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LATE PLIOCENE MOLLUSKS FROM SAN FRANCISCO PENINSULA, CALIFORNIA, AND THEIR PALEOGEOGRAPHIC SIGNIFICANCE[1]

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ABSTRACT: Late Pliocene marine mollusks occur in exposures of the Merced(?) Formation and Santa Clara Formation in the foothills of the Santa Cruz Mountains near Stanford University, Santa Clara County, California. The fauna of 39 molluscan taxa lived in a sandy, level-bottom, depositional environment located high in the inner sublittoral zone of a protected inner-coast environment. Nearly all of the dominant elements are represented by at least closely related taxa in modern bays or estuaries of the central California coast. There is, however, a small but abundant element of southern mollusks that suggests water temperatures somewhat warmer than those of modern central California bays. This assemblage marks the northernmost occurrence of several Pliocene index species previously unreported from this area that are common in central and southern California. The late Pliocene fossil localities of northern Santa Clara County lie directly across the San Andreas fault from lower Pliocene marine strata of comparable ecology mapped as the Purisima Formation. The distribution and facies of the Pliocene Purisima Formation in the northern Santa Cruz Mountains on the west side of the San Andreas fault suggest that late Pliocene deposition was restricted to a marine embayment that did not reach as far east as the early Pliocene one, which is truncated by the fault. Merced(?) strata of northern Santa Clara County may have been connected to the open ocean through an area on the southwest side of the fault that is now located some 20 to 25 miles to the northwest near Mussel Rock. The amount of right-lateral slip implied by this correlation is compatible with estimates of rates of movements along the fault during earlier parts of the Tertiary.

[1] Publication approved by the Director, U. S. Geological Survey.

Introduction

Fossiliferous marine sandstone of late Pliocene age crops out in the limbs of a northwest-trending syncline in the northeastern foothills of the Santa Cruz Mountains near Stanford University. Fossil mollusks occur abundantly near the base of a thin marine sandstone unit mapped as the Merced(?) Formation by Dibblee (1966a) and at scattered localities in overlying conglomerate, sandstone, and siltstone that he mapped as the Santa Clara Formation. The latter may be marine tongues in a predominantly nonmarine sequence, as suggested by Page and Tabor (1967, p. 5). The molluscan fauna of this area, although long recognized as of Pliocene age (Arnold, 1906), has never been described, nor has it been considered in accounts of the Pliocene history of the Santa Cruz Mountains. It is a moderately large fauna, numbering almost as many molluscan taxa as the late Pliocene fauna of the lower part of the type Merced Formation (Glen, 1959) of the northwestern San Francisco Peninsula. It is significant zoogeographically because it marks the northernmost occurrence of warm-temperate elements in the nearshore late Pliocene molluscan faunas of California. Its occurrence on the east side of the San Andreas fault, separated by many miles from outcrops of the relatively extensive upper Pliocene strata of the northern San Francisco Peninsula to the northwest, but opposite a band of presumably older Pliocene strata (Cummings and others, 1962) on the southwest side of the San Andreas fault, has an important bearing on Pliocene paleogeography and history of movement along the fault.

Principal collections upon which this report is based were assembled in 1962 and 1963 by several of the United States Geological Survey geologists, including me, from building excavations and pipeline trenches in the vicinity of Arastradero Road near the southern boundary of the Stanford University lands. I am indebted to J. G. Vedder, M. D. Crittenden, E. E. Brabb, E. H. Pampeyan, and T. W. Dibblee for stratigraphic information and assistance in making collections from these localities. Collections made from other localities by Stanford University students over a period of many years were kindly made available for study by Dr. A. Myra Keen of Stanford University. Identifications of material from these are incorporated into the report. Included are collections made by Ralph Arnold and others prior to 1900 that were referred to, but not listed, in Arnold (1906, 1908) and Branner and others (1909). L. G. Hertlein, who collected much of the Stanford material as a student, lent a muricid from a California Academy of Sciences collection for inclusion in this report. R. A. Loney furnished material collected from a locality about one-third mile north of Stanford University locality C308. Collections from the Pliocene Purisima Formation in Portola Valley west of the San Andreas fault were made by J. C. Cummings, E. H. Pampeyan, and me. The manuscript has been read by A. M. Keen, Druid Wilson, E. H. Pampeyan, V. A. Zullo, and J. C. Cummings. Their comments and suggestions are deeply appreciated. R. E. Petit and W. K. Emerson kindly provided assistance in classification of cancellariids considered in this report. Eugene Coan has discussed Pliocene tellinid identifications with me. Fossil photography is by Kenji Sakamoto, of the U.S. Geological Survey.

Earlier Studies

Initial notice of the occurrence of late Cenozoic marine strata in the southern part of the San Francisco Peninsula east of the San Andreas fault was through Conrad's (1856) description of *Schizopyga* [*Nassarius*] *californianus*. This small gastropod was collected from a locality "12 miles back from Santa Clara" associated with a coal bed (Newberry, 1856, p. 67), presumably in the Santa Clara Formation. Nearly 40 years later, Ashley (1895a, p. 322) reported fossiliferous strata from the foothills south of Stanford University which he referred to his "Merced Series." Judging by his faunal lists of mollusks associated with basalt in the "foothills" (p. 337), however, it seems likely that he was dealing with Miocene strata. Ashley's Pliocene faunal assemblages from near Searsville and Coal Mine Canyon are from the Purisima Formation in Portola Valley to the southwest and across the San Andreas fault from the Merced(?) and Santa Clara Formation localities of this report. The 25 species reported from the so-called Merced Series near Stanford (Ashley, 1895b) are in collections from these areas and not from the Merced(?) Formation of the present report. Arnold (1906, p. 29) included strata near Felt Lake (fig. 1) in his Pliocene and early Pleistocene Merced Formation and listed three species from this area: *Pecten latiauratus*, *Margarites pupilla*, and *Littorina planaxis*. The first two taxa have not since been recognized from this area and are not in the stratigraphic collections at Stanford University; the latter probably is *L. petricola* of this report. Subsequent to this listing, Arnold (1908) figured three additional taxa from the locality near Felt Lake (SU locality C321): *Thais ostrina*, *T. trancosana*, and *Littorina petricola*. These figures were reprinted in Branner and others (1909) and two additional fossiliferous localities in the vicinity of Felt Lake were mentioned, although the strata were not discriminated from the underlying so-called Purisima [Monterey] Formation. An inarticulate brachiopod, *Discinisca cumingi* Broderip, from a locality along Arastradero Road south of Felt Lake (fig. 1), was figured by Hertlein and Grant (1944). Recently two species of *Nassarius* from localities near Felt Lake were figured by Addicott (1965a, 1965b).

Stratigraphic Occurrence

The principal fossil localities are at the base of a late Pliocene marine-nonmarine sequence of conglomerate, sandstone, and siltstone most recently mapped as the Merced(?) Formation and Santa Clara Formation by Dibblee

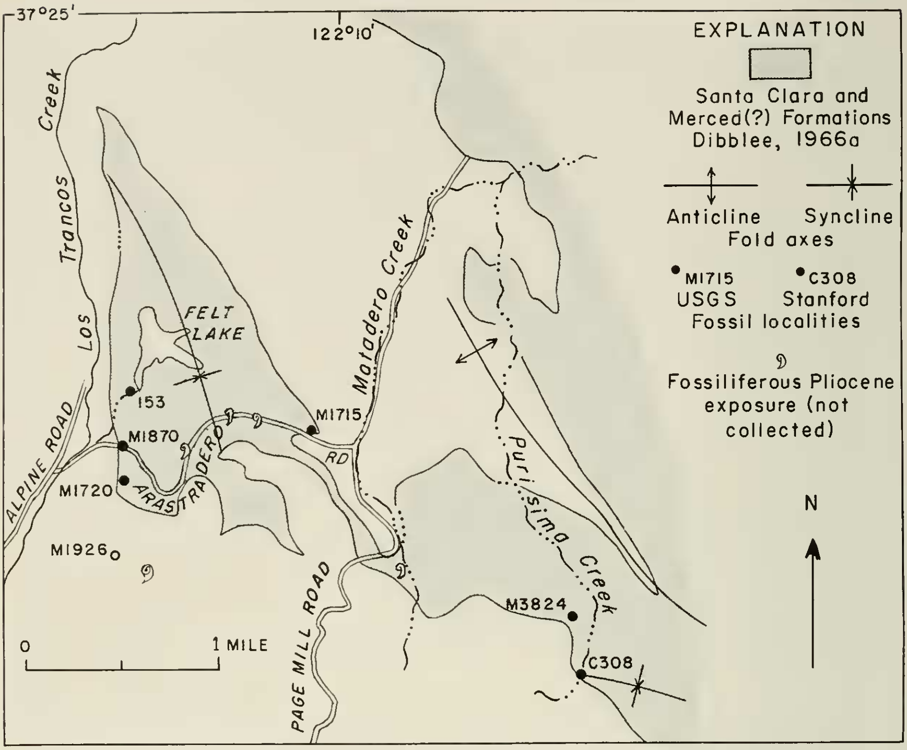

FIGURE 1. Map of part of northern Santa Clara County, showing distribution of the Merced(?) and Santa Clara Formations (after Dibblee, 1966a) and late Pliocene fossil localities [see fig. 2 for location].

(1966a). Nearly all of the faunal constituents occur in a basal 2- to 10-foot thick bed that crops out in the limbs of a northwest-trending syncline along Arastradero Road between Page Mill Road and Los Trancos Creek (fig. 1). This bed consists principally of broken pelecypod shells. Shell fragments and a few whole specimens indicative of Pliocene age have been collected or observed in fine-grained sandstone near the axis of this syncline (fig. 1) in stratigraphically higher beds mapped as the Santa Clara Formation by Dibblee (1966a). These occurrences seem best explained as marine tongues (Page and Tabor, 1967) within the dominantly fluviatile nonmarine Santa Clara Formation. The best fossil localities (USGS localities M1715, M1720, M1870) are from man-made cuts and excavations in otherwise poorly exposed fine-grained sandstone along Arastradero Road. Material can still be secured from a cut near the most productive locality (M1715) although the pipeline trench from which nearly all of the figured specimens were collected has long since been filled. The assemblage of 33 molluscan taxa from this locality is far richer than that of any of the type Merced localities of the northwestern San Francisco Peninsula, the largest of which has yielded only 14 species (Glen, 1959, p. 157). Both Earl Pampeyan and I tried unsuccessfully to relocate old Stanford University localities near Felt Lake; only a few scattered mollusk fragments were found as float in the ditch bank near Felt Lake.

The fossiliferous stratum is about 10 feet thick near USGS locality M1715 (fig. 1). It rests unconformably upon diatomaceous siltstone mapped as the Monterey Shale by Dibblee (1966a). Foraminifers indicative of a late Miocene Delmontian age were collected from near the top of this unit in the vicinity of locality M1715 according to Cummings and others (1962). However, a diatom assemblage from tuffaceous diatomite about 200 feet stratigraphically below locality M1715 studied by K. E. Lohman suggests correlation with the upper part of the Luisian Stage (late middle Miocene) or the lower part of the Mohnian Stage (early late Miocene) (E. H. Pampeyan, written communication, June 1968). About 500 feet stratigraphically below the unconformity, a poorly preserved molluscan assemblage of middle or possibly late Miocene age was collected by the writer from a cut northeast of the intersection of Junipero Serra Freeway and Page Mill Road (USGS locality M2547).

At locality M1715 the contact between the Merced(?) Formation and the Monterey Shale is marked by a well-developed zone of pelecypod borings. Some of the holes contain articulated valves of the pholad *Zirfaea* (pl. 2, fig. 9) in life position. Basal fossiliferous strata of the Merced(?) Formation appear to grade upward through lithologically similar unfossiliferous sand and sandy gravel into strata composed of debris from the Franciscan Formation that have long been mapped as the Santa Clara Formation (Branner and others, 1909; Davis and Jennings, 1954; Dibblee, 1966a). The Merced (?) and Santa Clara Formations are folded into a gentle synclinal structure that trends northwestward through Felt Lake (Dibblee, 1966a). Occurrences of marine Pliocene mollusks stratigraphically well above the base of the Santa Clara Formation as mapped by Dibblee include, 1) SU locality C308 (Arnold, 1908, loc. 8) and USGS locality M3824 near the head of Purisima Creek several hundred feet above the contact with the Monterey Shale, and 2) localities along Arastradero Road about 1000 feet west of the intersection with Arastradero Creek (fig. 1). *Nassarius californianus* and fragments of several kinds of pelecypods occur at all of these localities. Taking into account the isolated occurrences of late Pliocene mollusks near the axis of the syncline, and therefore well above the base of the Santa Clara Formation, it seems apparent that the post-Miocene marine-nonmarine section includes rocks of approximately the same age and that if an unconformity occurs between the Merced(?) Formation and the overlying Santa Clara Formation it cannot be assigned appreciable time significance.

TABLE 1. *Late Pliocene mollusks from northern Santa Clara County.*

	USGS localities					Stanford U. localities	
GASTROPODS	M1715	M1720	M1870	M1926	M3824	C308	153
Pupillaria pupilla (Gould)[1]							
Littorina petricola Dall (pl. 1, figs. 2–5)	X						
Bittium casmaliense Bartsch (pl. 1, figs. 9, 14)	X						
Crepidula cf. *C. princeps* Conrad (pl. 2, fig. 10)	X			X			
Cryptonatica aleutica Dall (pl. 1, fig. 12; pl. 4, fig. 2)	cf.	X	X				
Neverita (*Glossaulax*) cf. *N.* (*G.*) *recluziana* (Deshayes) (pl. 1, figs. 11, 13)	X						
Ocenebra interfossa Carpenter (pl. 1, figs. 20, 21)[2]							
Thais (*Nucella*) cf. *T.* (*N.*) *lima* (Gmelin) (pl. 4, figs. 10, 11)	X						
Thais (*Nucella*) *trancosana* Arnold (pl. 1, figs. 7, 8, 10)	X		X[3]				X
Thais (*Nucella*) *emarginata* forma *ostrina* Gould							X
Neptunea cf. *N. tabulata* (Baird) (pl. 1, fig. 17)	X						
Mitrella cf. *M. gouldi* (Carpenter) (pl. 1, fig. 19; pl. 4, fig. 4)	X	sp.		sp.	X		
Nassarius (*Demondia*) *californianus* (Conrad) (pl. 3, fig. 7)	X	X	X	X	X	X	X
Nassarius (*Caesia*) *grammatus* (Dall) (pl. 1, fig. 18; pl. 4, fig. 5)	X	X	X		cf.	cf.	X
Olivella biplicata (Sowerby) (pl. 3, fig. 9)	X	X	X				X
Cancellaria arnoldi Dall (pl. 1, figs. 15, 16, 22)	X		X				X
Cancellaria, new species (pl. 1, figs. 23, 24)	X						
Ophiodermella graciosana (Arnold) (pl. 3, figs. 2, 3)	X		X[3]			X	
Megasurcula remondi (Gabb) (pl. 3, fig. 10)	X						
Odostomia species	X						
PELECYPODS							
Anadara (*Anadara*) *trilineata* Conrad pl. 2, figs. 1, 3)	X	sp.		X	?	sp.	X
Modiolus species	X						X
Mytilus species							X
Leptopecten latiauratus (Conrad)[1]							
Clinocardium cf. *C. meekianum* (Gabb) (pl. 3, fig. 11)	X						
Spisula albaria coosensis Howe (pl. 3, figs. 1, 6, 8; pl. 4, figs. 8, 9)	X	sp.	X[3]				cf.
Spisula cf. *S. mercedensis* Packard	X						
Tresus pajaroanus (Conrad)	X						
Tellina (*Peronidea*) cf. *T.* (*P.*) *lutea* Wood (pl. 2, fig. 7)	X						
Tellina species (pl. 4, fig. 3)	X						
Macoma nasuta forma *kelseyi* Dall (pl. 4, fig. 6)	X						

TABLE 1. *Continued.*

GASTROPODS	USGS localities					Stanford U. localities	
	M1715	M1720	M1870	M1926	M3824	C308	153
Macoma new species? aff. *M. nasuta* (Conrad) (pl. 2, fig. 11; pl. 4, fig. 12)	X			sp.			sp.
Macoma secta (Conrad) (pl. 3, fig. 4)	X						
Solen cf. *S. sicarius* Gould	X	sp.		sp.			X
Katherinella species						X	
Humilaria perlaminosa (Conrad) Arnold (1907)? (pl. 3, fig. 12)	X						
Protothaca staleyi (Gabb) (pl. 2, figs. 5, 6, 8)	X	X			sp.	sp.	
Cryptomya californica (Conrad) (pl. 2, figs. 2, 4; pl. 4, fig. 7)	X	X					X
Zirfaea? species (pl. 2, fig. 9)	X						

1 Listed by Arnold (1906).
2 In collection from CAS locality 28617.
3 In collection from SU locality 2675.

PALEONTOLOGY

The molluscan fauna consists of 39 taxa (table 1), the majority of which are represented by material sufficiently well preserved to permit specific identification and illustration. The purpose of this section is to furnish supplementary documentation of specific identifications. To conserve space, conventional systematic treatment of each taxon is modified into systematically organized discussion in which only original descriptions of fossil species and other pertinent reference are indicated. This treatment seems appropriate here because nearly all of the species have been previously named and described and major taxonomic revisions are not set forth. Taxonomic notes are arranged systematically by families, and taxa are considered in the same order as on the faunal list (table 1). This abbreviated form of systematics was first employed in Pacific Coast Tertiary reports by Woodring and others (1940).

Included in the molluscan faunal list are three species reported by Arnold (1906, 1908) that do not occur in recent collections: *Pupillaria pupilla*, *Thais ostrina*, and *Leptopecten latiauratus*. Invertebrates other than mollusks are very rare. Scattered barnacle plates occur at USGS locality M1715 and an inarticulate brachiopod *Discinisca cummingi*, was reported from nearby exposures by Hertlein and Grant (1944).

GASTROPODS

TROCHIDAE. *Pupillaria pupilla* (Gould) identified by Arnold (1906) from an unspecified locality near Felt Lake does not occur in later collections from this area. His material is missing from the Pliocene stratigraphic collections at Stanford University.

LITTORINIDAE. Two of the figured specimens of *Littorina petricola* Dall (1909) (pl. 1, figs. 4, 5) compare favorably with the holotype, a thick-shelled spirally sculptured specimen from the Pliocene Coos Conglomerate at Coos Bay, Oregon. A third specimen (pl. 1, figs. 2, 3) has closely spaced axial growth lamellae but no spiral ribbing. As such it resembles an abraded specimen from the Pliocene Cebada Fine-Grained Member of the Careaga Sandstone of the Santa Maria basin, California, figured by Woodring and Bramlette (1950, pl. 19, fig. 12) as *Littorina* cf. *L. petricola*. In other characteristics, such as the relatively small aperture and flat subsutural segment of the body whorl, this smooth specimen closely resembles spirally sculptured individuals from the same locality. It is therefore included with this species as "*L. petricola* smooth form."

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PLATE 1

FIGURES 1, 6–8, and 10. *Thais* (*Nucella*) *transcosana* Arnold, USGS locality M1715. Figures 1 and 6, low-spired, spirally ribbed form; figure 1, height 16 mm., width 13.2 mm., USNM 650942; figure 6, height 13.6 mm., width 12 mm., USNM 650943. Figures 7 and 8, high-spired form; figure 7, height 29.7 mm., width 19.1 mm., USNM locality 650944; figure 8, height 25.3 mm., width 22.4 mm., USNM 650945. Figure 10, intermediate form, height 28.3 mm., width 19.8 mm., USNM 650946.

FIGURES 2–5. *Littorina petricola* Dall, USGS locality M1715. Figures 2 and 3, smooth form, height 16.3 mm., width 14.1 mm., USNM 650947; figure 4, height 8.3 mm., width 6.4 mm., USNM 650948; figure 5, height 10.4 mm., width 10.1 mm., USNM 950949.

FIGURES 9, 14. *Bittium casmaliense* Bartsch, USGS locality M1715. Figure 9, height 15.1 mm., width 5.8 mm., USNM 650950; figure 14, height 9.9 mm., width 4.4 mm. USNM 650951.

FIGURES 11, 13. *Neverita* (*Glossaulax*) cf. *N.* (*G.*) *recluziana* (Deshayes), USGS locality M1715. Figure 11, height 12.1 mm., width 13.4 mm., USNM 650952; figure 13, height 10.7 mm., width 10.5 mm., USNM 650953.

FIGURE 12. *Cryptonatica aleutica* Dall, USGS locality M1715. Height 11.2 mm., USNM 650954.

FIGURES 15, 16, and 22. *Cancellaria arnoldi* Dall, USGS locality M1715. Figure 15, height 21.5 mm., width 12.8 mm., USNM 650955; figure 16, height 31.5 mm., width 16 mm., USNM 650956; figure 22, height 23.5 mm., width 13 mm., USNM 650957.

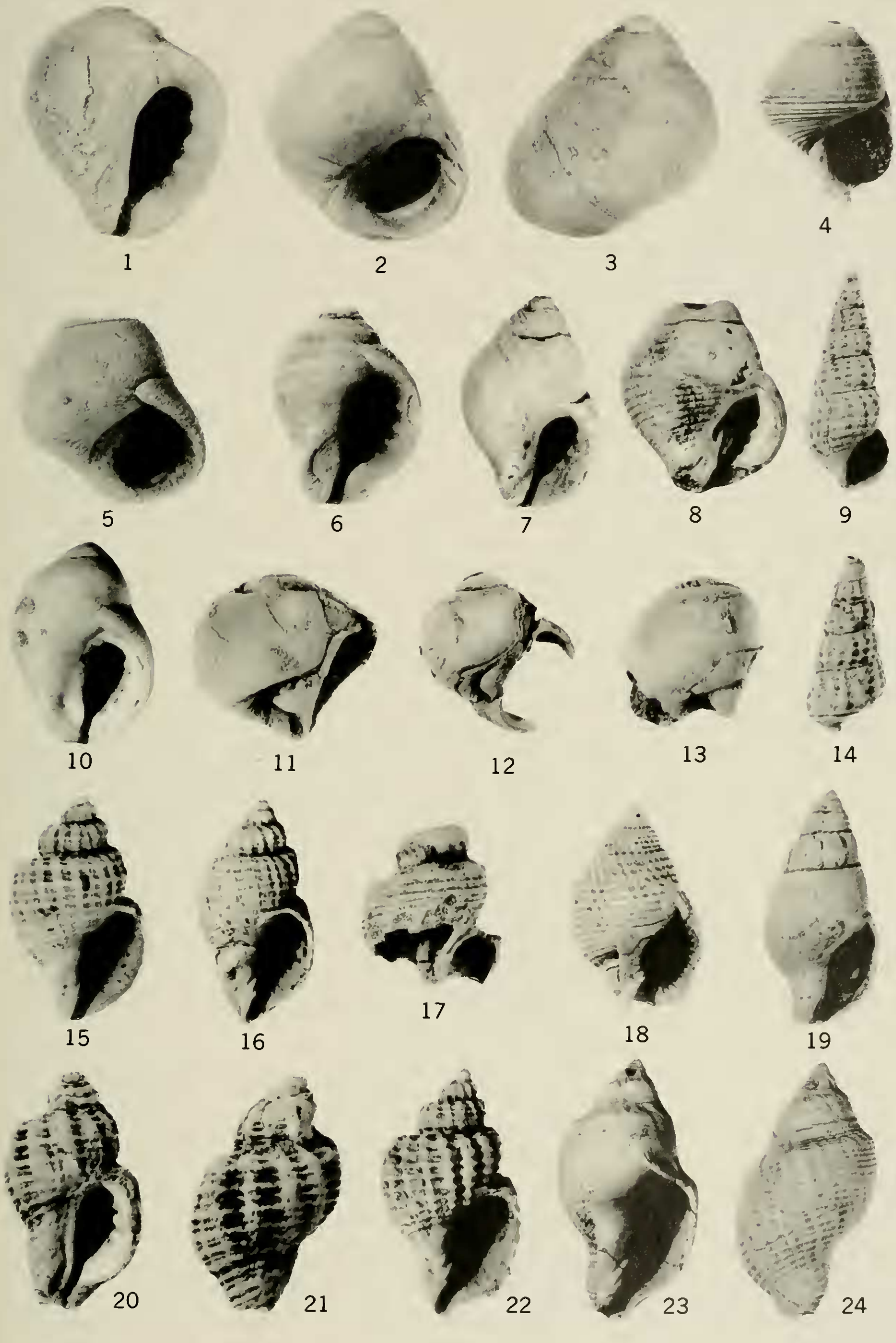
FIGURE 17. *Neptunea* cf. *N. tabulata* (Baird), USGS locality M1715. Diameter of fragment 9.8 mm., USNM 650958.

FIGURE 18. *Nassarius* (*Caesia*) *grammatus* (Dall), USGS locality M1715. Height 29 mm., width 18.7 mm., USNM 648570.

FIGURE 19. *Mitrella* cf. *M. gouldi* (Carpenter), USGS locality M1715. Height 13.1 mm., width 6.2 mm., USNM 650959.

FIGURES 20, 21. *Ocenebra interfossa* Carpenter, CAS locality 28617. Height 13 mm., width 7.6 mm., CAS 13108.

FIGURES 23, 24. *Cancellaria*, new species, USGS locality M1715. Height 36.5 mm., width 19.5 mm., USNM 650960.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The condition of the shell suggests that the absence of spiral sculpture is due to morphologic variation rather than wear.

This species was originally identified as *Littorina planaxis* by Arnold (1906) but was subsequently identified as *L. petricola* Arnold (1908, pl. 37, fig. 7).

Littorina petricola differs from the Pliocene and Pleistocene species *L. mariana* Arnold (1909, pp. 86–87, pl. 29, figs. 1, 2) from the Coalinga-Kettleman Hills area of the San Joaquin Valley by its thicker, much stouter shell and flatter whorl profile.

Cerithiidae. Specimens of *Bittium casmaliense* Bartsch (1911, p. 411, pl. 55, fig. 3) (pl. 1, figs. 9, 14) from USGS locality M1715 are characterized by four strong spiral cords crossed by much weaker, slightly arcuate axial ribs that form nodes at the intersection with the spiral cords. The two anterior spirals are of equal strength; the posterior spirals are weaker and more closely spaced. Superimposed on the primary sculpture is a network of microscopic spiral striae. All specimens are smaller than the holotype from the Pliocene Cebada Fine-Grained Member of the Careaga Sandstone of the Santa Maria basin, California.

This is a northward range extension of this Pliocene index species which had not previously been reported from north of the Salinas Valley area (Durham and Addicott, 1965).

Calyptraeidae. Apical fragments of a large, very thick-shelled *Crepidula* from localities M1715 and M1926 (pl. 2, fig. 10) probably represent the extinct Miocene and Pleistocene species *C. princeps* Conrad (1856). Miocene specimens of this species occur in the Monterey Shale about 500 feet stratigraphically below the base of the Merced(?) Formation of Dibblee (1966a) (USGS loc. M2547). It is also reported from many localities in the Merced Formation (Arnold, 1906; Martin, 1916; Dickerson, 1922; Glen, 1959).

Naticidae. A small naticid with nontabulate whorls (pl. 1, fig. 12; pl. 4, fig. 2) is identified as the Pliocene to Holocene species *Cryptonatica aleutica* (Dall). It and two doubtfully identified fragments from locality M1715 also have the fairly heavy shell and thick umbilical plug bordered posteriorly by a narrow crescent-shaped depression characteristic of this species. Pliocene records of *C. russa* (Gould) by Glen (1959) and Faustman (1964) presumably are of the *C. aleutica* of this report. Use of *C. russa* for this taxon seems unsatisfactory in the light of discussions by Keen (in Burch, 1946, no. 56, p. 27) and Woodring (in Woodring and Bramlette, 1950, p. 72), indicating that what Dall (1919) presumed to be the type specimen of *C. russa* appears to be *C. clausa*; a rather thin-shelled northern species.

Incomplete, abraded naticoid gastropods from USGS locality M1715 (pl. 1, figs. 11, 13) are similar to a form of *Neverita recluziana* (Deshayes) figured by Arnold (1907, pl. 54, figs. 14a, 14b) from the Pliocene Careaga Sandstone of the Santa Maria basin. The distinctive feature of this naticid is its restricted, strongly grooved bilobed callus. It also has an open umbilicus within which are faint spiral grooves. A similar *Neverita* occurs in the lower Pleistocene part of the Saugus Formation in the western Ventura basin. A large collection from USGS locality M1753 contains a weakly shouldered low-spired form and a high-spired form that have deeply impressed callus grooves which terminate posteriorly in a deep pit near the margin of the inner lip. Available specimens from the Merced(?) Formation are too poorly preserved, however, to determine relationship to the Pleistocene specimens.

MURICIDAE. A muricid from CAS locality 28617 identified as *Ocenebra interfossa* Carpenter (pl. 1, figs. 20, 21) is similar to rugose late Pleistocene specimens from Point Año Nuevo, southwestern San Mateo County, California (USGS locality M1690) but appears to have fewer, somewhat coarser axial ribs than the holotype (Palmer, 1958, pl. 23, fig. 1). This species has not previously been reported from the Merced Formation or coeval strata of late Pliocene age in the San Francisco Bay area, although it is doubtfully recorded from the Purisima Formation at Pillar Point, San Mateo County (Glen, 1959).

THAISIDAE. A variable population of *Thais* from locality M1715 is identified as *T. trancosana* Arnold (1908, p. 388, pl. 36, fig. 3). Only a few of the nearly 50 specimens available for study are closely comparable with Arnold's holotype. These forms (pl. 1, figs. 7, 8) are characterized by a short laterally constricted aperture, extremely thick shell walls, and a moderately well-developed spire. One specimen with a narrow slot-like aperture (pl. 1, fig. 8) has uniform spiral ribbing comparable to the holotype. The typical form is contrasted with a group of small, low-spired, spirally sculptured specimens (pl. 1, figs. 1, 6) that cannot be consistently separated from specimens that seem to have morphologic characters linking them with *T. trancosana*. On this form the penultimate

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PLATE 2

(All specimens are from USGS locality M1715)

FIGURES 1, 3. *Anadara trilineata* (Conrad). Figure 1, length 57 mm., height 48.5 mm., USNM 650961; figure 3, length 53 mm., height 44 mm., USNM 650962.

FIGURES 2, 4. *Cryptomya californica* (Conrad). Figure 2, length 33.5 mm., height 24 mm., USNM 650963; figure 4, length 30.5 mm., height 22 mm., USNM 650964.

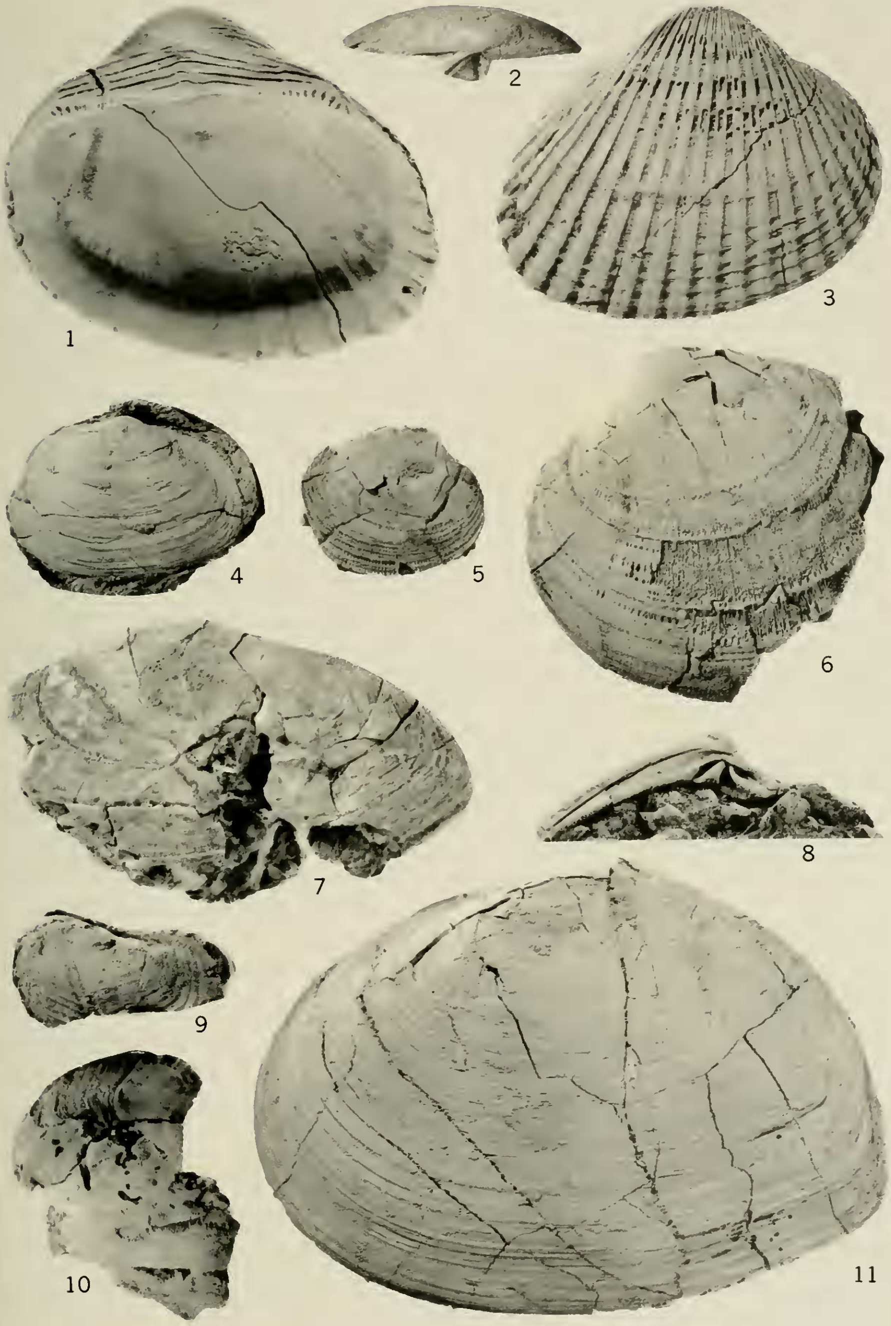
FIGURES 5, 6, and 8. *Protothaca staleyi* (Gabb). Figure 5, immature specimen, length 23.5 mm., height 19.2 mm., USNM 650965; figures 6, 8, height (incomplete) 49 mm., USNM 650966.

FIGURE 7. *Tellina* cf. *T. lutea* Wood. Length (incomplete) 63 mm., height (incomplete) 34 mm., USNM 650967.

FIGURE 9. *Zirfaea*? species. Length 26 mm., height 15 mm., USNM 650968, a rubber cast.

FIGURE 10. *Crepidula* cf. *C. princeps* Conrad. Diameter (incomplete) 36.5 mm., USNM 650969.

FIGURE 11. *Macoma*, new species? aff. *M. nasuta* (Conrad). Length 86 mm., height 63.5 mm., USNM 650970.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whorl is angulated by a spiral ridge and the relatively large body whorl is faintly shouldered below the suture. The large intermediate group of specimens are smooth, thick-shelled, low-spired and usually have a thin coating of whitish shell material within the aperture (pl. 1, fig. 10; pl. 3, fig. 5). This coating is also found on typical forms of *T. trancosana* but not on the spirally ribbed form. Denticles and corresponding spiral lines are found within the aperture of all three forms.

The typical high-spired form of *Thais trancosana* is similar to *T. etchegoinensis* Arnold (1909, p. 89, pl. 18, fig. 2) from the Etchegoin Formation of the San Joaquin Valley. It also resembles some of the smooth Holocene "morphs" (local populations) of *T. lamellosa* from the Puget Sound area figured by Kincaid (1957). On these taxa, however, the base of the body whorl is constricted into a longer, better defined anterior canal. Hertlein and Allison (1959) discuss other features by which these species can be differentiated.

The small, spirally ribbed form of *Thais trancosana* is similar to a smooth, low-spired form of *T. emarginata* (Deshayes), *T. emarginata* forma *ostrina* Gould, but its spirally ribbed, denticulate aperture and nonrecurved columellar lip serve to distinguish it from Gould's taxon. Arnold (1908, pl. 36, fig. 7) figured a specimen of *T. ostrina* from SU locality C321 near Felt Lake but additional specimens of this taxon were not found during the present study.

Thais trancosana has been reported from the Pliocene Cantil Costero Formation of Santillan and Barrera (1930) in northwestern Baja California, Mexico, and is known from several localities in the Merced Formation of the San Francisco Bay area (Hertlein and Allison, 1959).

A small, incomplete thaisid from USGS locality M1715 (pl. 4, figs. 10, 11) identified as *Thais* cf. *T. lima* (Gmelin) is distinguished from other species in the late Pliocene assemblages by its slender shell and unique sculpture of fine spiral ribs. Moreover, the aperture is smooth within and there is no evidence of spiral sculpture within the outer lip. The shell of *Thais* cf. *T. lima* is much thinner than on specimens of *T. trancosana* of comparable size.

Neptuneidae. A fragment of a small neptuneid consisting of two whorls with a cream-colored outer shell layer (pl. 1, fig. 7) has the spiral sculpture and strongly tabulate whorls of *Neptunea tabulata* (Baird), a widespread Pliocene to Holocene species. A large stout form of this species, *N. tabulata* forma *colmaensis* Martin (1914, pp. 188–189, pl. 20, fig. 1), is reported from upper Pliocene strata in the northernmost part of San Mateo County (Martin, 1914; Glen, 1959).

Columbellidae. Two specimens from USGS locality M1715 are doubtfully identified as *Mitrella* cf. *M. gouldi* (Carpenter). The larger of these (pl. 1, fig. 19; pl. 4, fig. 4) has convex whorls and a large evenly rounded body whorl. These characteristics suggest identification as *M. gouldi* rather than *M. gausapata* (Gould), at least in the sense that this taxon has been recognized by

Grant and Gale (1931, p. 695) and Abbott (1954, p. 222, pl. 20, fig. m). The doubtful identification is necessitated by the fact that the unfigured type specimen has been lost and the attendant uncertainties as to its correct identification. This taxon appears to be the same as *Astyris richthofeni* (Gabb) of Arnold (1908, pl. 36, fig. 8) and *M. gouldi* (Carpenter) of Touring (in Cummings and others, 1962, photo 16, no. 7), both from the Pliocene Purisima Formation of coastal San Mateo County.

Judging by Gabb's figure (1866, pl. 2, fig. 16) of the holotype of *M. richthofeni*, which has since been lost, this Pliocene species has a relatively high spire with flattened whorls. As such it seems more closely allied to *M. gausapata* than to *M. gouldi*, as suggested by others (Grant and Gale, 1931; Woodring and Bramlette, 1950).

NASSARIIDAE. Two species of *Nassarius*, *N. californianus* (Conrad, 1856) and *N. grammatus* (Dall, 1917), occur in the late Pliocene assemblages. There has been considerable confusion over the identification of these distinctive Pliocene species (Addicott, 1965a). The smaller species, *N. californianus* (pl. 3, fig. 7), the most abundant gastropod in these assemblages, was originally described from marine Pliocene strata in northern Santa Clara County presumably interbedded with the Santa Clara Formation. It is readily distinguished from the larger, *N. grammatus* (pl. 1, fig. 18; pl. 4, fig. 5), by its coarser sculpture, slender profile, and narrow umbilical callus. *Nassarius grammatus* is perhaps better, though incorrectly, known as *N. moranianus* (Martin), a late Pliocene and early Pleistocene species characterized by a medially angulated

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PLATE 3

(All specimens are from USGS locality M1715)

FIGURES 1, 6, and 8. *Spisula albaria coosensis* Howe. Figure 1, length 74 mm., height 58 mm., USNM 650971; figure 6, length 55.5 mm., height 45 mm., USNM 650972; figure 8, length 57.5 mm., height 44 mm., USNM 650973.

FIGURES 2, 3. *Ophiodermella graciosana* (Arnold). Height 17.8 mm., width 8 mm., USNM 650974.

FIGURE 4. *Macoma secta* (Conrad). Length 38.5 mm., height 26.5 mm., USNM 650975.

FIGURE 5. *Thais* (*Nucella*) *trancosana* Arnold. Intermediate form. Height 21.3 mm., width 16.4 mm., USNM 650976.

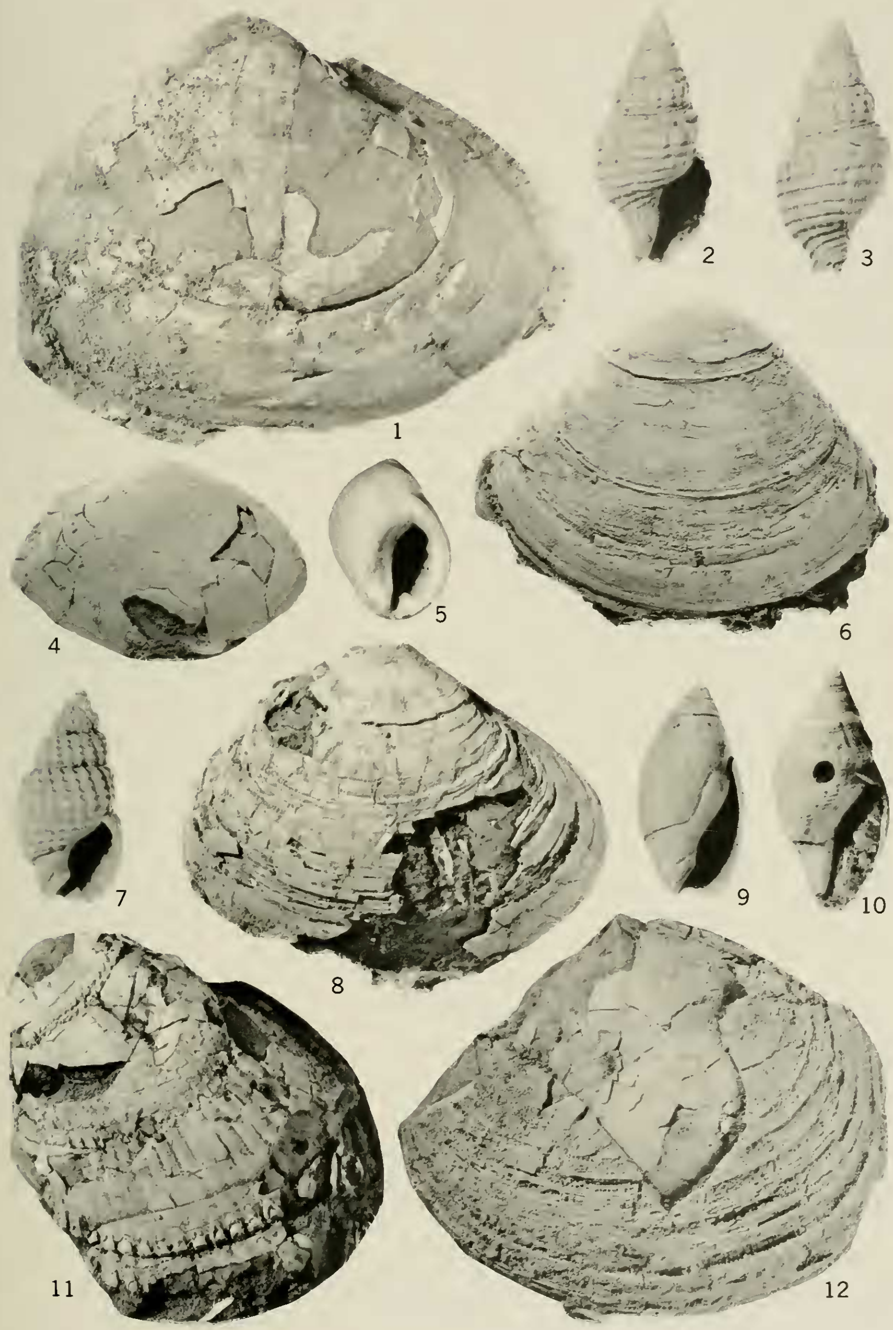
FIGURE 7. *Nassarius* (*Demondia*) *californianus* (Conrad). Height 15 mm., width 8.3 mm., USNM 648550.

FIGURE 9. *Olivella biplicata* (Sowerby). Height 19.5 mm., width 9.9 mm., USNM 650977.

FIGURE 10. *Megasurcula remondi* (Gabb). Height 34.5 mm., width 16.4 mm., USNM 650978.

FIGURE 11. *Clinocardium* cf. *C. meekianum* (Gabb). Length (incomplete) 46 mm., height (almost complete) 47.5 mm., USNM 650979.

FIGURE 12. *Humilaria perlaminosa* (Conrad) of Arnold (1907)? Length of fragment 66 mm., USNM 650980.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body whorl and sculptural features that are more closely allied to the Quaternary species *N. fossatus* than to *N. grammatus*.

Cancellariidae. Specimens of *Cancellaria arnoldi* Dall (1909, pp. 29–30, pl. 14, fig. 7) are characterized by strongly shouldered whorls and a well-developed siphonal fasciole. Twenty-five specimens of this slender cancellariid in the collection from USGS locality M1715 exhibit considerable variation in sculptural detail. Axial sculpture is dominant on some specimens (pl. 1, fig. 22) and weak on others (pl. 1, fig. 16). Secondary spiral sculpture is developed on some of the specimens. The thickness of the parietal callus and development of the siphonal fasciole are also variable. Collection from locality M1715 is a northward range extension of this species; it was previously reported only from localities in the southern part of California: Santa Maria basin (Woodring and Bramlette, 1950), doubtfully from the eastern Ventura basin (Winterer and Durham, 1962), and the San Diego area (Dall, 1909). It has recently been collected from the Purisima Formation near Capitola, Santa Cruz County, California (USGS locality M2462), where it occurs in a shallow water assemblage similar to Merced assemblages from the San Francisco Bay area.

A finely sculptured cancellariid from USGS locality M1715 appears to be undescribed. It resembles *Cancellaria lipara* Woodring (*in* Woodring and Bramlette, 1950, p. 76, pl. 16, figs. 13, 14) but has a moderately high spire, a well-defined anterior canal, and a concave subsutural slope. *Cancellaria* new species seems to be conspecific with a small abraded specimen from the Pliocene San Diego Formation (USNM 56207) which Woodring (*in* Woodring and Bramlette, 1950, p. 76) compared with the holotype of *C. lipara*. There is no suggestion of sculptural intergradation between this relatively smooth species and the more than 30 specimens of *C. arnoldi* in the collection from USGS locality M1715.

Olividae. Specimens of *Olivella biplicata* (Sowerby) (pl. 3, fig. 9) characterized by a low spire, heavy parietal callus, and a grooved spiral fold at the base of the columella occur abundantly at locality M1715. Some of the minute specimens resemble *O. pedroana* (Conrad) but can be distinguished by their bilobed basal columellar fold and lower spire.

Turridae. Specimens of *Ophiodermella graciosana* (Arnold, 1907, pp. 430–431, pl. 54, fig. 18) compare very closely with the abraded holotype from the upper Pliocene Careaga Sandstone of the Santa Maria basin. *Drillia mercedensis* Martin (1914, pp. 194–195, pl. 22, figs. 2a–2c) is a synonym of this species. Available records of *D. graciosana* (Glen, 1959; Woodring and Bramlette, 1950; Martin, 1916; Nomland, 1917; Waterfall, 1929; Soper and Grant, 1932) suggest that this Pliocene and early Pleistocene species ranges no lower than formations generally designated as late Pliocene in a twofold provincial division of the epoch. However, a satisfactory age assignment cannot be made for some occurrences of this species in bulk collections from the Purisima

Formation of the Santa Cruz Mountains (Martin, 1916) for which stratigraphic data are lacking.

Megasurcula remondi (Gabb, 1866, p. 3, pl. 1, fig. 5), a low-spired and rather stout species, is represented by two well-preserved specimens from USGS locality M1715. The larger of these (pl. 3, fig. 10) is of the same size as the lectotype. It compares very closely with Stewart's figure (1927, pl. 31, fig. 5) and has the general proportions of Gabb's original figure, a poor line drawing. This species was described from the Merced Formation of Sonoma and Marin County northwest of San Francisco but was subsequently identified as *M. carpenteriana fernandoana* (Arnold) by Dickerson (1922). Although this short, weakly angulated turrid has been treated as a form of *M. carpenteriana* (Gabb), it seems sufficiently distinct to recognize it as a separate species. This species seems to be limited to strata of Pliocene age, although there is a single specimen reported (Grant and Gale, 1931, p. 496) from undifferentiated Pliocene and Pleistocene strata in the Ventura basin near Fillmore.

PYRAMIDELLIDAE. The two strongly abraded, incomplete specimens of *Odostomia* from USGS locality M1715 are specifically indeterminate and too poorly preserved to be figured.

PELECYPODS

ARCIDAE. About 25 large, disarticulated valves of *Anadara trilineata* (Conrad, 1856) were collected from USGS locality M1715. Although the exterior and perimeter of these specimens are considerably abraded (pl. 2, figs. 1, 3), there are small specimens in the collection that shows the beaded ornamentation of ribs characteristic of this species. Most specimens have 26 ribs, although there are as few as 24 on some specimens and as many as 28 on others.

MYTILIDAE. Two incomplete, specifically indeterminate specimens of *Modio-*

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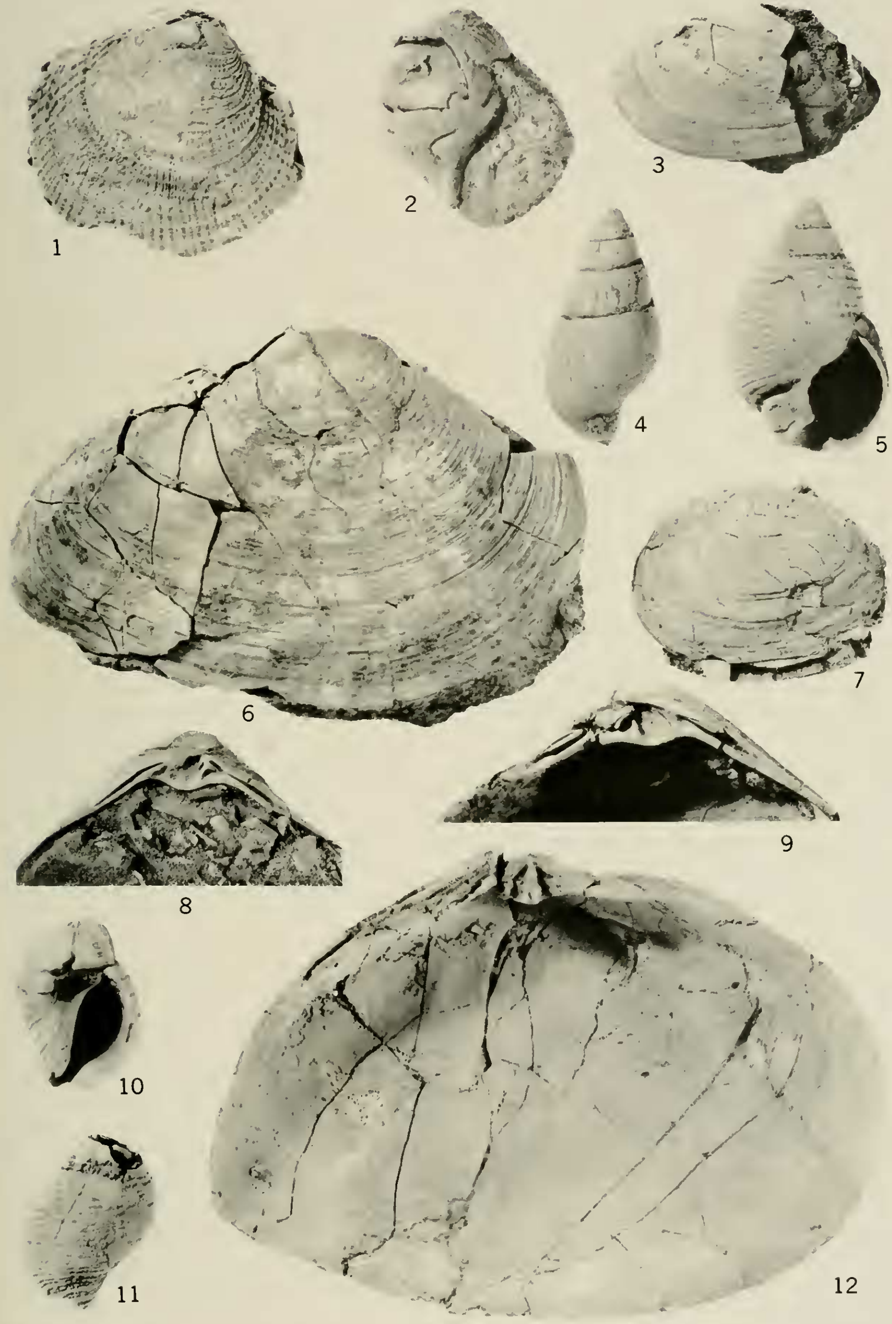
PLATE 4

FIGURE 1. *Protothaca staleyi* (Gabb), USGS locality M1720. Length 18 mm., height 17 mm., USNM 650981. FIGURE 2. *Cryptonatica aleutica* Dall, USGS locality M1720. Height 15.3 mm., width 8.5 mm., USNM 650982. FIGURE 3. *Tellina* species, USGS locality M1715. Height 21 mm., USNM 650983. FIGURE 4. *Mitrella* cf. *M. gouldi* (Carpenter), USGS locality M1715. Height 13.1 mm., width 6.2 mm., USNM 650959. FIGURE 5. *Nassarius* (*Caesia*) *grammatus* (Dall), USGS locality M1715. Height 27.6 mm., width 18.2 mm., USNM 648592. FIGURE 6. *Macoma nasuta* forma *kelseyi* Dall, USGS locality M1715. Length 78 mm., height 50.5 mm., USNM 650984. FIGURE 7. *Cryptomya californica* (Conrad), USGS locality M1715. Length 33.5 mm., width 24 mm., USNM 650963. FIGURES 8, 9. *Spisula labaria coosensis* Howe, USGS locality M1715. Figure 8, Hinge 1, USNM 650972; Figure 9, hinge 1, USNM 650985. FIGURES 10, 11. *Thais* (*Nucella*) cf. *T.* (*N.*) *lima* Gmelin, USGS locality M1715. Height 11.8 mm., width 8.8 mm., USNM 650986. FIGURE 12. *Macoma*, n. sp.? aff. *M. nasuta* (Conrad), USGS locality M1715. Length 86 mm., height 63.5 mm., USNM 650970.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lus were collected from USGS locality M1715. The largest (110 mm.) is severely deformed.

The fragment of a beak of a *Mytilus* with a broadly acute apical angle is in a Stanford University collection from a ditch connecting Felt Lake with Los Trancos Creek (SU loc. C321).

PECTINIDAE. Arnold (1906) reported *Leptopecten latiauratus* (Conrad) from exposures near Felt Lake. This record has not been substantiated by subsequent collecting, nor has the material upon which the identification was based been found in Stanford University collections.

CARDIIDAE. A badly exfoliated cardiid (pl. 3, fig. 11) is identified as *Clinocardium* cf. *C. meekianum* (Gabb, 1866). Although poorly preserved, the trigonal shape, strongly inclined beaks, and the character of ribbing indicates a close degree of similarity to this Pliocene index species. Moreover, the size and density of radial ribs are comparable to doubtfully identified specimens from the Kettleman Hills Pliocene of the San Joaquin Valley (Woodring and others, 1940) and specimens in U.S. Geological Survey collections from the Empire Formation near Cape Blanco, Oregon.

MACTRIDAE. Several specimens of *Spisula albaria coosensis* Howe (1922) were collected from USGS locality M1715. The absence of a distinct posterior ridge and the relatively weak development of the left anterior cardinal tooth (pl. 4, fig. 8) are features noted by Howe (1922, p. 100) that distinguish this taxon from *Spisula albaria* (Conrad), a Miocene species from the Astoria Formation of northwestern Oregon. There is considerable variation in outline of these specimens—from a form with a strongly produced anterior extremity (pl. 3, figs. 1, 8) to one which is almost equilateral (pl. 3, figs 6, 8). Similar variation in profile of middle Miocene specimens from the Astoria Formation of Oregon was described by Moore (1963, p. 83). The nonequilateral form compares very closely in external morphology with middle Miocene specimens in U.S. Geological Survey collections from the Astoria Formation of the Newport embayment, Oregon. The equilateral form is similar to a taxon from the Astoria Formation of southwestern Oregon named *S. albaria goodspeedi* by Etherington (1931, pp. 86–87, pl. 9, fig. 3).

One incomplete left valve of a *Spisula* in the collection from locality USGS M1715 is much larger than the others and has a subquadrate outline. Although not suitable for illustration, it is doubtfully identified as *Spisula* cf. *S. mercedensis* Packard (1916) because of its unique profile and similar hinge. Although poorly preserved, it can be differentiated from the similar *S. catilliformis* Conrad because the anterior lateral tooth is separated from the anterior cardinal.

Tresus pajaroanus (Conrad, 1857) is identified on the basis of a crushed right valve from USGS locality M1715 that has the broad siphonal gape characteristic of the genus and a very long posterior dorsal slope. The specimen is unsuitable for figuring.

Solenidae. Several broken, thin-shelled specimens of *Solen* collected from locality USGS M1715 are doubtfully identified as *Solen* cf. *S. sicarius* Gould. Two of the fragments seem to have a gently curved dorsal margin, the principal shell character by which this species is distinguished from the similar Recent species *S. rosaceus* Carpenter.

Tellinidae. An incomplete left valve of a large, thick-shelled tellinid is identified as *Tellina* cf. *T. lutea* Wood. The concentric sculpture and broadly obtuse umbonal angle resemble the living circumboreal species, which ranges from northern Japan (Habe, 1964, p. 202) to Cook Inlet, Alaska. The Pliocene specimen (pl. 2, fig. 7) has a somewhat broader umbonal angle and a heavier shell and hinge plate than specimens of *T. lutea* in U.S. Geological Survey Holocene collections from Alaska. Similar forms occur in the Pliocene of the Santa Maria basin (Woodring and Bramlette, 1950, p. 87) and the Salinas Valley (Durham and Addicott, 1965, p. A14).

The genus *Tellina* is further represented by a fragment of a moderately small, thick-shelled specimen identified as *Tellina* species (pl. 4, fig. 3). Although the posterior part of the valve is missing, there is an impression in the sandstone matrix in which the shell is imbedded that indicates a short, steep posterior dorsal slope unlike that of *Tellina* cf. *T. lutea* with which it occurs. Indeed, the posterior location of the beak and outline inferred from the sandstone cast are more similar to *T. bodegensis* (Hinds), although the shell seems thicker for its size and is much more produced ventrally than that species. The smooth surface of the shell is sculptured by evenly spaced concentric bands that are slightly tilted ventrally, giving the surface a finely imbricate appearance.

The left valve of a very large specimen of *Macoma* (pl. 2, fig. 11; pl. 4, fig. 12) allied to *M. nasuta* (Conrad) may represent an undescribed species, but there is insufficient material to confidently separate it from *M. nasuta*. The pallial sinus extends forward to the anterior muscle scar as in *M. nasuta*, but the ligamental groove is much longer and the posterior extremity is broadly truncated rather than acute. Moreover, the beak is situated posterior to the midline of the valve and the valves are strongly flexed. On the only well-preserved specimen, the flexure begins midway between the umbo and the posterior extremity in dorsal view, whereas it begins in the anterior quarter of the shell along the ventral margin. In *M. nasuta* flexing of the ventral margin usually takes place directly below the beaks near the middle or slightly anterior to the middle of the shell. The degree of flexing may be a variable characteristic because a broken right valve from USGS locality M1715 that seems to belong with *Macoma* new species? because of its relatively long ligamental groove and posteriorly situated beak appears to be very weakly flexed.

There is an unfigured, poorly preserved right valve (about 70 mm. long) that has a strong posterior flexure and broadly truncate posterior extremity similar to the larger left valve described above. Yet there are too few specimens to provide an adequate measure of possible variation. Accordingly, one cannot rule out the possibility that it is an aberrant *Macoma nasuta* (Conrad), as it occurs with the large thick-shelled variety *M. nasuta* forma *kelseyi* (Dall).

A few incomplete specimens identified as *Macoma nasuta* forma *kelseyi* Dall are differentiated from the previously described taxon by their acutely pointed posterior extremities. These also are large, thick-shelled individuals (pl. 4, fig. 6) similar to late Pliocene specimens from the Careaga Sandstone of the Santa Maria basin figured by Woodring and Bramlette (1950, p. 87, pl. 20, figs. 2, 8) but they have an apparently stronger posterior flexure of the valves.

Macoma secta (Conrad), represented by a thin-shelled immature right valve (pl. 3, fig. 4), is differentiated from the other macomas with which it occurs by its very short ligamental area and characteristic arcuate dorsal margin above the posterior ridge.

Veneridae. The genus *Katherinella* is represented by a poorly preserved specimen from an old Stanford University locality (SU loc. C308) on Purisima Creek about 1½ miles southeast of USGS locality M1715.

An incomplete, thick-shelled valve of venerid pelecypod (pl. 3, fig. 12) identified as *Humilaria perlaminosa* (Conrad)? has been compared with a holotype (USNM 165252) figured by Arnold (1907, pl. 58, figs. 1a, 1b) from the Santa Barbara Formation of southern California. Both specimens have rugose primary concentric sculpture which, where well preserved, tends to conceal a secondary network of fine radial ribs. However, specific identity is uncertain because about a third of the valve, including the hinge, is missing. If identification as *H. perlaminosa* (Conrad) were undoubted, this would be the northernmost recorded occurrence of this species in addition to its first record in strata of Pliocene age. Previously reported occurrences are from rocks of early Pleistocene age in southern California (Arnold, 1907; Waterfall, 1929; Woodring and others, 1946).[2]

Protothaca staleyi (Gabb, 1866) (pl. 2, figs. 5, 6, 8; pl. 4, fig. 1) is represented by several thick-shelled valves and many fragments. The subquadrate outline of the valves and incised line defining these specimens are features which Howe (1922, p. 98, pl. 10, fig. 1) used to separate a form from the Pliocene Empire Formation at Coos Bay, Oregon (*P. staleyi* forma *hannibali* Howe), from the typical form. Yet the rather smooth exterior with only faint radial sculpture is characteristic of the neotype from the Merced Formation of Sonoma County (Stewart, 1930, p. 233, pl. 15, fig. 4). The hinge of this species differs from that of the Pliocene to Holocene *P. staminea*. The lower part of the anterior cardinal tooth of the left valve of *P. staleyi* is strongly reflected anteri-

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2 There is an unreported occurrence in an unnamed Pliocene formation at Newport Bay, Orange County, California (J. G. Vedder, oral communication, January 1968).

orly, whereas in *P. staminea* it is straight, much shorter, and oriented at 90 degrees to the long axis of the valve.

MYIDAE. Several disarticulated valves of *Cryptomya californica* Conrad occur in the late Pliocene collections from northern Santa Clara County (pl. 2, figs. 2, 4; pl. 4, fig. 7). The outline of these specimens is variable; some are elongate, others are suborbicular. Some compare closely with *C. ovalis* Conrad (Arnold, 1908, pl. 36, fig. 9), one of several names proposed for late Tertiary cryptomyas which seem to be best regarded as forms of the Holocene *C. californica* (Grant and Gale, 1931, p. 417; Woodring and Bramlette, 1950, p. 91).

PHOLADIDAE. Two incomplete external molds of a small pholadid pelecypod found in extensively bored blocks of Monterey Shale collected from locality M1715 are doubtfully identified as *Zirfaea* species. A rubber cast of the better of these is figured (pl. 2, fig. 9).

AGE AND POSITION IN THE PROVINCIAL CHRONOLOGY

More than a third of the taxa in the Merced(?) assemblages from northern Santa Clara County are extinct.[3] Thus in the context of classical Lyellian age classification (Keen, 1939; Bird, 1967), probably the only way by which the highly endemic Neogene molluscan faunas of the Pacific Coast can be directly compared with those of European type sections, a Pliocene age is clearly indicated. Distinctive extinct taxa include *Littorina petricola, Thais trancosana, Cancellaria arnoldi, C. lipara, Anadara trilineata, Clinocardium* cf. *C. meekianum, Protothaca staleyi, Tresus pajaroanus,* and *Spisula albaria coosensis.* None of these species have been reported from strata usually classified as Pleistocene in the Pacific coast provincial sequence (Weaver and others, 1944; Woodring, 1952; Valentine, 1961). Some workers now place the Pliocene-Pleistocene boundary within the upper part of the traditional marine Pliocene sequence of the Pacific Coast (Moore, 1949; Durham *in* Durham and MacNeil, 1967; Repenning, 1967) on the basis of indirect correlation of mammalian assemblages and associated radiometric age determinations with the European nonmarine mammal chronology. Lowering of this boundary vitiates the long-standing criteria upon which the marine shallow water Pliocene of the Pacific Coast is discriminated from the Pleistocene (Woodring, 1952). Accordingly, use of Pliocene in this report is in a provincial sense and is dictated by utilitarian considerations. Although it is in keeping with long-established standards that honor extinction percentages compatible with the Lyellian principle, it is not necessarily comparable to European usage. Clearly, provincial stage-age classification of the Pacific Coast marine Pliocene would obviate the need for utilization of European epoch terminology, but unfortunately, adequately defined provincial time-stratigraphic terminology based upon larger invertebrates has not been proposed.

Assignment to the late Pliocene, in the sense of a twofold division of the

[3] A comparable percentage of extinct species was determined for the Merced Formation by Smith (1919, p. 145).

Pliocene molluscan sequence in California (Vedder, 1960; Durham and Addicott, 1965), is based upon faunal correlation with well known Pliocene sequences that are generally used as reference sections for the shallow water Pliocene of California. The principal one is the type section of the Merced Formation along Seven Mile Beach near the northwestern end of the San Francisco Peninsula. This section spans the provincial Pliocene-Pleistocene boundary as long recognized on the Pacific Coast (Arnold, 1906; Weaver and others, 1944; Woodring, 1952; Valentine, 1961). About two-thirds of the taxa either occur in the lower Merced fauna or are represented by closely related taxa, many of which are doubtfully identified forms that might be conspecific. The general aspect of the present faunal assemblages also corresponds closely to the ecologically comparable upper part of the classic Pliocene section of the Kreyenhagen Hills-Kettleman Hills area (Arnold, 1909; Nomland, 1917; Woodring and others, 1940) of the San Joaquin Valley about 125 miles to the southeast. More of the species occur in the diverse molluscan fauna of the upper part of the Pliocene sequence of the Santa Maria Basin (Woodring and Bramlette, 1950) located somewhat farther to the southeast than in other California sections. However, this seems to be in part a manifestation of the greater diversity of the late Pliocene molluscan fauna of the Santa Maria basin.

An early Pliocene age seemingly can be ruled out by the fact that none of the early Pliocene index species characteristic of the Pancho Rico Formation of the Salinas Valley area or the Jacalitos Formation of the San Joaquin Valley occur in this fauna. Moreover, species such as *Ophiodermella graciosana, Humilaria perlaminosa, Cancellaria arnoldi, C. lipara,* and *Leptopecten latiauratus* are not known to occur in strata generally classified as lower Pliocene according to a twofold division of the Pliocene Series. In this regard, if one accepts limits of about 3 million and 10 or 11 million years for the Pliocene Series in California, there seems to be an unrealistically short interval of time to permit a threefold division based upon evolutionary phenomena. The Miocene Series in California, for example, has been divided by recent workers (Corey, 1954; Repenning and Vedder, 1961; Addicott, 1965c) into only three, or possibly four, time-stratigraphic units based upon molluscan data, although its duration is more than twice that of the Pliocene.

Assignment of this fauna to the late Pliocene is not a new concept. It was initially considered to be late Pliocene by Arnold (1906) by inclusion of exposures near Felt Lake in his upper Pliocene "zone" or "horizon"—the Merced Formation.[4] However, the only recorded taxa from this locality (Arnold, 1906; p. 25) were living species.

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[4] Despite the use of the term Formation, which is now considered to be a lithostratigraphic term, Arnold's utilization of zone and horizon, together with type sections and references of fossiliferous sections from widely separated areas in California to his Tertiary Formations, very nearly fulfills our modern time-stratigraphic concept of stages. He included only the lower part of the type Merced Formation in the Pliocene.

PALEOECOLOGY

By and large the molluscan assemblages represent a very shallow, water-nearshore environment not unlike modern bays and estuaries of the central California coast. Many of the species, for example, are still living in the intertidal zone or uppermost part of the inner sublittoral zone (Hedgpeth, 1957) of nearby San Francisco Bay: *Pupillaria pupilla, Ocenebra interfossa, Thais ostrina, Olivella biplicata, Leptopecten latiauratus, Solen sicarius,* and *Cryptomya californica* (Packard, 1918).[5] These and other taxa that are represented by closely related species in San Francisco Bay or nearby Elkhorn Slough (latitude 36.8° N.) comprise more than half of the specifically identified taxa in the late Pliocene assemblages (table 2). There are, however, relatively deep-water elements, as well as both northern and southern faunal elements, that suggest environmental conditions at least somewhat different from these modern, shallow-water bays.

Pertinent molluscan bathymetric data on living species, modern analogs, or supraspecific taxa (chiefly from Packard, 1918; Oldroyd, 1924; Burch, 1944–1946; Fitch, 1953; Abbott, 1954; Quayle, 1960; Coan *in* Keen, 1963; and Parker, 1964) suggest that the late Pliocene assemblages lived in the littoral (intertidal) zone or the highest reaches of the inner sublittoral zone. Although nearly all of the living species and comparable generic taxa range downward into the middle or lower reaches of the inner sublittoral zone (20–50 fathoms), the most abundant species—*Thais trancosana, Nassarius californianus, N. grammatus, Olivella biplicata, Cancellaria arnoldi, Anadara trilineata, Protothaca staleyi, Macoma nasuta* group, and *Cryptomya californica*—are certainly indicative of a very shallow-water, level-bottom community. Excepting the two extinct warm-water taxa that have no closely related survivors along the California coast, *Anadara* (*Anadara*) *trilineata* and *Cancellaria arnoldi*, each of these is either still living or is represented by an analogous species in San Francisco Bay or Elkhorn Slough.

There are, however, three gastropods of deeper water aspect in the assemblage: *Cryptonatica* cf. *C. aleutica*, *Neptunea* cf. *N. tabulata*, and *Megasurcula remondi*. These species are still living in the latitude of central California at depths of 20 fathoms or greater. The seemingly anomalous association of these with the shallow-water, nearshore assemblage which includes the intertidal gastropod *Littorina* is difficult to interpret. Perhaps these species are best regarded as strays that somehow ventured into unusually shallow water. That this is not their preferred environment is suggested by the fact that each is represented by only one or two individuals.

The apparently equal representation of gastropods and pelecypods suggested by the faunal list (table 1) does not accurately reflect the numerical dominance

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[5] Packard's study preceded the effects of urbanization of the San Francisco Bay area on the molluscan fauna, and the concomitant establishment of many introduced mollusks.

Table 2. *Some late Pliocene mollusks that are still living, or are represented by closely related species, in central California bays or estuaries.*

Gastropods	Occurrence (Packard, 1918; Fitch, 1953)
Thais trancosana	Related form (*T. lamellosa*) living in San Francisco Bay
Nassarius californianus	Related form (*N. mendicus*) living in San Francisco Bay
Pelecypods	
Nassarius grammatus	Related form (*N. fossatus*) living in San Francisco Bay
Clinocardium cf. *C. meekianum*	Related form (*C. nuttallii*) living in San Francisco Bay
Protothaca staleyi	Related form (*P. laciniata*) living in Elkhorn Slough
Spisula cf. *S. mercedensis*	Similar form (*S. catilliformis*) living in San Francisco Bay
Tresus pajaroanus	Similar form (*T. nuttallii*) living in San Francisco Bay
Macoma aff. *M. nasuta*	Similar form (*M. nasuta*) living in San Francisco Bay
Macoma nasuta kelseyi	Related form (*M. nasuta*) living in San Francisco Bay
Macoma secta	Living in Elkhorn Slough

of pelecypods in the faunal assemblages. Factors of preservation and the mode of accumulation may account for a gastropod : pelecypod ratio that is not representative of comparable shallow-water, sand-flat biotopes of modern bays along the California coast. Broken pelecypod shells are the dominant faunal element, yet whole or nearly complete shells are rarely encountered. Entire pelecypod valves could be collected only from large blocks that were excavated by power equipment at construction sites. Excellent gastropod specimens, on the other hand, were relatively simple to collect because of their small size and simple, cylindrical shape. And in this assemblage, abundance figures taken from collections would be highly biased toward gastropods; this is simply a measure of their ability to withstand destruction prior to burial because of their streamlined form. Thus gastropods probably represent a much more thoroughly collected faunal element than pelecypods, because of the limited availability of large blocks and the tendency for the disarticulated, essentially two-dimensional pelecypod shells to be broken by wave or current action prior to final burial.

The large percentage of broken shells and the usual disarticulated condition of the valves of burrowing pelecypods suggests that the shell beds represent a death assemblage that has undergone considerable modification by wave or current action. Yet the numerically dominant mollusks in the assemblage are allied to modern taxa that characteristically inhabit a sandy, level-bottom substrate in the intertidal zone or high inner-sublittoral depths of bays and estuaries. Only minor mixing of elements from another biotope is suggested by the occurrence of rare specimens of three taxa charactersitic of the middle or lower parts of the inner sublittoral zone.

Zoogeography

Included in the late Pliocene assemblages from northern Santa Clara County are a few molluscan taxa whose descendants or modern analogs do not occur together in the molluscan fauna now living off the central and northern California coast. These extralimital mollusks consist of both northern and southern elements (table 3) whose modern endpoints of latitudinal range are separated by at least several hundred miles along the Pacific Coast.

It is difficult to interpret the joint occurrences of molluscan taxa that do not have overlapping zoogeographic distributions in the modern, shallow-water provinces of the northeastern Pacific Ocean. One possibility is that some invertebrates may have become adapted to different environmental conditions through competitive pressure or physiologic change. Were both the northern and southern elements represented by large populations in the assemblages, this would seem a good likelihood. In this case, however, only the southern forms of *Cancellaria* and *Anadara*[6] are represented by large, apparently well-established reproductive populations. In addition, the genus *Neverita* is not definitely known to occur north of the Californian molluscan province (northern boundary near 34.5° N.) according to Burch (1946) and Smith and Gordon (1948). By way of contrast, the northern taxa *Tellina* cf. *T. lutea* and *Macoma nasuta* forma *kelseyi* are represented by only one or two specimens. Accordingly, it can be argued that these northern taxa represented a brief southerly range extension during relatively cool parts of the marine climatic cycle but were unable to establish reproductive populations because of unfavorable environmental conditions, presumably excessively warm water temperatures.

Cancellaria and *Anadara* occur, then, in a temperate, or possibly warm-temperate, protected inner-coast assemblage in which additional warm-water taxa are not represented. Possibly this assemblage reflects discontinous late

[6] This is about the northernmost occurrence of *Anadara s.s.* in the late Pliocene of the Pacific Coast. A more northerly occurrence in the Ohlson Ranch Formation of Higgins (1960) in Sonoma County (Peck, 1960) may be of early Pliocene age judging by the associated fauna. In the early Pliocene it occurred as far north as southwestern Oregon, where it is found in the Empire Formation. By early Pleistocene time the genus had disappeared entirely from California. A species referable to the subgenus *Cunearca* occurs in the late Pleistocene of southern California. Two modern records of *A.* (*Larkinia*) *multicostata* from southern California (Burch, 1945) have not been verified by subsequent collecting and are regarded doubtful. Further doubt is cast upon these records by the fact that this species is not known from the late Pleistocene of southern California (J. G. Vedder, oral communication, 1968).

Table 3. *Extralimital late Pliocene taxa from northern Santa Clara County.*

Species	*Distribution of modern analog*
Taxa with southern affinities:	
1. *Neverita* cf. *N. recluziana* (Deshayes)	Living from Point Conception, Calif. to Tres Marias Islands, Mexico (Burch, 1946). Old records from central and northern California are doubtful (Burch, 1946; Smith and Gordon, 1948)
2. *Cancellaria arnoldi* Dall	Presumably referable to *Cancellaria, s. s.* species of which range from Cedros Island, Baja California, southward (Keen, 1958). *Cancellaria emydis* Dall and Ochsner, a Quaternary species from the Galápagos Islands, seems to be most closely related to *C. arnoldi.* There are no closely related species in modern Californian or Oregonian molluscan provinces.
3. *Cancellaria*, new species	
4. *Megasurcula remondi* (Gabb)	Living from Monterey Bay to Todos Santos Bay, Baja California (Burch, 1946)
5. *Anadara* (*Anadara*) *trilineata* (Conrad)	Subgenus ranges from Cedros Island, Baja California southward (Keen, 1958)
Taxa with northern affinities:	
1. *Tellina* cf. *T. lutea* Wood	Living from northern Japan to Cook Inlet, Alaska (Habe, 1964; Burch, 1944)
2. *Macoma nasuta kelseyi* Dall	Living from Puget Sound to Coos Bay, Oregon (Burch, 1944).

Pliocene zoogeographic distributions in which isolated populations of warm-water taxa existed far north of their normal outer-coast distribution by inhabiting the relatively warm water of protected bays.

The co-occurrence of northward and southward ranging mollusks is not unique in the California Neogene. Similar joint occurrence of late Pliocene mollusks with mutually exclusive modern geographic ranges is reported by Soper and Grant (1932) from the Los Angeles basin. The subject is also treated by Woodring and others (1946), Valentine (1955; 1961) and Emerson (1956) as it concerns late Pleistocene mollusks from southern California and northwestern Baja California.

The sum of the zoogeographic evidence seems to point, therefore, to a shallow-water marine climate that was probably somewhat warmer than occurs in bays along the California coast today. This is at variance with Smith's (1919) conclusion that the coeval lower type Merced fauna indicated water temperatures that were much cooler than exist today in the vicinity of San Francisco. Durham (1950), noting the occurrence of the small warm-temperate element in the type Merced assemblage, suggested minimum water temperatures as warm as or slightly warmer than at this latitude today. It is notable that the warm-water cancellariids have not been reported from the type Merced. The genus *Neptunea*, however, is relatively abundant at localities in this formation (USGS loc. M1661; UCMP loc. 1736), suggesting at least local deeper and cooler water conditions than occur in the northern Santa Clara County Pliocene to the southeast.

Late Pliocene Paleogeography

Correlation of the late Pliocene fauna of the northern Santa Clara County area has significant bearing on Pliocene paleogeography of the San Francisco Peninsula and on the history of movement along the Santa Cruz Mountains segment of the San Andreas fault. Principal exposures of late Pliocene strata on and near the San Francisco Peninsula are, 1) Bolinas Bay (Martin, 1916), 2) San Francisco and northwestern San Mateo Counties (Lawson, 1893; 1895; Ashley, 1895; Arnold, 1906; Martin, 1916; Glen, 1959), 3) upper part of the Purisima Formation along the San Mateo County coast (Ashley, 1895; Haehl and Arnold, 1904; Martin, 1916; Cummings and others, 1962), and 4) northern Santa Clara County (Arnold, 1906; 1908; Branner and others, 1909; this report). Apparently correlative strata occur along the north shore of Monterey Bay and in the Sargent-Pajaro River area to the southeast (Martin, 1916) and in Sonoma County to the northwest (Osmont, 1905; Dickerson, 1922). As indicated on the paleogeographic map (fig. 2), these exposures define relatively narrow, northwest-trending embayments. Of particular concern is the relationship of the northern Santa Clara County Pliocene to the coeval lower Merced Formation of the northern San Francisco Peninsula. The continuous band of Merced Formation extends from San Francisco southward to near Burlingame, from which point Lawson (1914) theorized that it continued southeastward beneath San Francisco Bay. However, a comprehensive recent study of the subsurface stratigraphy and bedrock configuration of the South [San Francisco] Bay area (Finlayson and others, 1967) indicates that flat-lying Quaternary alluvium unconformably overlies a "basement" of Miocene and older rocks beneath this part of the Bay and surrounding alluvial plains. Moreover, earlier accounts of the Neogene history of San Francisco Bay (Louderback, 1951; Howard, 1951) concluded that the Pliocene Merced embayment was a narrow coastal feature that did not occupy the present southern part of San Francisco Bay.

If the northern Santa Clara County Merced(?) exposures were not directly connected to the Merced Formation to the northwest, they must have formed the nearshore part of a westward-oriented embayment that was subsequently truncated by the San Andreas fault. The Merced(?) and Santa Clara Formations of the Palo Alto area are located less than 3 miles northeast of a 1600-foot section of Pliocene Purisima Formation (Cummings, 1960) situated less than one mile southwest of the San Andreas fault. These exposures have been correlated with the lower Pliocene Tahana Member of the Purisima Formation by Cummings and others (1962). The fauna consists of 37 mollusks (table 4) including taxa such as *Colus recurvus*, *Clementia*, *Dosinia*, and *Spisula moss-*

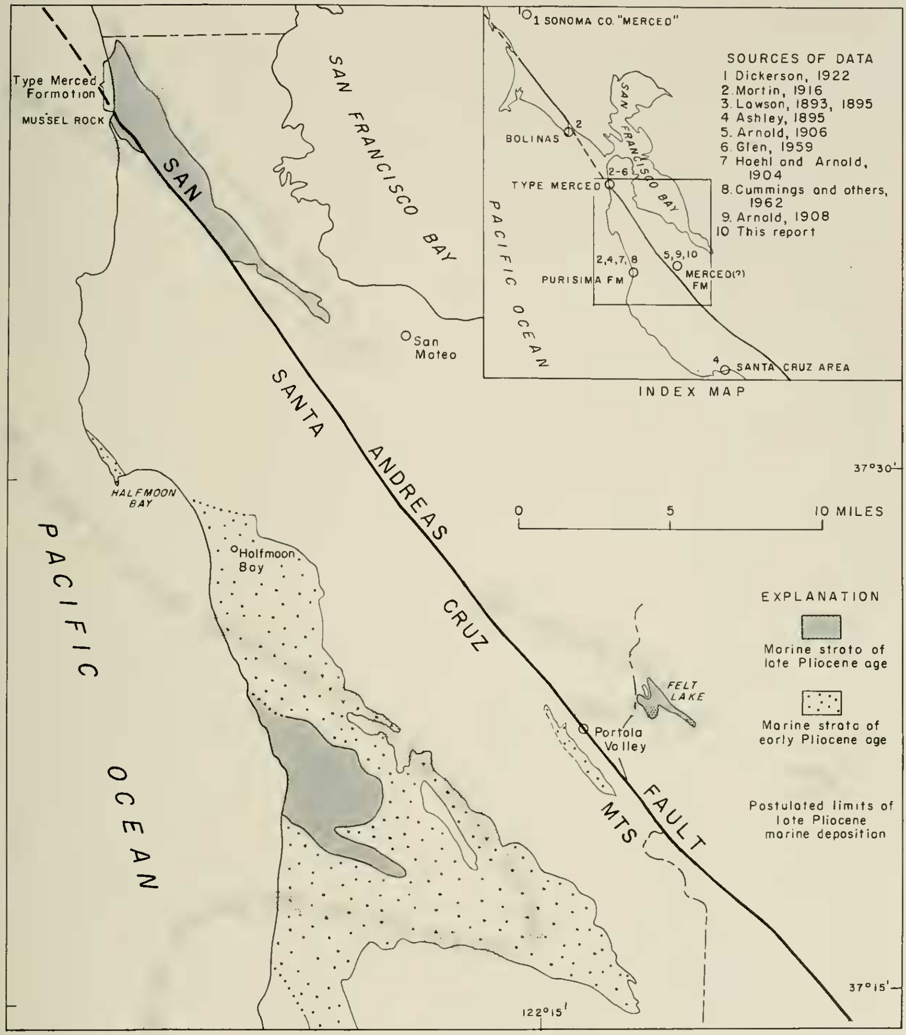

FIGURE 2. Distribution of marine Pliocene rocks and late Pliocene paleogeography in the northern Santa Cruz Mountains (geology modified from Jennings and Burnett, 1961).

beachensis (Ashley, 1895; Cummings, 1960; Cummings and others, 1962) that are suggestive of an early Pliocene age. None of these taxa occur in the nearby exposures of Pliocene strata northeast of the fault.[7] The inferred non-contemporaneity between these assemblages on opposite sides of the San Andreas

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[7] The warm temperate to tropical genus *Dosinia* is suggestive of an early Pliocene or older age at this latitude. Its northernmost late Pliocene and Pleistocene occurrences are in the warmer water faunas of southern California.

Table 4. *Mollusks from the Tanana Member of the Purisima Formation (Cummings and others, 1962) from Portola Valley, California. Different names used by Ashley (1895a); Arnold (1908); and Cummings (1960) are shown in brackets.*

				USGS localities					
Gastropods	Ashley 1895a	Arnold 1908	Cummings 1960	M2664	M2665	M3253	M3254	M3255	M3256
Calicantharus portolaensis (Arnold)		X						?sp.	
[*Fusus (Buccinofusus) portolaensis* Arnold (1908)]									
Calyptraea mamillaris Broderip			X					sp.	
Colus recurvus (Gabb)	X								
[*Neptunea recurva* Gabb (Ashley, 1895a)]									
Crepidula princeps Conrad	X		X						
[*Crepidula grandis* Middendorff (Ashley, 1895a)]									
Mitrella species								X	
Polinices lewisi (Gould)	X		sp.						
[*Lunatia lewisii* Gould (Ashley, 1895a)]									
Nassarius californianus (Conrad)				X	X		X	X	
Nassarius grammatus (Dall)	X		X						X
[*Nassarius moranianus* (Martin) (Cummings, 1960); ? *Nassa californica* Conrad (Ashley, 1895a)]									
Pelecypods									
Acila (Truncacila) castrensis (Hinds)			X						
Anadara trilineata (Conrad)	X		X	X		cf.		?sp.	?sp.
[*Arca microdonta* Conrad (Ashley, 1895a)]									
?*Clementia* species									X
Clinocardium meekianum (Gabb)	X								
[*Cardium meekianum* Gabb (Ashley, 1895a)]									
"*Crassatella collina* Conrad?"	X								
Cryptomya californica Conrad				X					?sp.
Dosinia ponderosa (Gray)	X								
Katherinella subdiaphana (Carpenter)	X		X						
[*Saxidomus gibbosus* Gabb? (Ashley, 1895a); *Compsomyax*									

subdiaphana (Carpenter) (Cummings, 1960)]									
Lucinisca nuttalli (Conrad)	X								
[*Lucina nuttalli* Conrad (Ashley, 1895a)]									
Macoma nasuta (Conrad)	X				cf.				
Modiolus cf. *M. rectus* (Conrad)								X	
Pandora punctata Conrad			X		sp.				
Pandora filosa Carpenter								X	
Panope abrupta (Conrad)	X								
[*Glycymeris generosa* Gould (Ashley, 1895a)]									
Protothaca staleyi (Gabb)	X		X	X	X		X	X	X
[*Protothaca staminea* (Conrad) (Cummings, 1960);									
Tapes staminea Conrad (Ashley, 1895a)]									
Protothaca tenerrima (Carpenter)	X		X						
[*Tapes tenerrima* Carpenter (Ashley, 1895a)]									
Florimetis biangulata (Carpenter)			X						
[*Apolymetis biangulata* (Carpenter) (Cummings, 1960)]									
Pseudocardium densatum (Conrad)			X						
Siliqua cf. *S. alta* (Broderip and Sowerby)					sp.				X
Solen sicarius Gould	X		X	sp.	X			cf.	
Spisula catilliformis (Conrad)	X								
[*Standella californica* Conrad (Ashley, 1895a)]									
Spisula falcata (Gould)	X		X						
[*Standella planulata* Conrad? (Ashley, 1895a)]									
Spisula albaria (Conrad)			X	sp.	sp.	sp.	cf.	sp.	sp.
Spisula mossbeachensis Glen				cf.					X
Tresus nuttalli (Conrad)	X								
[*Schizothaerus nuttalli* Conrad (Ashley, 1895a)]									
Tresus pajaroanus (Conrad)	X		X			?			
[*Mactra* (not *Venus*) *pajaroensis* Conrad (Ashley, 1895a)]									
Yoldia cooperi Gabb			X						X
Yoldia thraciaeformis (Storer)			X						
Yoldia species			X						

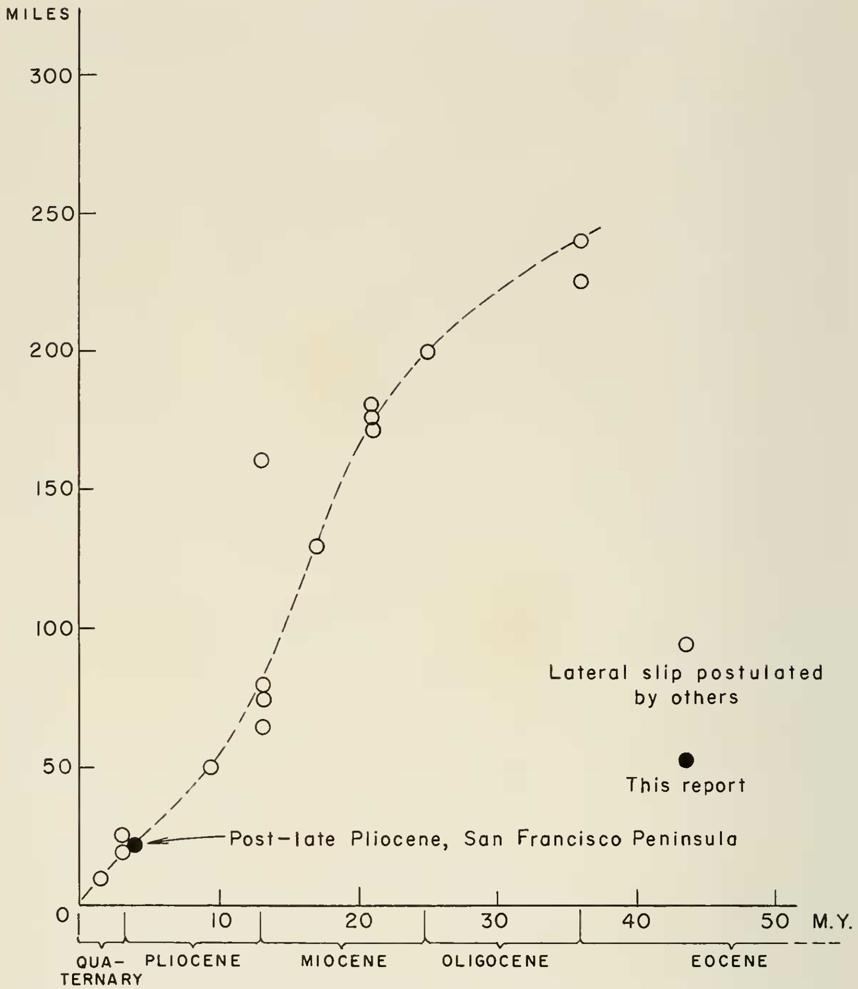

FIGURE 3. Comparison of indicated lateral offset of marine late Pliocene strata on the San Francisco Peninsula with Tertiary offsets postulated by other workers (modified from Grantz and Dickinson, 1968).

fault is supported by the fact that there is a much smaller number of species in common, 14 out of 33, than might normally be expected, since both represent comparable very shallow water inner sublittoral environments and are so close together.

The upper Pliocene members of the Purisima Formation of Cummings and others (1962) of the western slope of the Santa Cruz Mountains seem to define an eastward oriented depositional basin of very shallow water aspect (upper inner sublittoral zone) that did not reach nearly as far inland as the much thicker, somewhat deeper water lower Pliocene member. The nearest exposures of Pliocene strata along the San Andreas fault occur along the coast between the fault and Mussel Rock (Glen, 1959), about 20 to 25 miles to the northwest. Although Higgins (1961) believes that these exposures have been displaced by landsliding across the San Andreas fault to their present position on the southwest side, it is noteworthy that they contain species such as *Anadara trilineata* (USGS loc. M1618) and *Tresus pajaroanus* that have not been reported from localities in the lower part of the type Merced Formation (Glen, 1959) on the northeast side of the fault. Most of the mollusks from exposures of Merced Formation on the southwest side of the San Andreas fault near Mussel Rock also are recorded from the Merced(?) Formation of northern Santa Clara County. Perhaps the most significant of these is *A. trilineata* which, interestingly, is not recorded from strata in the type Merced Formation northeast of the San Andreas fault (Glen, 1959). The indicated post-depositional right-lateral slip on the order of 20 to 25 miles is compatible with postulated rates of lateral slip along the San Andreas fault during earlier parts of the Neogene (Hill and Dibblee, 1953; Dibblee, 1966b; Galehouse, 1967; Addicott, 1968). It is also in close agreement with Cummings' (1968) estimate of about 18 miles of displacement of distinctive nonmarine facies in the Pliocene and Pleistocene Santa Clara Formation in this area. The relationship of the apparently offset late Pliocene marine strata on the San Francisco Peninsula to earlier postulates of Tertiary slip along the San Andreas fault is shown on a recent graph (fig. 3) compiled by Grantz and Dickinson (1968).

Localities

United States Geological Survey Cenozoic localities (USGS) (Menlo Park Register)

M1618. In large cut on east side of new location of Highway 101 where it crosses a ridge trending northwestward through the center of the NE ¼ sec. 23, T. 3 S., R. 6 W., San Francisco South 7½′ quadrangle, California. Altitude 525 feet Merced Formation. Collectors: M. Bonilla and W. O. Addicott, 1962.

M1661. In large excavated area 950 feet S. 61° W. of intersection of Junipero Serra Boulevard and Arroyo Drive. Map coordinates: 1, 434,850 feet E., 423,600 feet N., California coordinate system, zone 3. San Francisco South quadrangle, California. Merced Formation. Collectors: M. Bonilla and G. O. Gates, 1962; W. O. Addicott, 1963.

M1715. Cut and pipeline trench on north side of Arastradero Road, 1200 feet west of intersection with Page Mill Road, Palo Alto 7½′ quadrangle, California. Merced(?) Formation, late Pliocene. Collectors: E. H. Pampeyan, J. G. Vedder, and W. O. Addicott, 1963.