK (a)	OK	OK	OK
/mandarin	--	OK (a)	OK (a)	OK	OK	OK
Eureka leman/All	No (c)	--	--	No (c)	No (c)	No (c)
Lisbon lemon/All	No (c)	--	--	No (c)	No (c)	No (c)
Grapefruit/Sour orange	No (d)	? (a)	? (a)	--	OK	OK
/citrange	OK	? (a,b)	? (a)	--	OK	OK
/all others	OK	? (a)	? (a)	--	OK	OK
Mandarin/All	OK	No (a)	No (a)	OK	--	OK
Tangelo/All	OK	? (a)	? (a)	OK	OK	--

Legend:
(a) Lemon scion overgrowth may limit life of tree.
(b) Possible incompatibility may limit life of tree.
(c) Lemon trunk makes poor interstock - short life.
(d) Tristeza-prone.

Any tree to be topworked and scions used for topworking should be free from viral, fungal, and mycoplasma-like diseases.

*In some cases there may be exceptions to the above, but in general, the compatibilities are as indicated.

R.G Platt, April 1972
UCAES Riverside

TABLE 13

VARIETIES COMPATIBLE WITH CALAMONDIN ROOTSTOCK AND FREE OF BUDUNION CREASE FOR MORE THAN 30 MONTHS WHEN GROWN AT MONTE ALTO, TEXAS

- Kumquats (*Fortunella*)
  - Marumi (N)[a]
  - Meiwa (N)
  - Nagami (OL)[a]
  - Obovata (S)[a]
  - Hongkong (S)
- Lemons
  - Lemonquat (N)
  - Meyer lemon (OL)
  - Rough lemon (N)
- Sour orange hybrid
  - Taiwanica (N)
- Limes
  - Eustis limequat (OL)
  - Eustis limequat (S)
  - Mexican lime (N)
  - Rangpur mandarin lime (N)
- Trifoliate orange hybrids
  - Glen citrangedin (S)
  - Thomasville citrangequat (N)
  - Morton citrange (N)
- Mandarins
  - Cleopatra (N)
  - Changsha (N)
  - Dancy (N)
  - Kansu (N)
  - Satsuma (N)
  - Satsuma hybrid (S)
  - Suen Kat (N)
  - Sun Chu She Kat (N)
  - Szincal No. 9 (S)
  - C52-76-9 (Umatilla x Honey)
  - C54-2-1 (Clementine x Satsuma)
- Miscellaneous
  - *C. tachibana* (Mak.) Tan (S)
  - *Poncirus trifoliata*

---

[a] N = nucellar, OL = old budline, S = open-pollinated seedlings.

After Olson and Frolich (1968).

TABLE 14

VARIETIES INCOMPATIBLE WITH CALAMONDIN ROOTSTOCK AND SHOWING BUDUNION CREASE WITHIN 30 MONTHS WHEN GROWN AT MONTE ALTO, TEXAS

C. ichangensis Swing. Hybrid
- Ichang pummelo (S)[a]

Grapefruit
- Redblush (O)[a]
- Redblush (N)[a]

Lemons
- Eureka (N)
- Lisbon (N)

Sour orange
- Chinotto (N)

Sweet oranges
- Jaffa (N)
- Moroblood (S)
- Shamouti (OL)
- Shamouti (N)
- Valencia (OL)
- Valencia (N)

Trifoliate orange hybrids
- Troyer citrange (N)
- C61-220 (Cleopatra x Troyer hybrid) (S)
- C53-30-1 (Citradia[b] x unknown)

Mandarins
- Clementine (OL)
- Fortune (Clementine x Dancy)
- Honey (OL)
- Kara (King mandarin x Satsuma) (N)
- Lee (Clementine x Orlando)
- Long Huang Kat (N)
- Murcott (N)
- Ponkan (N)
- Richard's Special (S)
- Tim Kat (N)
- Temple "orange" (OL)
- De Ba Ahmed (S)
- C54-1-4 (Clementine x Silverhill Satsuma)
- C54-1-5 (Clementine x Silverhill Satsuma)

---

[a] S = open-pollinated seedling, OL = old budline, N = nucellar

[b] Citradia = sour orange x P. trifoliata.

After Olson and Frolich (1986).

TABLE 15

RELATION OF INTERSTOCKS TO COMPATIBILITY OF CALAMONDIN UNIONS BASED ON OCCURRENCE OF BUDUNION CREASE THREE OR MORE YEARS AFTER BUDDING AT MONTE ALTO, TEXAS, OR LOS ANGELES, CALIFORNIA

Scion-rootstock combination	Interstock	No. plants in test	No. plants with budunion crease
Redblush grapefruit (N)[a] on calamondin rootstock	none	5	5
Cleopatra mandarin (N) on calamondin rootstock	none	5	0
Redblush grapefruit (N) on calamondin rootstock	Cleopatra mandarin (N)	3	0
Calamondin (OL)[a] on sweet orange rootstock	none	3	3
Calamondin (OL) on Rough lemon rootstock	none	5	0
Calamondin (OL) on sweet orange rootstock	Rough lemon	5	0[b]

[a] N = nucellar, OL = old budline.

[b] Severe brown-colored grooving occurred above budunion; both budunions were mechanically strong, unlike budunion crease.

APPENDIX II

Figures

Figure 1

Figure 2

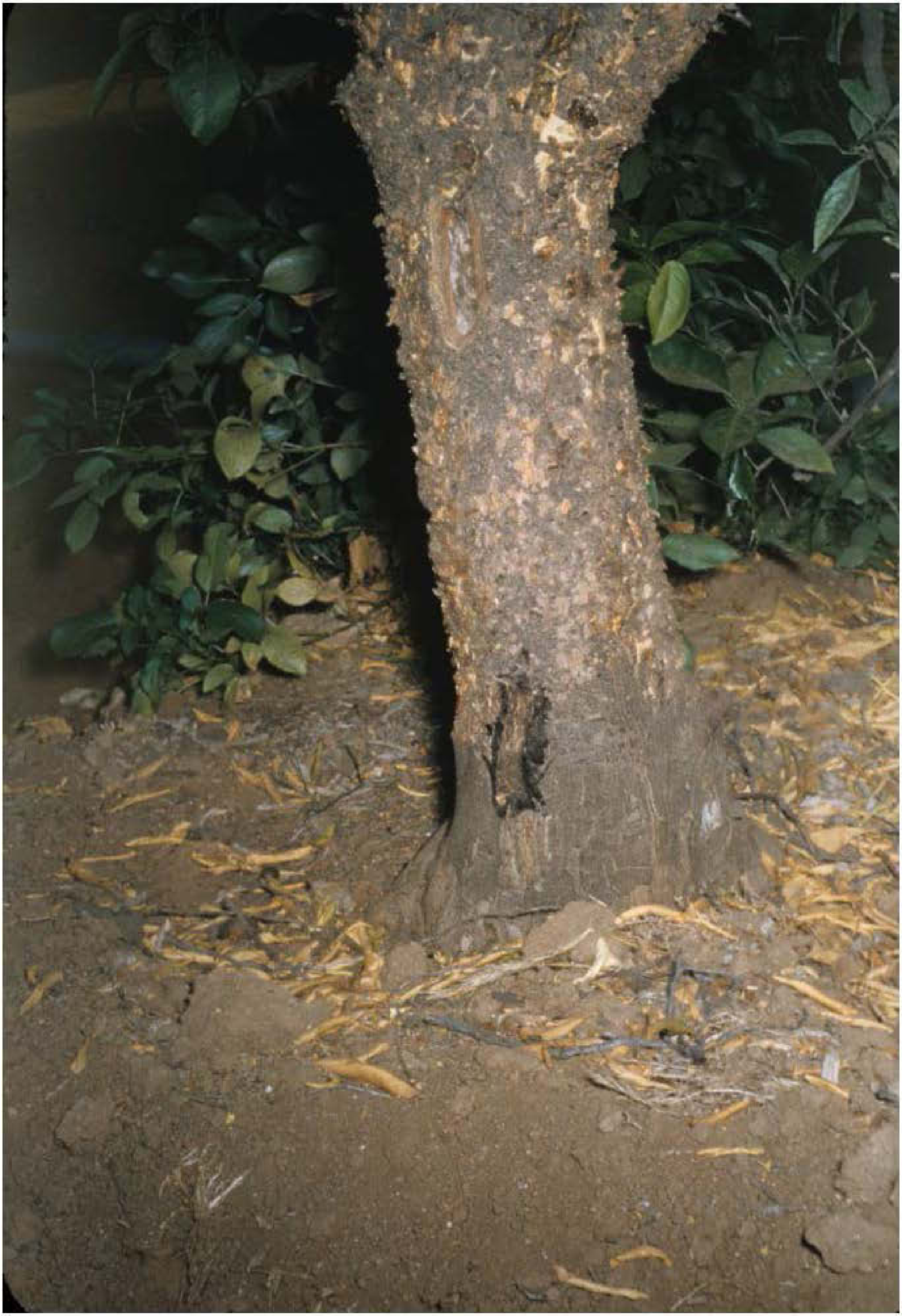


Figure 5

Figure 6

Figure 9-1

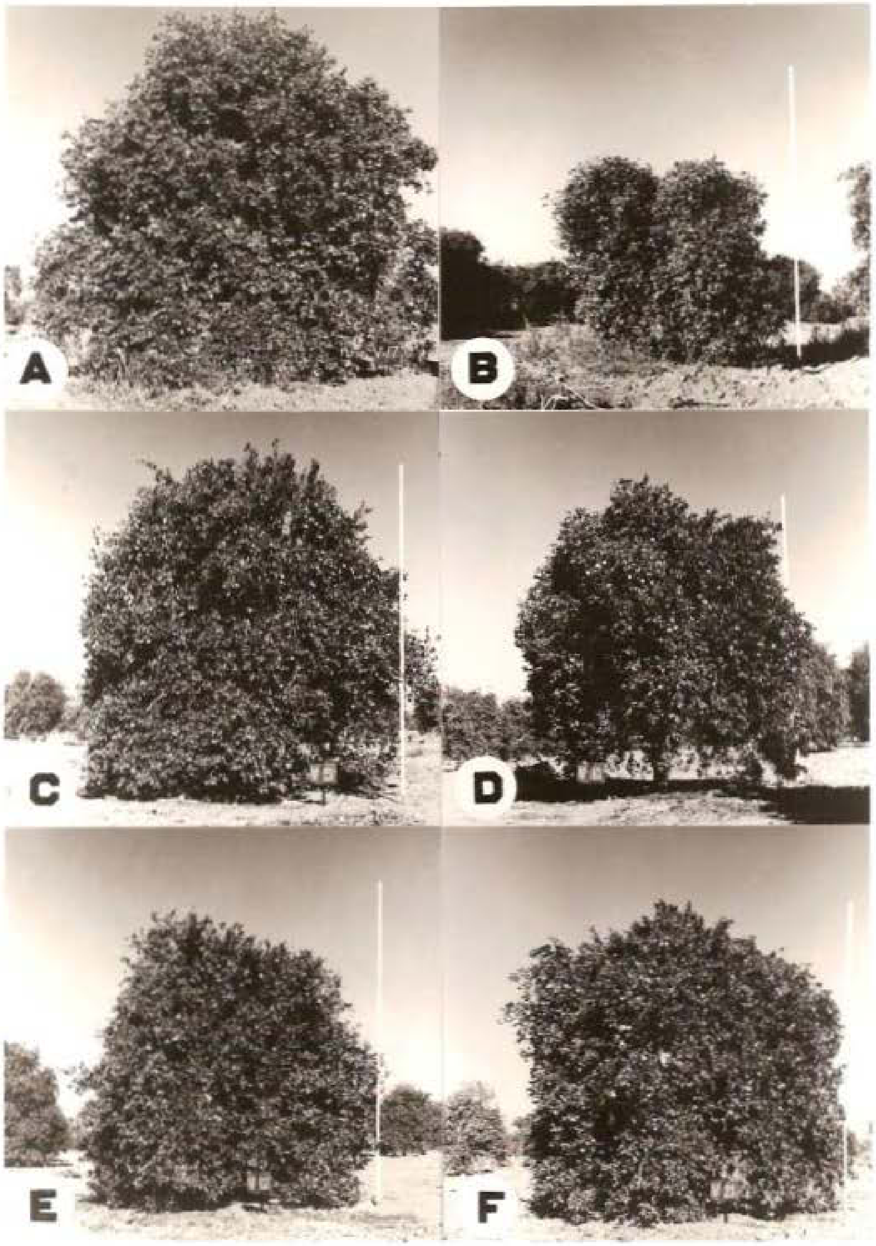


Figure 9-2

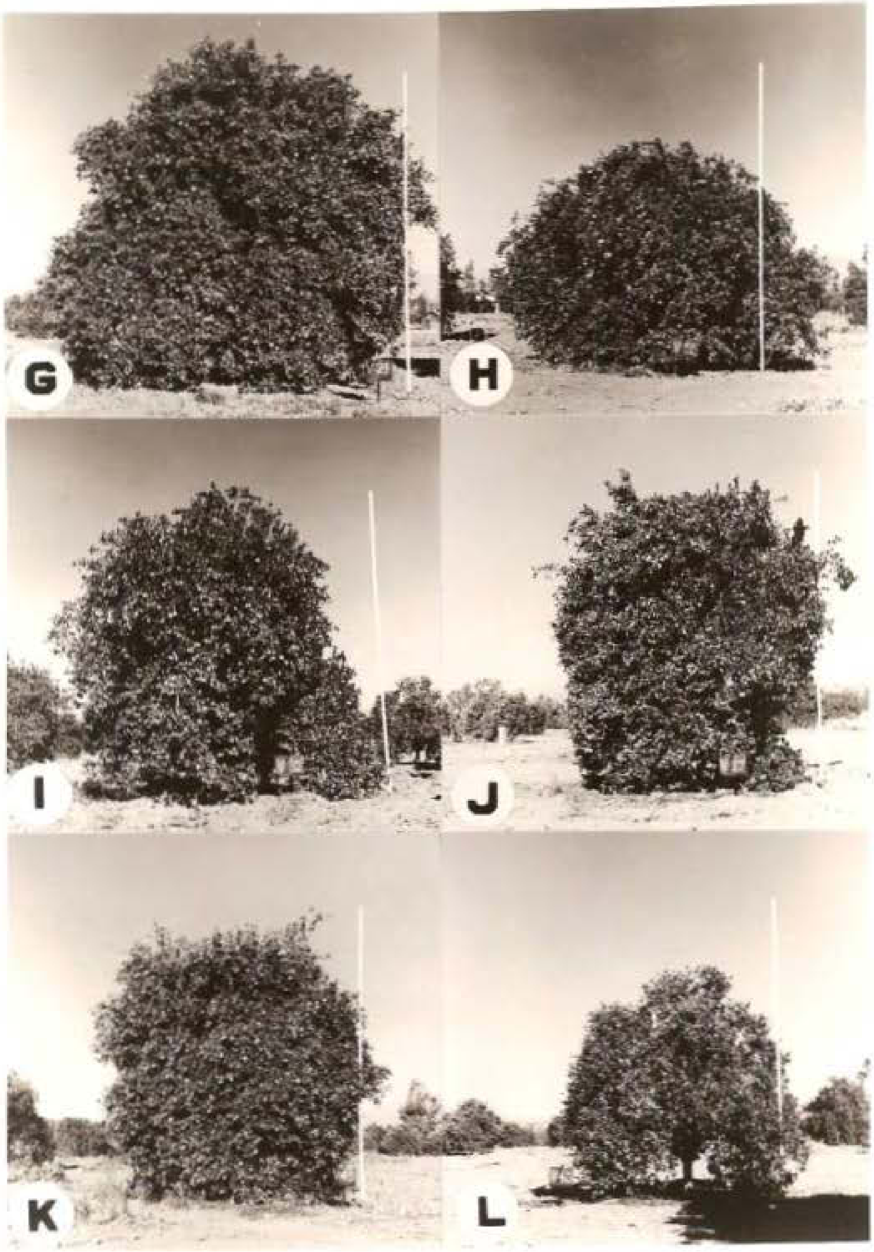


Figure 10

Figure 11

Figure 12

Figure 13

Figure 14

Figure 15

Figure 16

Figure 17

Figure 18

Figure 19

Figure 20

Figure 23

Figure 24

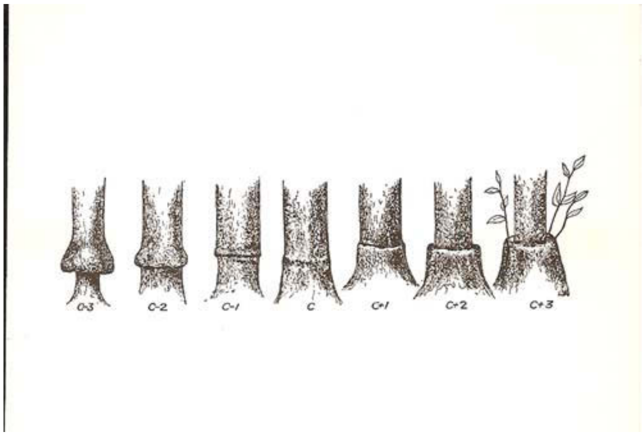


Figure 25

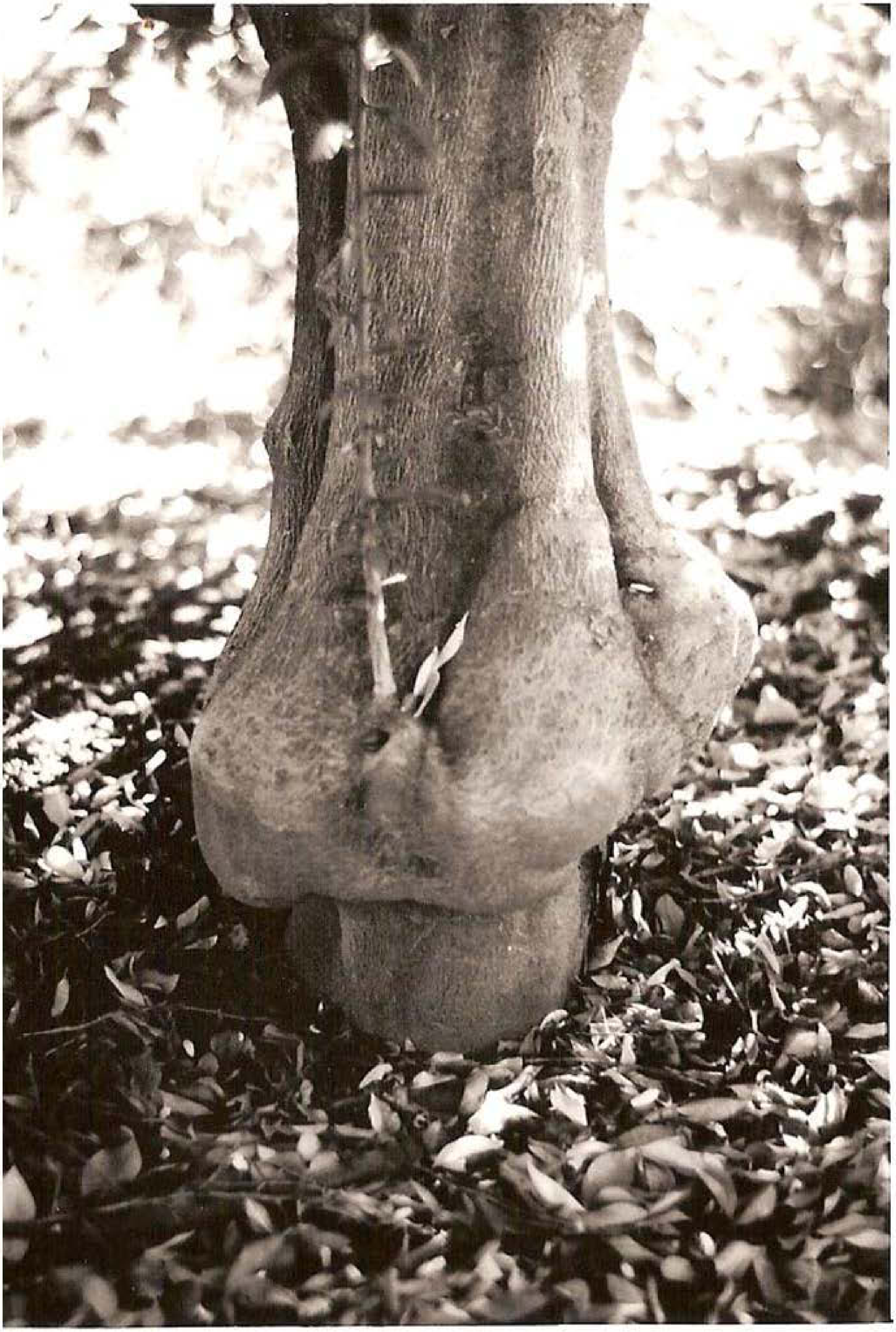


Figure 26

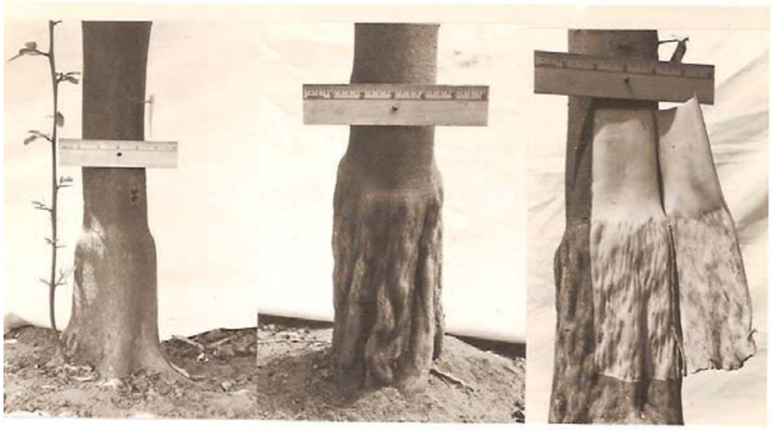


Figure 28

Figure 29

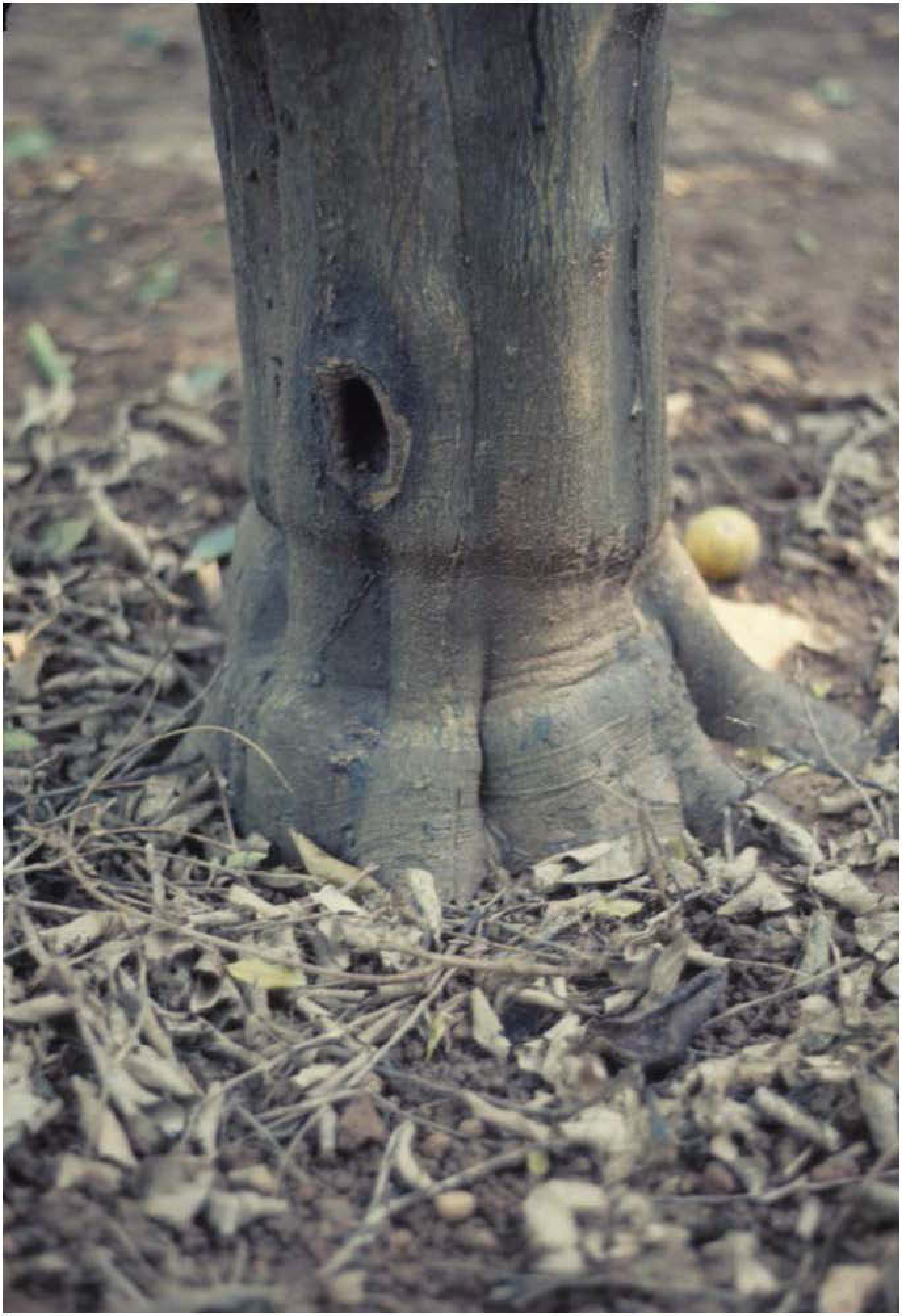


Figure 31

Figure 32

Figure 33

Figure 36-1

Figure 36-2

Figure 39

Figure 48

Figure 49

Figure 50-1

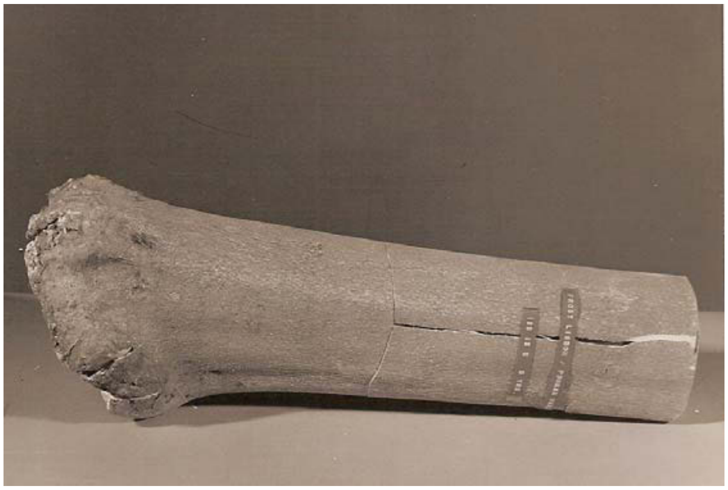


Figure 50-2

Figure 52-1

Figure 52-2

Figure 53-1

Figure 53-2

Figure 54

Figure 55-1

Figure 55-2

Figure 56

Figure 57-1

Figure 57-2

Figure 58-1

Figure 58-2

Figure 58-3

Figure 59-1

Figure 59-2

Figure 60

Figure 61-1

Figure 61-2

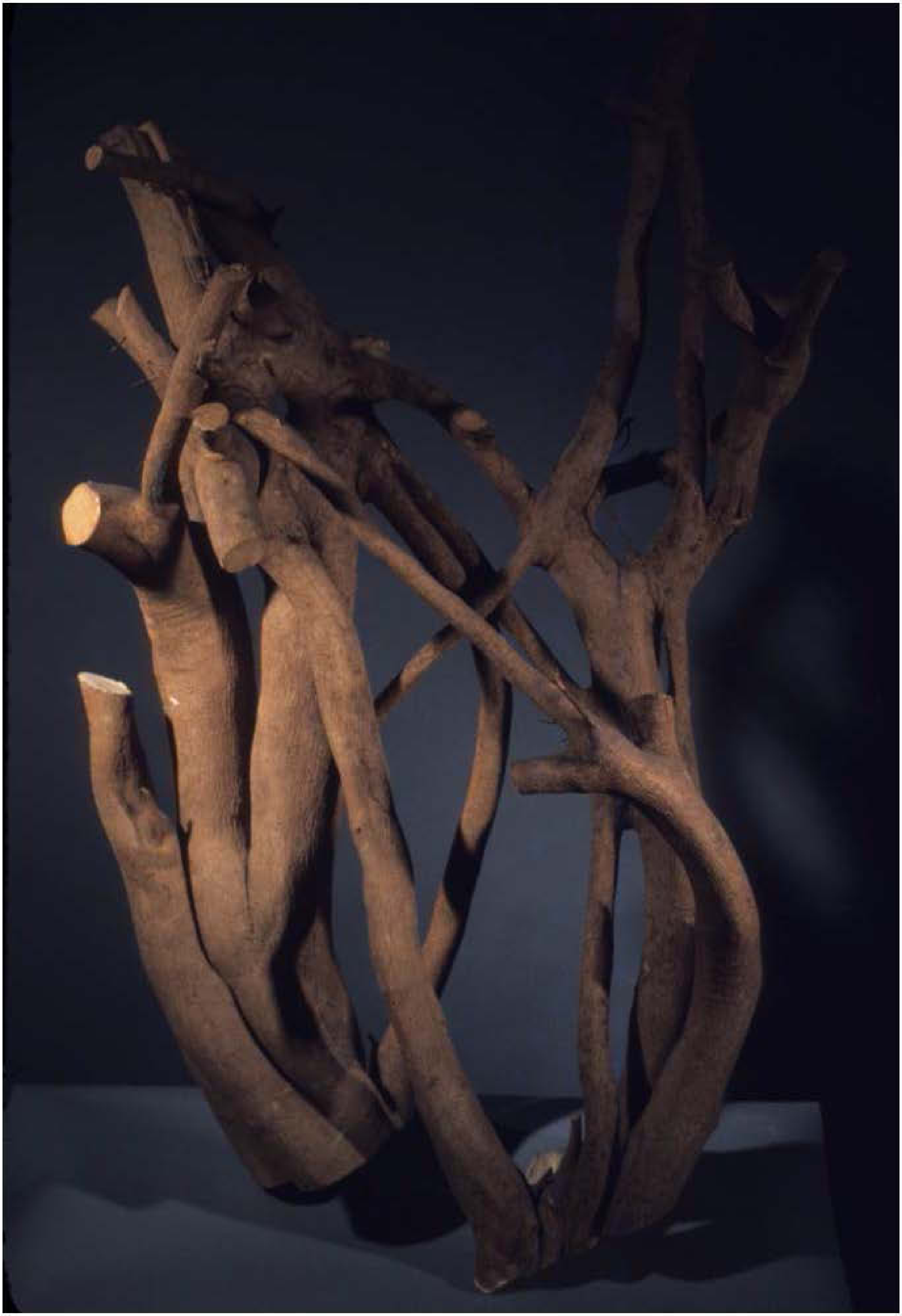


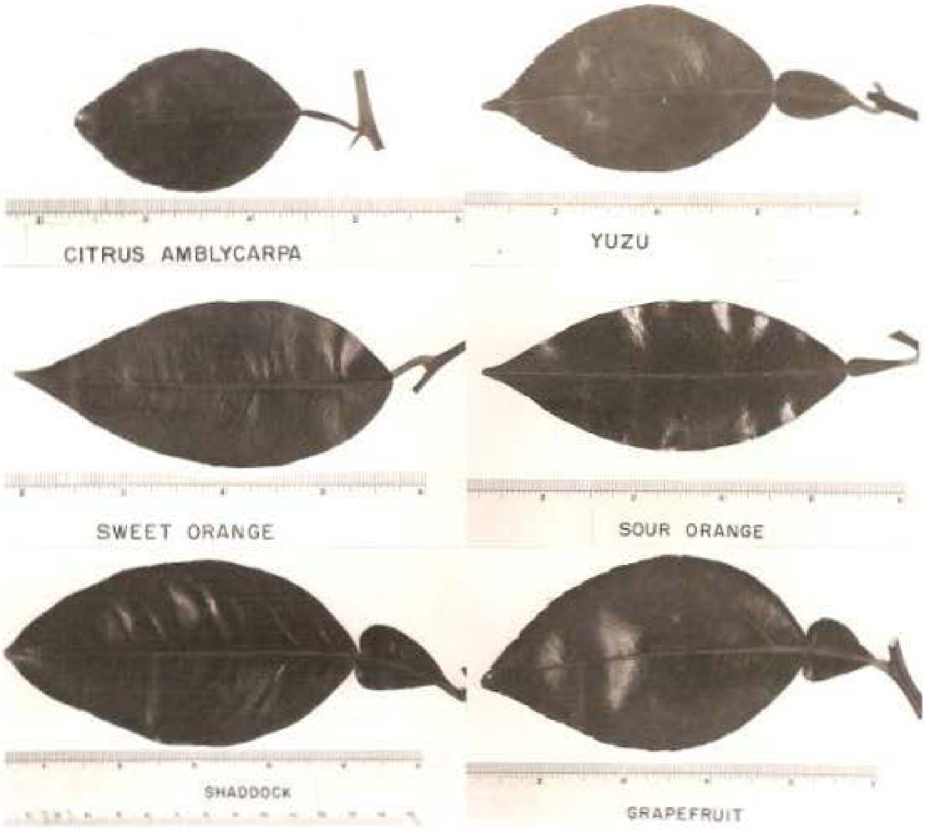
Figure 62-1

Figure 62-2

Figure 63

Figure 65

Figure 71-1



CITRUS AMBLYCARPA

YUZU

SWEET ORANGE

SOUR ORANGE

SHADDOCK

GRAPEFRUIT

Figure 71-2

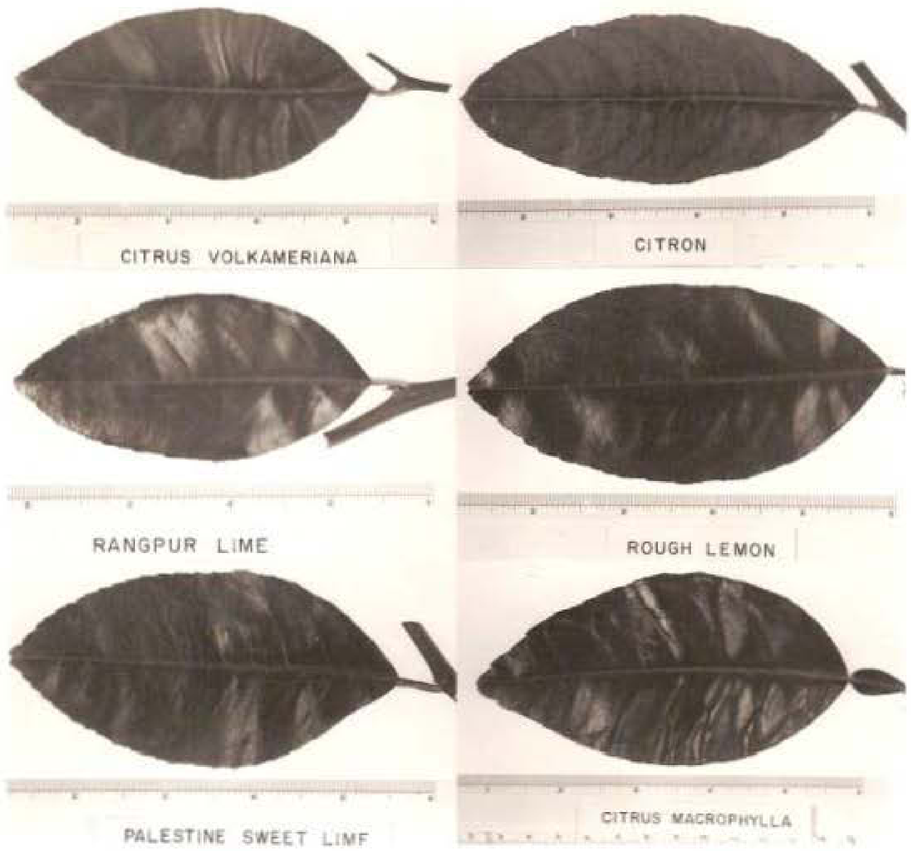
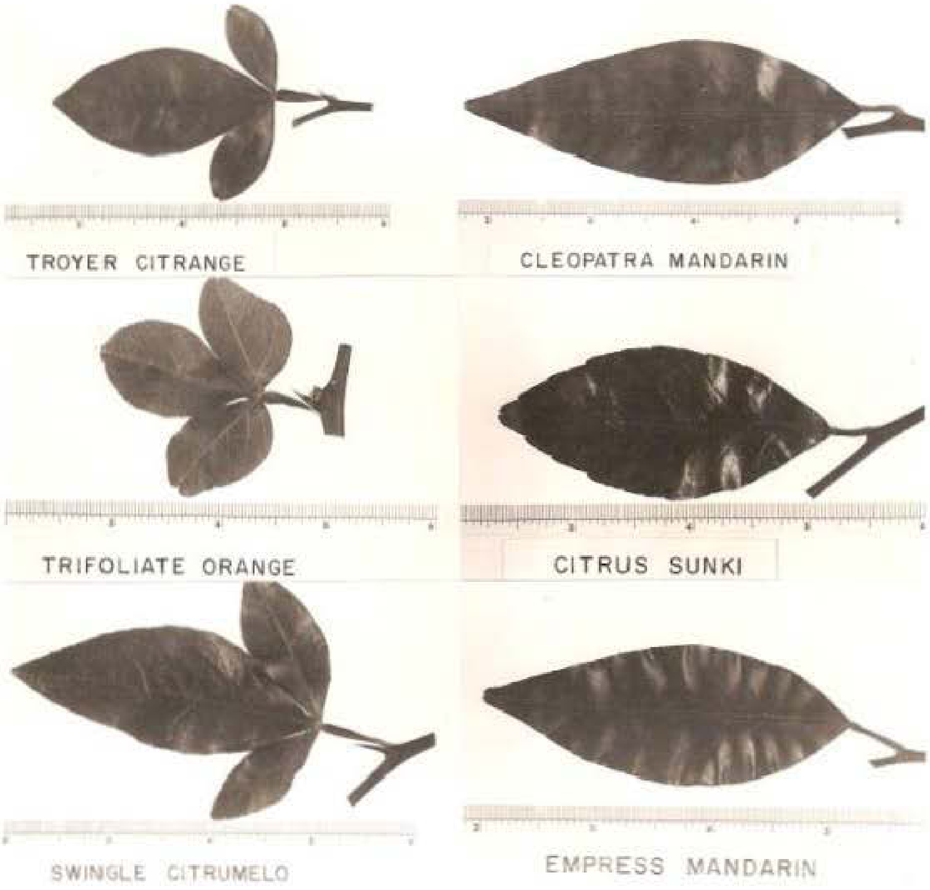

CITRUS VOLKAMERIANA
CITRON
RANGPUR LIME
ROUGH LEMON
PALESTINE SWEET LIME
CITRUS MACROPHYLLA

Figure 71-3



TROYER CITRANGE

CLEOPATRA MANDARIN

TRIFOLIATE ORANGE

CITRUS SUNKI

SWINGLE CITRUMELO

EMPRESS MANDARIN

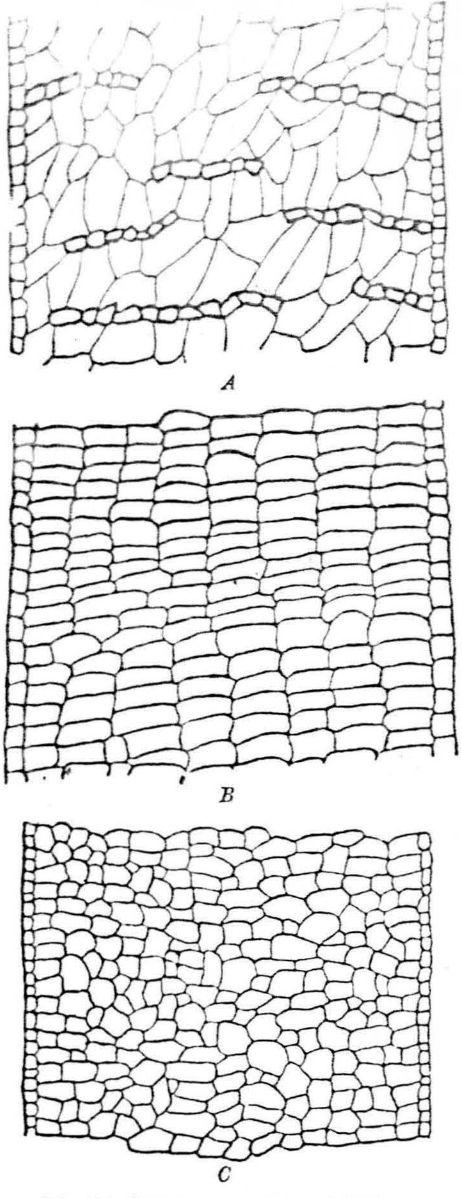


Fig. 66. Cellular structure of different citrus species, as shown in longitudinal sections of pith of young stems: *A*, trifoliate orange, showing crossplates of thick-walled cells and irregular arrangement of thin-walled cells; *B*, sour orange, showing arrangement of cells in series; *C*, yuzu orange, showing irregular arrangement of cells, without crossplates. (After Wolf, 1912.)

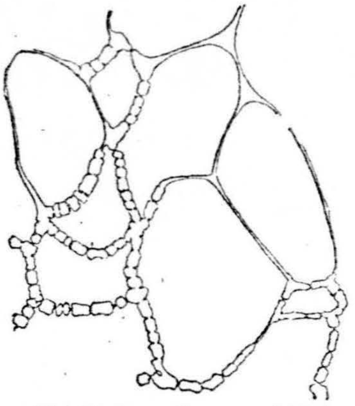


Fig. 67. A small group of thick-walled cells from pith of trifoliate orange. Magnified 375 diam. (After Swingle, 1909.)

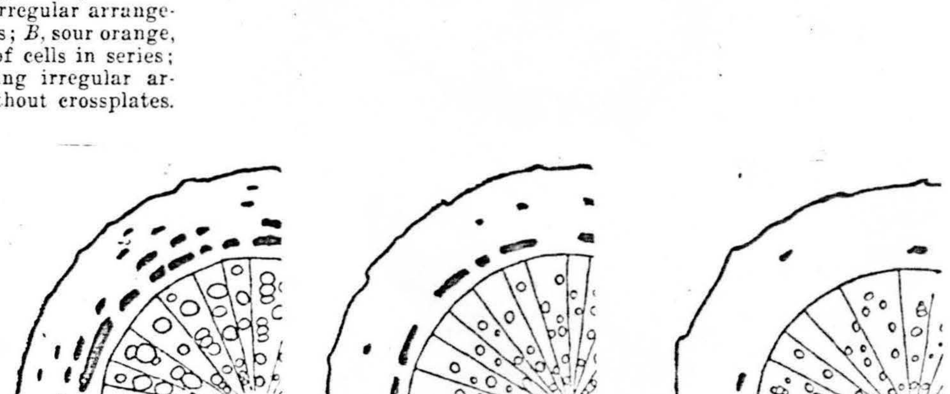


Fig. 68. Diagrammatic cross sections of roots of citrus species, illustrating the characteristic arrangement of groups of bast fibers in the bark, and the comparative size and arrangement of large vessels in the woody cylinder: *A*, trifoliate orange; *B*, sour orange; *C*, yuzu orange. (After Wolf, 1912.)

Figure 79

Figure 80

Figure 83

Figure 84-1

Figure 84-2

Figure 86

Figure 87