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THE VEGETATION ZONATION OF THE TIBETAN PLATEAU

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ABSTRACT From the first extensive study of the vegetation of Tibet it is concluded that neither the traditional altitudinal nor lowland latitudinal zonations can be applied. A special case of "high plateau zonation" is proposed. The Tibetan vegetational plateau zones are as follows from southeast to northwest: montane forest; high-cold meadow; high-cold steppe; semi-desert; and high-cold desert. This formation has resulted from the geologically recent massive uplift of the plateau and its impact on the atmospheric circulation. The Southwest Monsoon exerts a major influence on the tropical and subtropical forest zones. The main level of the plateau, however, is controlled by the Tibetan High and the Westerlies. The July mean isotherms of 9°C (in the west) and 11°C (in the east) are the determinant "high-cold" vegetation lines. The boundary between steppe and meadow closely coincides with the 400 mm annual isohyet in the north and the 500 mm isohyet in the south. The transition between steppe and desert approximates the 100 mm isohyet.

Because of its special vegetational characteristics the Tibetan Plateau must be recognized as an independent region; the montane forest zone, in contrast, is part of the Eastern and Southeastern Asiatic subtropical and tropical forest regions. Tibet is situated at the "crossroads" of the vegetation regions of the Old World and is the key to an understanding of the geographic zonality and regionalism of Asiatic vegetation. This new knowledge is also important as a basis for rational exploitation of renewable natural resources.

RÉSUMÉ *Le zonage de la végétation du Plateau Thibetain.* A la suite de la première étude poussée de la végétation du Thibet, on peut conclure que ni le zonage altitudinaire traditionnel, ni le zonage latitudinaire des régions basses ne s'appliquent ici. Un cas spécial de "zonage de hauts plateaux" est avancé. Les zones de végétation du plateau Thibetain sont les suivantes, du sud-est au nord-ouest: forêt alpine, herbages hauts-froids; steppes hautes-froides; semi-désert; et désert haut-froid. Cette formation est le résultat d'un soulèvement massif du plateau à une époque récente et de son impact sur la circulation atmosphérique. La Mousson du Sud-Ouest exerce une influence majeure sur les zones forestières tropicales et subtropicales. Néanmoins, le climat au niveau principal du plateau est déterminé par l'anticyclone Thibetain et les vents d'Ouest. Les isothermes moyennes de juillet a 9°C (à l'Ouest) et 11°C (à l'Est) déterminent en grande partie les lignes de végétation "haute-froide." La démarcation entre les steppes et les herbages coincide presque avec l'isohyète annuelle de 400 mm au Nord et l'isohyète de 500 mm au Sud. La transition entre les steppes et le désert est approximativement à l'isohyète de 100 mm.

A cause des caractéristiques particulières de sa végétation, le Plateau Thibetain se doit d'être reconnu comme une région indépendente; par contre, la zone de forêt alpine fait partie des régions forestières tropicales et subtropicales de l'Asie de l'Est et du Sud-Est. Le Thibet est situé au "carrefour" des régions de végétation du Vieux Monde; il est la clef d'une bonne compréhension du zonage géographique et de régionalisme de la végétation asiatique. Ces nouvelles connaissances sont également importantes en tant que fondation pour une exploitation rationnelle des ressources naturelles renouvelables.

ZUSAMMENFASSUNG *Einteilung in Vegetationszonen des tibetischen Plateau.* Aus der ersten umfassenden Studie über die Vegetation in Tibet ergibt sich, daß weder die herkömmliche Einteilung nach Höhenlagenzonen noch nach Tiefland-Breiten angewendet werden kann. Eine besondere "Hochland-Zonierung" wird vorgeschlagen. Die Vegetationsgürtel des tibetischen Hochlandes sind vom Südosten zum Nordwesten hin folgende: Gebirgswald, hoch-kalte Wiesen und hoch-kalte Steppe, Halbwüste und Wüste. Diese Gliederung ist durch die geologisch jüngste Erhebung des Plateaus und deren Folgen auf die Luftströmung entstanden. Der Südwest Monsun übt einen beträchtlichen Einfluß auf die tropischen und subtropischen Waldzonen aus. Das tibetische Hoch und Westwinde (Westerlies) beherrschen das Hauptgebiet des Plateaus. Die mittleren Juli-Temperaturlinien von 9°C im Westen und 11°C in Osten bestimmen die hoch-kalten Vegetationsgrenzen. Die Grenze zwischen Steppe und Wiesenland liegt im Norden an der 400 mm Linie der Jahresniederschlagsmenge und im Süden an der 500 mm Linie. Der Übergang von Steppe in Wüste liegt ungefähr bei einem Jahresniederschlag von 100 mm.

Wegen seiner besonderen Vegetationseigenschaften muß die tibetische Hochebene als selbstständige Region angesehen werden, die Gebirgswaldzone hingegen ist Teil der östlich-südöstlichen, subtropischen und tropischen Waldzonen. Tibet liegt am Scheidepunkt der Vegetationszonen der "alten Welt" und ist der Schlüssel zum Verständnis der geographischen Zoneneinteilung und regionalen Aufteilung der asiatischen Vegetation. Solches Wissen dient außerdem als Grundlage für eine vernünftige Ausnutzung der erneuerbaren Naturschätze.

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INTRODUCTION

In the past, there was little knowledge about the vegetation and ecological conditions of Tibet, the highest, largest, and youngest plateau on earth. Tibet had been considered a morainal plateau mainly occupied by monotonous cold desert. Through an investigation of the Plateau by the Interdisciplinary Scientific Expedition of Academia Sinica in recent years, we now have a new understanding of the differentiation of vegetation zones, vegetation types, basic characteristics, and ecological environments. This has also led to a more complete comprehension of the relationships between the vegetation of the Plateau and that of the surrounding areas. These relate to important problems in phytogeography and will also have significance for the rational exploitation and management of vegetation resources. This paper attempts a general statement of this recent understanding.

PLATEAU ZONALITY OF THE VEGETATION IN TIBET

During the Quaternary period, the Tibetan Plateau underwent the greatest changes of any region in the world. Since the Neogene a series of enormous and drastic geologic and climatic events has occurred. The Indian plate collided with the Eurasian plate; the highest mountain and plateau region in the world arose from the ancient sea, the Tethys Sea, which was forced far to the west; atmospheric circulations changed their routes, and some new systems were formed; and mountain glaciers progressed and withdrew repeatedly. As a result of these changes, large-scale movement and exchange took place in the floras and vegetations on the Plateau. After passing through this period of harsh natural selection and evolution, some of the specialized young plateau vegetation types emerged; for instance, the high-cold desert, steppe, and meadow. But there remain some ancient forest vegetation types which have been re-established somewhat to the south. In particular, the vegetational gradient or zonal system now peculiar to the Plateau developed.

Past treatments of the Tibetan vegetation have been undertaken by Liu Shen-E (1934), Ward (1935), Zhong Bu-Qiu (1954), Schweinfurth (1957), and others. In recent years, Zhang Jing-Wei and Wang Jin-Ting (1963, 1966) proposed the concept of horizontal zonal differentiation of the vegetation on the Tibetan Plateau. They pointed out that there is a vegetation gradient from the southeast to the northwest as follows: meadow-steppe zone, plateau steppe zone, desert-steppe zone, and plateau desert zone. Zheng Du *et al.* (1975) also mentioned that the pattern of the horizontal zones which changed from southeast to northwest was mainly determined by the moisture conditions on the Plateau. Troll (1972) described the vegetational and geographic character of the northwestern part of Tibet and the three-dimensional vegetation patterns of the Himalaya.

Vegetational zonation along these principal dimensions is present on the Tibetan Plateau, but the experience of working there and among massive mountains made us sense that the so-called "horizontal zonality," which includes the changes from south to north and from east to west, cannot be assumed merely because the local topography is level. It must also be greatly influenced by elevation. On the plains at the same latitude but at different elevations, there are very different climates and vegetations. The true zonal horizontal vegetation should be situated close to sea-level, should receive the standard amount of light and heat from solar radiation, and should have moisture conditions typical of the atmospheric circulations of the given latitude and continentality. Where the altitude is greater, the vegetation should belong to the mountain vertical vegetation or the plateau vegetation. There is not yet a generally accepted limit to the elevation of horizontal zones, and also it is impossible to define a uniform standard for the whole earth. Murry (see Good, 1964) generally defined this limit as 3,000 ft (approximately 1,000 m). Makeev (1956) considered that the general climatic structure of a lowland may not exceed to 700 to 1,000 m on average, and this is just the limit of horizontal zones. But the limit will vary in different latitudes and climatic regions. Generally, its height increases from near sea-level in the Arctic to about 1,500 m at the Equator. It will reach its highest limit, however, in the subtropical zone, especially in continental climatic regions, where it may reach up to about 2,000 m. The moisture-heat index would still be in the range of the horizontal zone in the lowland, and the same type of vegetation as the horizontal zone would be present up to that limit. As the elevation exceeds 1,500 to 2,000 m, a vertical zonation of the climate, the vegetation, and the whole biota (all of which change with increasing altitude) ensues. A vertical zonation of the vegetation which differs from the horizontal vegetation on the plains or in low mountains is formed.

The Tibetan Plateau reaches great heights. Its mean elevation exceeds 4,500 m and it extends upwards about half-way through the troposphere. Atmospheric pressure is only about 50 to 60 percent of that at sea-level, and the heat budget (cumulative temperature, summer temperature, growing season) is markedly lower than all lower elevations (less than 1,000 m) at the same latitude. Also, the patterns of atmospheric circulation, precipitation, and water-heat ratio are very different. The vegetation is mainly composed of species adapted to the high-cold, alpine conditions of mountains, though some of them occur at higher latitudes. The plateau and montane vegetation of Tibet should not be ascribed to the horizontal lowland zones, the vegetation of which is not represented at all on the Plateau.

However, the vegetation of the Plateau also cannot be considered to belong to the mountain vertical zonal vege-

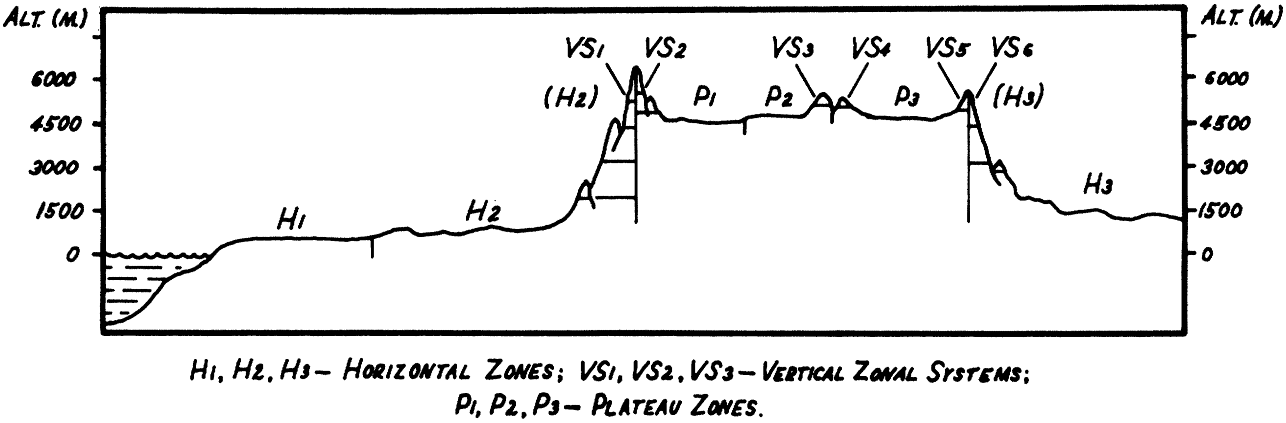

FIGURE 1. Diagram to show plateau zonation and its relationship to the standard horizontal and vertical zonations.

tation. The Plateau vegetation shows the following characteristics in zonation, ecological conditions, and vegetation physiognomies which are very different from the general mountain vegetations:

1. The vegetation zones on the mountains surrounding the Plateau fit into the mountain vertical zonational scheme, yet the main zonal differences in the vegetation on the Plateau are not caused by differences in elevation, but by horizontal gradients in moisture and temperature conditions. Nevertheless, the altitudinal variations do introduce further modifications.

2. The widths of the vegetation zones on the Plateau are much greater than those of mountain vegetation zones. Mountain vertical vegetation zones are known for their narrow width, rapid transition, extensive fragmentation, and for the complex interdigitation of their vegetation types. These characteristics are due to the complex relief of mountains. The vegetation zones on the Plateau are horizontally extensive; they are usually several hundred kilometres wide. They also have more internal continuity and uniformity, and more gradual transitions than mountain vegetation zones. In these respects, at least, the zonation of plateau vegetation is similar to the usual horizontal lowland vegetational zonation.

3. The effective heat on the Plateau is greater than on mountains of the same latitude and altitude. This is due to the heating of the great mass of the Plateau, where the summer temperature of the whole troposphere is higher than that of surrounding regions (at the same elevation). In addition, on the Plateau solar radiation is stronger and there is less moisture, so the heat loss through evaporation is also less. Therefore, the distributional limits of the vegetation types are much higher on the Plateau than on solitary or smaller mountains. For example, the upper limit of vegetation on Mt. Daxüeshan in the province of Sichuan (Guan and Zhang, 1961) and Mt. Yülongxüeshan in the province of Yünnan (Qiu and Jin, 1957) is 900 to 1,500 m lower than that on the Plateau. The snowline on the Plateau is also higher by 700 to 1,200 m.

4. There are many mountains which rise above the Plateau. On these mountains there is a series of vertical vegetation zones. The vegetation zones on the level of the Plateau are the basic horizontal zones to which these vertical zonal systems relate, much as other mountain vegetations relate to lowland zones.

5. Finally, the sheer mass of the Tibetan Plateau causes its climates to differ from those that would be characteristic of isolated mountains in this area. The climates on the Plateau are more continental and more arid because the water vapour content of the atmosphere is less than that in the free atmosphere or of a normal mountain atmosphere. This relative drought results in part from the massive "Tibetan High" that forms at a high level because of the heating effect of the Plateau. Furthermore, the high mountain ranges surrounding the Plateau produce rainshadow effects which ensure a considerable reduction in precipitation. Therefore, vegetation on the Plateau is semi-arid to arid, with xeric steppe vegetation having a dominant position. High-cold meadow vegetation is represented mainly by low *Kobresia* meadow with cryo-xeric physiognomy. The cushion plants are even more adapted to cold and dry sites and are extensively distributed on the high mountains of the Plateau, even on the poorest high-cold desert in its northwestern section. These high-cold vegetation types that are adapted to the continental climate of the Plateau are different from vegetation of subtropical mountains at the same latitudes.

Therefore the plateau zones are in part a combination of the characteristics of more ordinary horizontal and vertical zones (horizontally extensive belts, but at high elevations), in part distinctive to the Tibetan Plateau as a vast region with its own climates. The pattern may be described as "plateau zonation" of vegetation.

The major relationships between the horizontal, the mountain vertical, and the plateau vegetation zones are demonstrated diagramatically in Figure 1.

ATMOSPHERIC CIRCULATION CONDITIONS AND CLIMATIC INDICES WHICH DETERMINE THE ZONALITY OF PLATEAU VEGETATION IN TIBET

The latitudinal differences in solar radiation and temperature are basic determinants of the plateau vegetation zones in Tibet. Although the enormous height of the Plateau may tend to diminish the latitudinal temperature differences, the relief (which is higher in the northwest and lower in the southeast) compounds the effects of the latitudinal gradient of heat. Therefore, on the southern slope, there are tropical and subtropical mountain forests; in the central part, mesothermal steppe and desert vegetation prevail; and there are high-cold steppes and deserts in the north. The main ridge of the Great Himalaya provides the northern limit of tropical mountains. In the east the Himalaya extend to 29° north latitude. This is almost the northernmost limit of the tropical zone on earth. The extensive mountains, which protect the area to the south from cold air masses that move across interior Asia, permit this northward extension of the Tropics. The limit between mesothermal and high-cold climate or vegetation corresponds approximately to the mean July isotherm of 9°C in the west and 11°C in the east. South of this limit on the Plateau, or in the mountains below it, temperate vegetation occurs, mesothermal or meso-microthermal forest, steppe or desert. North of this limit on the Plateau, or above it on mountains, the vegetation changes to alpine meadow, low scrub, high-cold steppe, or desert types. However, moisture affects the plateau vegetation even more strongly than temperature.

Precipitation decreases from southeast to northwest, and provides a moisture gradient from humid and subhumid to semi-arid and arid corresponding to a vegetational gradation from forest and meadow to steppe and desert. The gradients of temperature and precipitation interact to form seven plateau vegetation zones, of which five are plateau zones (Figure 2). These are: the humid-hot tropical montane forest zone on the southern slope of the Himalaya; the moist-warm subtropical montane forest zone in southeastern Tibet; the moist-cryophilic high-cold meadow and low scrub of eastern Tibet and western Sichuan; the arid mesothermal montane steppe and shrubland zones in the Tsangpo River Valley of southern Tibet; the arid and cryophilic high-cold steppe zone of Chiangtang (northern Tibet) and western Qinghai; the arid and mesothermal montane desert zone of western Ali; and the very arid and cryophilic high-cold desert zone of northwestern Tibet. Among these the boundary between the moist meadow and forest zones and the semi-arid steppe zone corresponds approximately to the annual isohyet of 400 mm in the north and of 500 mm in the Tsangpo River Valley. The aridity* index at this limit is about 1.0. The limit between the semi-arid steppe zone and very arid desert zone corresponds approximately to the 100 mm isohyet and an aridity index of 3.5.

The particular features of the atmospheric circulation above the Plateau have a major effect on these climatic conditions. With the uplift of the mountains during the Quaternary, the Tibetan Plateau became a "hot island" in the troposphere, impeding atmospheric circulations (Yie *et al.*, 1974), and bringing about significant changes in climate and vegetation both on the Plateau and in surrounding areas. The uplift disrupted the planetary wind system resulting from the earth's rotation, and changed atmospheric circulation resulting from the temperature effects caused by the heating of the Plateau. Anomalous patterns thus caused are: the Tibetan High which forms at high elevations on the Plateau; the Mongolian-Siberian anticyclone, which develops to the north in the winter; and the summer Southwest Monsoon in the south. The climate of the Plateau, then, is largely controlled by a strong high pressure centre with continental climatic characteristics. It is also strongly influenced by two other major circulations: the tropical maritime Southwest Monsoon coming from the Indian Ocean which drenches the southeastern part of Tibet in the summer but rapidly weakens toward the inner reaches of the Plateau, and the Westerlies which control the climate of the Plateau during the winter.

The southeastern mountains of Tibet, including the southern slopes of the Eastern Himalaya and the southern part of the Traverse Mountain Ranges (Hengduan Mountains), face the humid Southwest Monsoon in summer and receive abundant rainfall. Even in winter there is a warm and moist region of convergence with low pressure and high precipitation. Due to the protection afforded by the northern mountains and the Plateau, the influences of the dry west wind and northern cold current are minimal. The humid Southwest Monsoon may extend along valleys of the Tsangpo River and the Three Rivers (the Nu, Lancang, and Jinsha rivers) into the southeastern part of the Plateau. Luxuriant montane forest vegetation grows in those parts of Tibet which are influenced by the humid maritime monsoon. Forest vegetation occurs in peripheral valleys and on the southern slopes of the Plateau, but it is never found on the level of the Plateau itself with its cold continental climate.

The Tsangpo River Valley is located in the rain shadow behind the Himalaya, and is influenced by the warming and drying foehn effect of the descending Westerlies in the winter. The precipitation is about 10 percent of that on the Himalayan southern slope. The climate is arid and warm, but the area still receives some rainfall from the portion of the Southwest Monsoon which comes up the valley in the summer, and from the weather system which is produced by the "Plateau Monsoon." The vegetation is dominated by montane steppe and xeric shrubland with a warmer climate expressed in a more mesothermal flora.

On the main level of the Plateau, the climate is controlled by the Westerlies, and a strong high-pressure system is always present. As a result, the Plateau has a conti-

*Aridity (A) = 0.16 Σ 10°C/precipitation in period of Σ 10°C. It is not well suited to the high-cold desert zone.

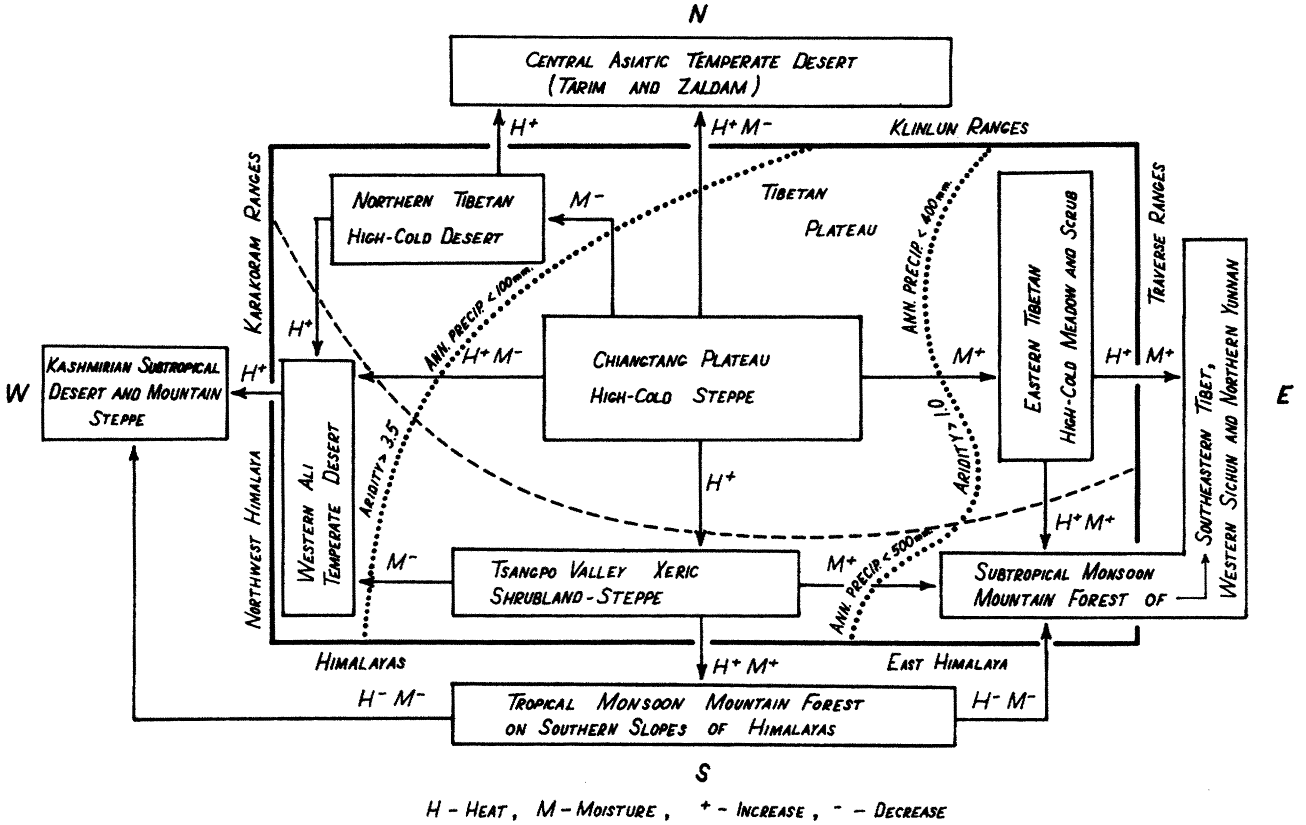

FIGURE 2. Diagrammatic representation of the vegetation zones of Tibet.

nental climate with dry cold weather, and great annual and daily temperature ranges. In the summer a thermal low, caused by the heating effect of the Plateau, draws air from lower levels up into the inner parts. In the winter, the low-pressure cell weakens or even becomes a high-pressure cell. These phenomena give rise to the peculiar "Plateau Monsoon." A convergence line exists in the central part of the Chiangtang Plateau in the summer that produces some rainfall, but the area has very strong winds and is severely cold in the winter. Consequently, arid and cryophilic high-cold steppe vegetation occupies the greater part of the Chiangtang Plateau. The centre of the thermal low is situated over the western part of the Plateau, the Ali region, its hottest and driest area. Despite converging and rising air masses, the Hindu Kush and Northwestern Himalayan ranges largely prevent moisture from reaching the area. As a result, instead of steppe, very arid true desert prevails. In the northwesternmost part of the Chiangtang Plateau, combined effects of the more northerly latitude, the higher altitude, the divergence of air masses, and the decreasing precipitation cause severely cold and arid conditions with sparse, high-cold desert vegetation.

In contrast, on the eastern part of the Plateau (the Naqü region) near the humid low-pressure centre of the source regions of the Yangtze and Yellow Rivers, there is a convergence of air-flows at about 32° north latitude, which gives rise to a more humid climate with abundant hail and thunderstorms in the summer. Tropical cyclonic storms from the Bay of Bengal bring summer rainfall, whereas the winter is very cold and snowy. This area is the wettest part of the Plateau proper, supporting mesic high-cold meadow and shrubland vegetation. The vegetation zones on the Plateau effectively express these features of the atmospheric circulation (Figures 3 and 4).

VEGETATION ZONES IN TIBET

According to the features of Tibetan vegetation which are determined by macrotopography and atmospheric circulation, two vegetation regions can be recognized: the tropical and subtropical monsoon-affected montane forest region, which is a part of the Eastern and Southern Asian forest area, and the Tibetan Plateau high-cold vegetation region. Within these two regions, according to the vegetation types as determined by water and heat conditions, there are seven vegetation zones as follows (Figure 5):

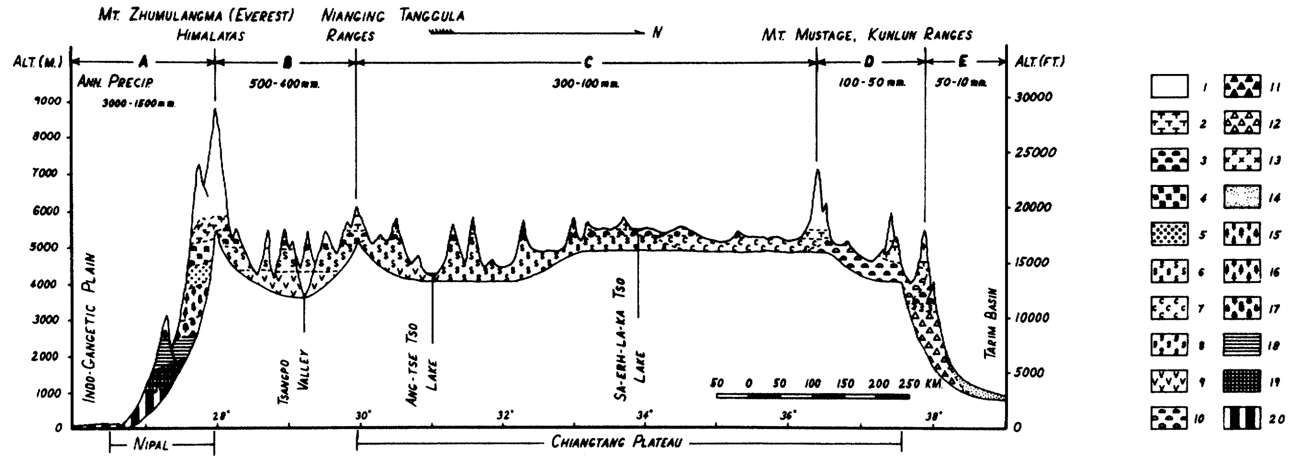

FIGURE 3. A north-south vegetational profile across the Tibetan Plateau along longitude 85° East. A. Tropical monsoon forest zone; B. Tsangpo Valley xeric shrubland-steppe plateau zone; C. Chiangtang high-cold steppe plateau zone; D. Northern Chiangtang high-cold desert plateau zone; E. Tarim temperate desert region.

Key:

1. Nival zone
2. Subnival zone with sparse alpine plants
3. High-cold cushion plant vegetation
4. High-cold *Kobresia* meadow
5. Subalpine *Rhododendron* scrub
6. High-cold steppe (*Stipa purpurea*)
7. High-cold steppe (*Carex moorcroftii*)
8. Desert-steppe (*Stipa glareosa*)
9. Temperate steppe and shrubland
10. High-cold desert
11. Steppe-desert (*Ceratoides latens*)
12. Temperate desert
13. Steppe-desert (*Artemisia* spp.)
14. Sand desert
15. Mountain coniferous forest (*Picea*)
16. Mountain coniferous forest (*Abies*)
17. Mixed needle-broadleaf forest
18. Evergreen broadleaf forest (*Quercus glauca*)
19. Evergreen broadleaf forest (*Castanopsis indica*)
20. Monsoon forest (*Shorea robusta*)

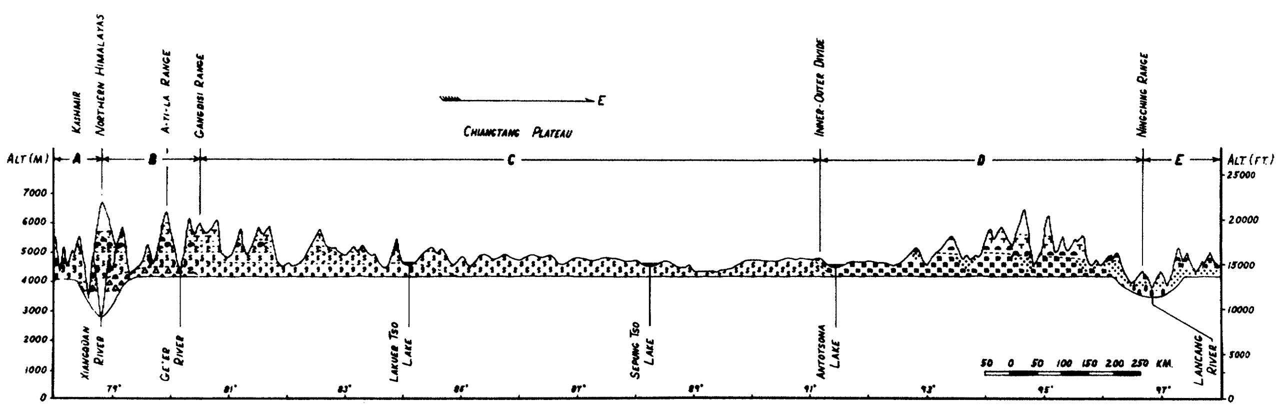

FIGURE 4. An east-west vegetational profile across the Tibetan Plateau along latitude 32° North. A. Kashmirian subtropical desert and mountain steppe region; B. Western Ali temperate desert plateau zone; C. Chiangtang high-cold steppe plateau zone; D. Naqu high-cold meadow and scrub plateau zone; E. Eastern Tibetan subtropical mountain forest zone (for *Key* see Figure 3).

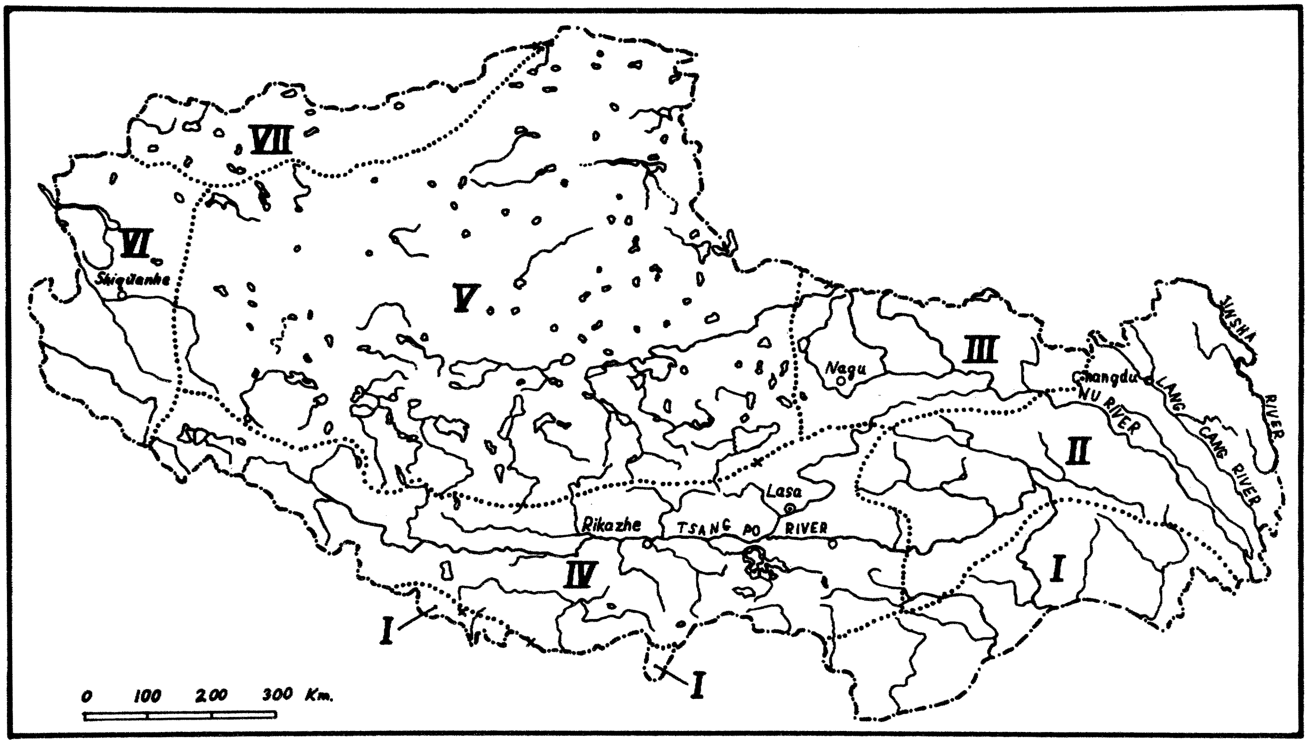

Figure 5. Map of the vegetation zones of Tibet.

Southwest Monsoon tropical and subtropical montane forest region

I. Tropical montane forest zone of the southern slope of the Himalaya.

II. The subtropical montane coniferous forest zone of southeastern Tibet.

Tibetan Plateau high-cold vegetation region

III. Naqü (eastern Tibet) high-cold meadow and low scrub plateau zone.

IV. Tsangpo (upper Brahmaputra) Valley's xeric shrubland-steppe plateau zone.

V. Chiangtang (northern Tibet) high-cold steppe plateau zone.

VI. Western Ali montane desert plateau zone.

VII. Northwestern Chiangtang high-cold desert plateau zone.

Southwest Monsoon Tropical and Subtropical Montane Forest Region

The region includes the mountain forests along the southeastern periphery of Tibet and the southern slopes of the Himalaya. To the east, it contacts the subtropical montane forests in western Sichuan and northern Yünnan. To the west, it connects with the tropical montane forests of Bhutan, Sikkim, Nepal, and western India on the southern slopes of the Himalaya. Wherever there are high mountains and gorges in the area, they are watered by the Southwest Monsoon. The major components of the vegetation are the Indo-Malayan floral element and the Sino-Himalayan floral element of Eastern Asia. If the main ridge of the Himalaya is viewed as a limit between tropical and subtropical zones, then this region may be divided into two montane forest zones.

Tropical Montane Forest Zone of the Himalayan Southern Slope

The southern slope of the Eastern Himalaya faces the Southwest Monsoon and receives abundant rainfall. Its annual rainfall generally exceeds 2,500 mm. The mean annual temperature on the lower mountains exceeds 20°C (Figure 6-1). Although there is a relatively dry season of 2 to 3 months (during which monthly rainfall is less than 100 mm), the area is always fog-bound in these months which keeps the air moist. The range in elevation in this narrow area is more than 7,000 m (from 200 to 7,765 m). Consequently, one of the most complex and perfect systems of mountain vertical vegetation zones on earth has developed on its slopes, with tropical montane rain forest in the basal zone. The vertical vegetation zonal spectrum of Moto region in southern Tibet is as follows:

a) The tropical lower montane rain forest and semi-evergreen forest zone includes the lower mountains and hills, below 1,100 m, in the Eastern Himalaya. The luxuriant tropical rain forest in the valleys consists mainly of *Dipterocarpus turbinatus, Mesua ferrea, Canarium resiniferum, Artocarpus chaplasha, Tetrameles nudiflora, Dillenia indica,* and *Talauma phelocarpa.* Most of these are evergreen trees belonging to the Indo-Malayan floral element. Some of them have prominent tropical characteristics such as plank buttresses on roots and cauliflory. Lianas (*Dendrocalamus hamiltonii, Calamus* spp.) and epiphytes are abundant in these forests. Usually *Bambusa pallida* is found in the understory, and *Pandanus furcatus* is present in gaps. On the slopes of the lower mountains, 600 to 1,000 m, there are tropical montane semi-evergreen forests mainly consisting of semi-deciduous gigantic trees, such as *Dysoxylon gobara, Terminalia myriocarpa,* and *Altingia excelsa,* and luxuriant lower tropical evergreen trees (e.g. *Beilschiedia, Cinnamomum*). Lianas and epiphytes are also abundant.

b) The montane evergreen broadleaf forest zone lies at elevations between 1,100 and 2,200 m, and can be divided into upper and lower parts. The lower subzone is dominated by *Castanopsis histrix* and *C. indica,* and is mixed with many tropical evergreen broadleaf trees, such as *Machilus, Machilia, Cinnamomum,* and *Phoebe,* belonging to the Lauraceae, and *Magnolia, Engelhardtia spicata,* and *Schima wallichii.* At forest edges there is usually *Alsophila* present. The forests of the upper subzone consist mainly of *Quercus lamellosa, Q. glauca* var. *gracilis,* and *Lithocarpus xylocarpus.* In addition to some further species of evergreen broadleaf trees, deciduous trees are increasingly common. These include *Acer* spp., *Alnus nepalensis, Mallotus nepalensis, Carpinus viminea,* and the arborescent *Rhododendron.*

The zone of the montane evergreen broadleaf forest is very humid, with annual rainfall that may exceed 3,000 mm. Trunks of trees and the ground are often fully covered by thick mosses. It can be called a "mossy forest," but it differs from the low "elfin" forests and the mossy forests in other tropical mountains in its much taller trees.

c) The montane mixed coniferous and broadleaf forest zone lies between 2,200 and 2,800 m and is dominated by *Tsuga dumosa,* which sometimes mixes with *Quercus pachyphylla* and *Q. lamellosa* to form mixed evergreens, coniferous, and broadleaf forests. Also present are *Taxus baccata, Magnolia campbellii, Acer campbellii, A. pectinatum,* and *Rhododendron* spp. *Arundinaria griffithii* often is present in the understory, and ferns are very abundant in ground herbaceous layers.

d) The upper montane dark coniferous forest is located between 2,800 and 3,600 (or 3,900) m. The climate is wet, cold, and always foggy. The vegetation is dominated by *Abies delavayi* var. *motuoensis,* and has a large amount of *Rhododendron* spp. and *Sinarundinaria* as understory. *Larix griffithii* often is present on open ground, and *Betula utilis* forms "krummholz" at the upper forest line.

e) The subalpine *Rhododendron* shrubland and meadow zone is situated between 3,600 (3,900) and 4,000 (4,200) m and transitional from forests to the alpine zone. The luxuriant subalpine shrubland consists of many *Rhododendrons: R. campanulatum, R. barbatum, R. lepidotum,* and others, with deciduous shrubs such as *Salix, Rosa, Cotoneaster, Viburnum,* and *Lonicera,* and interspersed luxuriant forb meadows.

f) The alpine scrub and meadow zone occurs between 4,000 (4,200) and 4,600 m. The alpine dense scrub consists of lower *Rhododendron setosum* and *R. nivale.* The alpine meadow contains abundant species of colourful forbs. Most of them belong to the Sino-Himalayan floral element. Because the seasonal changes are great, and in the winter there is a thick snow deposit on the alpine zone of the Himalaya, the alpine vegetation there does not have tropical characteristics and belongs to subtropical or temperate types. Thus a meeting of the essentially temperate-zone alpine vegetation type with tropical lower montane forests is a special characteristic of the vertical zonal spectrum on the northern periphery of tropical mountains.

West of Bhutan, the climate of the Himalaya becomes progressively drier, and there is a well-developed arid season. The tropical monsoon forest consists of deciduous *Shorea robusta* instead of the tropical rain forest on the lower hills. In the upper montane coniferous zone, the more drought-resistant *Picea smithiana* and *Larix griffithii* occur. In the alpine zone, the eastern Himalayan forb meadow is replaced by a *Kobresia* meadow.

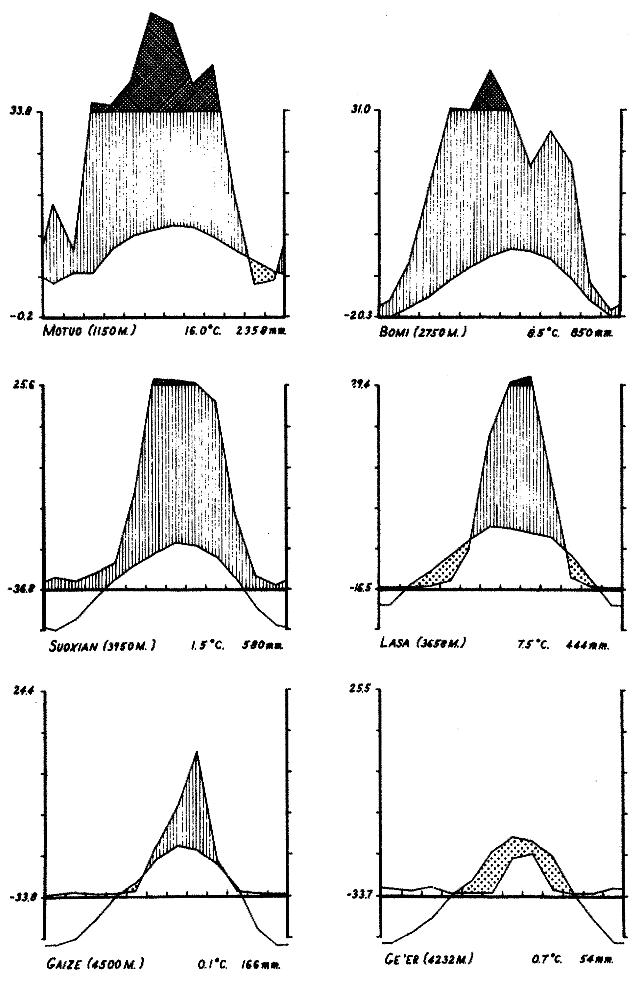

FIGURE 6. Climatic diagrams for vegetation zones I to VI.

Subtropical Montane Coniferous Forest Zone of Southeastern Tibet

The zone includes mountains and valleys along the middle reaches of the Tsangpo (Brahmaputra) River, its tributaries (Niyan, Yegongqu, and Polong-Tsangpo), and three eastern rivers (Nu, Lancang, and Jinsha). These rivers cut deeply into the southeastern part of the Plateau. The humid Southwest Monsoon passes through their valleys and penetrates into this corner of the Plateau. The dense forest vegetation is distributed correspondingly on the valley slopes. The rainfall is obviously less than that on the southern slopes of the Himalaya, varying between 500 and 1,000 mm (Figure 6-2). Northward along the upper rivers onto the inner part of the Plateau the forest vegetation becomes sparse and vanishes as a consequence of decreasing moisture.

The lowest elevation in this area is above 2,000 m, and the basic topography is of mountains and valleys (the Plateau has been strongly eroded, and only fragments of the original surface remain). The vegetation consequently all belongs to the montane vertical-zoned types. The basic vegetation zones are:

a) Subtropical evergreen-broadleaf forests, which are distributed widely along the eastern periphery of the Plateau (Western Sichuan and Northern Yünnan), occur in only a very limited region in Tibet: the Tongmai Valley to the north of the great curvature of the Tsangpo River which is reached by humid and hot air currents and supports subtropical evergreen-broadleaf forests between 2,000 and 2,500 m. These forests consist mainly of oaks (*Quercus incana* and *Q. gilliana*) and contain abundant subtropical Eastern Asian floral elements. Because the elevation of most valleys in this region exceeds 2,500 m, the subtropical broadleaf zone usually is not present here.

b) From 2,500 to 3,200 m there is a lower montane mixed coniferous and broadleaf forest zone or coniferous forest zone. On southern slopes it is composed of forests of *Pinus densa, Quercus aquifolioides,* or mixed forest of both species. Forests of *Pinus armandii* exist where it is a little more moist. On northern slopes forests composed mainly of *Picea balfouriana* (in the eastern part) or *P. likiangensis* var. *linzhiensis* (in the western part) extend from 2,500 to 3,200 m. Usually this is the basic subzone of the upper montane dark coniferous forest zone. The biomass of this spruce forest is immense. The height of trees may be more than 60 m, and the timber volume can reach over 1,500 m^3/ha. Under spruce forest canopies, there is abundant undergrowth: *Enkianthus deflexus, Lindera cercidifolia, Litsea cubeba, Acer campbellii, Rhus succedanea, Deutzia corymbosa, Rhododendron* spp., and *Sinarundinaria spathiflora.* The moss layer is very well developed.

c) From 3,200 to 4,000 m or somewhat higher, there is a dark-coloured coniferous forest zone consisting of *Abies delavayi* (in the eastern part) or *A. spectabilis* (in the western part). The most common undergrowth species are: *Rhododendron houlstani, R. przewalskii, Sorbus* spp., *Rosa omeiensis, Lonicera succata, Deutzia corymbosa,* and *Sinarundinaria spathiflora.* Most of these undergrowth and herb species in the coniferous forests belong to Eastern Asian floral elements (Sino-Himalayan element). Some boreal elements (*Vaccinium* spp., *Bergenia, Chamaenerion angustifolium, Circaea alpina, Fragaria vesca, Polygonum viviparum, Thalictrum alpinum,* especially, and some mosses) appear in the upper montane forest regions, and the subtropical evergreen broadleaf forest floral element dominates in the lower montane regions.

In the northern part of this forest region, the climate becomes drier and colder. In the upper part, particularly on southern slopes, the forests are often composed of *Juniperus (Sabina) tibetica* and *J. convallium.* Their upper limits reach 4,300 or even 4,600 m. On the western edge of this region where the forest vegetation changes gradually to steppe, the humid dark coniferous forest zone disappears, and a sparse coniferous forest of *Cupressus gigantea* is present and merges into steppe vegetation.

d) The transitional alpine vegetation above treeline is low *Rhododendron* scrub (*R. ramosissimum, R. nivale, R. anthopogon*) on northern slopes and *Cassiope fastigiata* scrub on southern slopes. The alpine meadow which consists mainly of *Kobresia angusta* and *K. pygmaea* occupies higher areas above the scrub vegetation. Some alpine herbs are often present in the meadow, among them *Polygonum viviparum, Anaphalis nepalensis, Gentiana* spp., *Meconopsis horridula, Oxygraphis polypetala,* and *Thalictrum alpinum.*

A special case should be mentioned. In the hot and dry valleys of the Three Rivers, the coniferous forest vegetation is distributed only on upper slopes, whereas the valley bottoms are occupied by xeric thorny scrub which consists mainly of *Sophora vicinifolia* and *Elsholtzia capituligera,* sometimes with cacti (introduced *Opuntia*).

TIBETAN PLATEAU HIGH-COLD VEGETATION REGION

The extensive plateau between the Himalayan and Kun Lun Mountain Ranges has relatively low mountains, platform plateaus, and lake and valley basins. The elevation of the main plateau level is about 4,500 m in the southeast and over 5,000 m in the northwest. Some valleys in the south may extend down to approximately 3,000 m. The Plateau is controlled by the Westerlies in the winter half of the year, and has an arid, cold, and continental climate. From east to west, with increasing drought, the high-cold meadow, steppe, and desert vegetation occur in sequence. The flora of the eastern meadow zones is dominated by Tibetan endemic species and Sino-Himalayan elements. The flora of the central and western steppe and desert zones is dominated by Central Asiatic (Tethys) elements and Tibetan endemic species.

Naqü (Eastern Tibet) High-Cold Meadow and Scrub Plateau Zone

The elevation of the Plateau in eastern Tibet is approximately 4,000 to 4,500 m. Although the landscape is more eroded here than in western Tibet, it remains a prominent and relatively complete plateau plain. The climate is cold and somewhat moist. The annual mean temperature is between −3.0 and 0°C. The mean temperature of the warmest month is 8-10 (12)°C, and the frostless season is

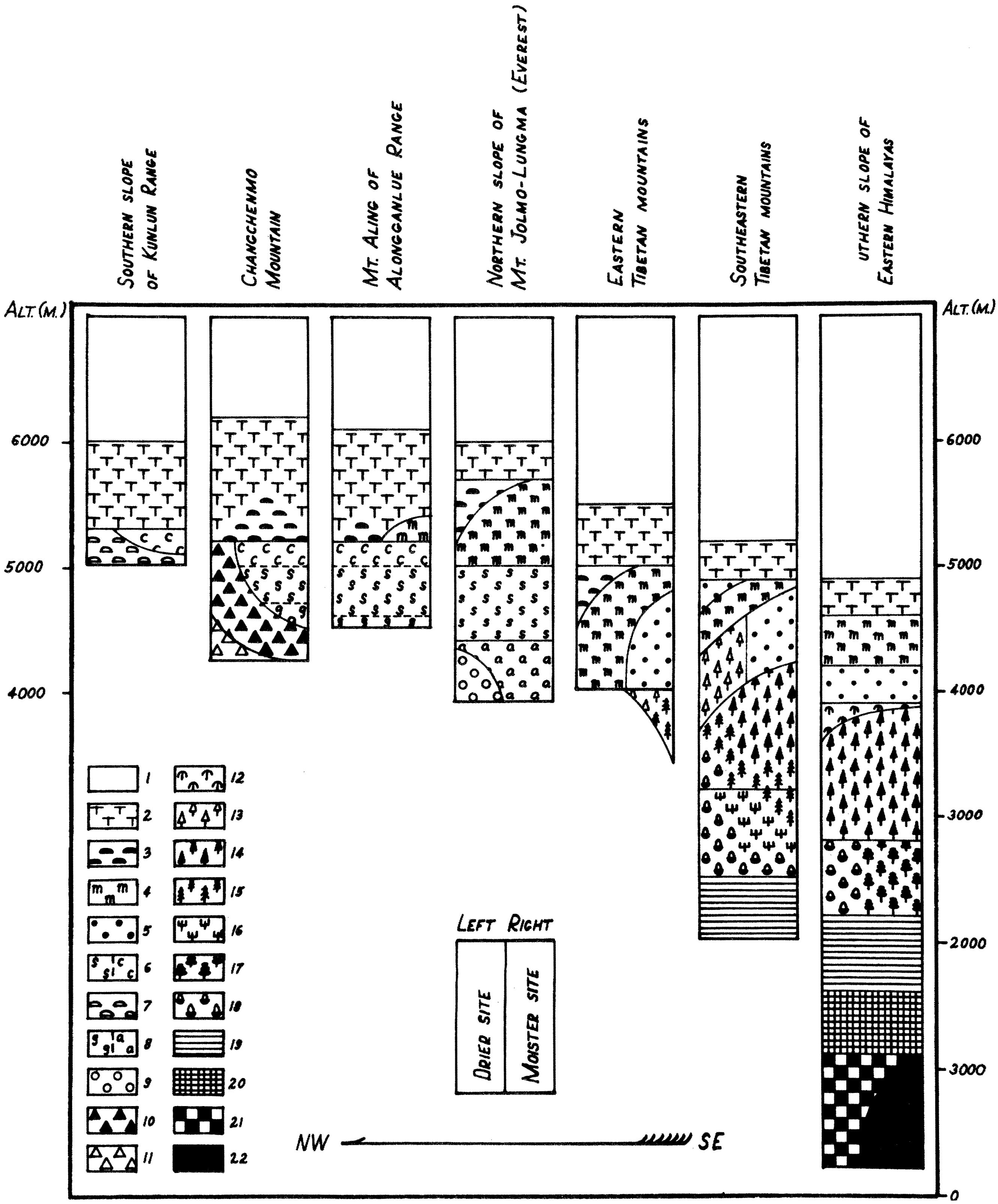

Figure 7. Vertical zonal systems for the seven horizontal and plateau zones of Tibet.

Key:

1. Nival zone
2. Subnival zone with sparse alpine plants
3. Cushion plant vegetation
4. Alpine or high-cold meadow (*Kobresia pygmaea*) (to be continued at bottom of opposite page)

from 20 to 100 days. The annual rainfall is 400-700 mm. There are thunderstorms with hailstones in the summer, and relatively abundant snow accumulation in the winter and spring (Figure 6-3).

Judged by its vertical zones, vegetation of this Plateau zone seems much like an extension of the upper part of the preceding mountain forest zonation onto the Plateau. In the valleys of its southeastern part fragmentary coniferous forests persist. On the Plateau proper there is extensive high-cold meadow which consists mainly of low-growing *Kobresia pygmaea* and *K. humilis,* usually associated with *Polygonum sphaerostachyum* and other forbs, including *Thalictrum alpinum, Anaphalis xylorrhiza, Leontopodium pusillum, Carex atrata* var. *glacialis, Meconopsis horridula, Polygonum viviparum, Potentilla stenophylla, Pedicularis, Gentiana,* and cushion plants such as *Arenaria musciformis* and *Androsace tapete.* High-cold evergreen sclerophyllous scrub, composed of microphyllous *Rhododendron, R. cephalanthus,* and *R. setosum* on northern slopes, and deciduous shrubs of *Salix* spp., *Potentilla fruticosa,* and *Caragana jubata* in valleys or on southern slopes, are always found in conjunction with the high-cold meadow. In level areas and swampy valleys there occur high-cold swampy meadows with a mound-like growth-form of *Kobresia littledalei.*

Westward, as the climate becomes drier, the importance of mesic forbs decreases gradually, leaving almost pure *Kobresia* meadow. Finally, some steppe species appear in the community, and the *Rhododendron* scrub disappears to be replaced by *Juniperus* spp. on the inner Plateau.

The high-cold *Kobresia* meadow differs in floristic composition, community structure, and other ecological features from the humid dicotyledonous alpine meadows of the Alps or other moist-temperatemountains, and the alpine tundras of higher latitudes. This vegetation is referred to as "Tibetan high-cold meadow." It has evolved under drier and harsher high mountain and plateau conditions with continental climates.

By its ecological features and phytogeographic situation, *Kobresia* meadow appears to be a transitional or intermediate type between cryo-mesic alpine meadow and cryo-xeric high-cold steppe. It develops a compact tussock physiognomy and has a series of typical mesic meadow species but its dominant, *Kobresia,* has xeromorphic characteristics and it contains some xeric steppe species (Lubtsov, 1966; Zhou Xin-Ming, 1978). In fact, the *Kobresia* meadow zone is situated between the humid alpine meadow and mountain forest vegetation zone in the east, and the arid high-cold steppe plateau zone in the west. The range of *Kobresia* meadow is mainly the Tibetan Plateau and its surrounding mountain regions[1], such as the Pamir, Kun Lun, Tien Shan, Qilian, Altai, Hangai, and Traverse Mountains, northward to the Ural and Caucasus. Its centre[2] is an inland mountain and plateau area with an extremely continental climate. In its floristic features (with the exception of a few species representing boreal elements), most species of *Kobresia* belong to Sino-Himalayan elements endemic to Tibet and Central Asia.

Tsangpo (Upper Brahmaputra) Valley Xeric Shrubland and Steppe Plateau Zone

The Tsangpo Valley, located between the northern piedmont of the Himalaya and Nyenching-Tangula and Gangdisi Mountains, is a subduction zone at the margin of two continental plates. It extends east-west through the south section of the Plateau. Its altitude increases westward from 3,500 m to 4,500 m. Because of the rain-shadow effect of the Himalaya, annual precipitation is generally between 300 and 500 mm and decreases gradu-

[1]A rather small disjunct area of *Kobresia* meadow occurs in the Rocky Mountains of North America.

[2]According to Ivanova (1939), there are two original centres of *Kobresia.* One of them is Kun Lun and another the high latitudes of Angaraland in Siberia, but the centre of species diversity for the genus is in the southeastern periphery of Tibet.

5. *Rhododendron* scrub
6. High-cold steppe (*Stipa purpurea, Carex moorcroftii*)
7. High-cold desert (*Ceratoides compacta*)
8. Temperate steppe (*Stipa glareosa* or *Aristida triseta, Stipa bungeana, Pennisetum flaccidum, Orinus thoroldii*)
9. Xeric shrubland (*Sophora moorcroftiana, Ceratostigma griffithii, Leptodermis sauranja*)
10. Mountain steppe-desert (*Ceratoides latens, Stipa glareosa, S.* spp.)
11. Temperate mountain desert (*Ceratoides latens*)
12. Krummholz (*Betula utilis*)
13. Coniferous forest (*Juniperus* spp.)
14. Coniferous forest (*Abies* spp.)
15. Coniferous forest (*Picea* spp.)
16. Coniferous forest (*Pinus* spp.)
17. Mixed needle-broadleaf forest (*Tsuga dumosa*)
18. Sclerophyllous forest (*Quercus lamellosa, Q. aquifolioides*)
19. Upper evergreen broadleaf forest (*Quercus incana, Q. gilliana, Q. lamellosa, Lithocarpus xylocarpus*)
20. Lower evergreen broadleaf forest (*Castanopsis histrix*)
21. Semievergreen forest
22. Rain forest

ally from east to west. In Pulan, west of the headwaters of the Tsangpo River, annual precipitation is less than 200 mm. Mean annual temperatures are between 4 and 8°C. The mean temperatures of the warmest month vary between 10 and 16°C (Figure 6-4). Sunshine is abundant and the growing season is longer than that of the high-cold meadows.

Lower elevation, more southerly latitude, and stronger solar radiation warm the valley and permit cultivation of some crops and vegetables such as barley, wheat, buckwheat, peas, potato, rape, cabbage, turnip, and carrot. Some fruit trees may also be cultivated; apple orchards occur at altitudes of up to 4,200 m (Jiangzi) and produce very sweet fruits.

The slopes on both sides of the valley are occupied by steppe and shrubland vegetation. The dominants of the steppe are mesothermal xeric grasses and forbs: *Aristida triseta, Stipa bungeana, Pennisetum flaccidum, Orinus thoroldii, Artemisia webbiana,* etc. Xeric shrubs such as *Sophora moorcroftiana, Leptodermis sauranja,* and *Ceratostigma griffithii,* are mixed with steppe vegetation, or are found in association as distinct shrubland communities.

FIGURE 8. Dark coniferous forest of *Picea likiangensis* var. *lintziensis* in the Tsangpo Valley at 3,200 m.

FIGURE 9. High-cold meadow of *Kobresia pygmaea*. The mud-crack and flow on the surface is caused by freeze-thaw processes.

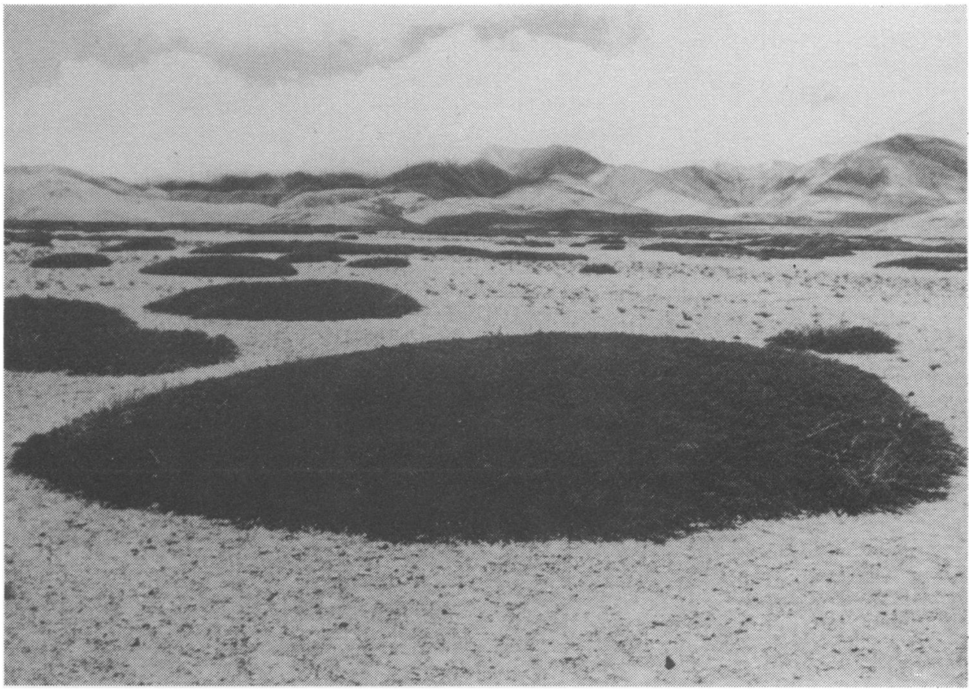

FIGURE 10. Xeric shrubland of *Caragana versicolor* in the western Tsangpo Valley at 4,300 m.

Above about 4,400 m, the slope vegetation changes from mesothermal steppe to high-cold steppe which is dominated by *Stipa purpurea*. The shrubland vegetation of *Potentilla fruticosa, Lonicera tibetica* (in the east), and *Caragana versicolor* (in the west) occurs widely in this range in conjunction with the steppe communities. On the southern slopes of the Gangdisi and Nyenching-Tangula ranges, there are extensive *Juniperus* shrubland communities in the steppe zone.

From 4,600 to 5,400 m in the east and 5,000 to 5,600 m in the west, the mountains and plateaus are occupied by high-cold meadow and cushion plant vegetation. These are composed mainly of *Kobresia pygmaea* and the cushion plants *Arenaria musciformis, Androsace tapete,* and *Oxytropis chiliophylla*. The *Kobresia* meadow usually occupies relatively flat or gentle, stable slopes with rather well-developed soil. On the steep or rocky slopes there is sparse cushion plant vegetation. The latter extends down into the lower steppe zone and forms a special cushion plant-steppe vegetation type there.

Above 5,400 (5,600) m and to approximately 6,000 m, there is a subnival zone where sparse alpine forbs (*Saussurea, Saxifraga, Gentiana, Draba, Braya, Androsace, Potentilla*) grow in rock fractures and on slopes of rock debris. The surfaces of rocks are covered with lichens (e.g. *Rhizocarpon geographicum, Glypholecia scabra, Caloplaca elegans, Parmelia consporsa*). The nival zone begins between 5,800 and 6,200 m.

Along the western edge of the valley steppe region, in the Pulan Valley and the basin of Mafamutso and Langaktso lakes, the climate and vegetation tend toward desert. Mountain desert-steppe vegetation consisting of *Stipa glareosa* and *Ceratoides latens* occurs there and is characteristic of the transition from steppe plateau zone to desert plateau zone.

Chiangtang (Northern Tibet) High-Cold Steppe Plateau Zone. "Chiangtang" means "Northern great plain" in Tibetan. It extends between the Gangdisi, Nyenching-Tangula, and Kun Lun ranges. It is a whole plate which uplifted at the end of the Tertiary, and is a landform consisting of a plateau basin of gently undulating plains with abundant scattered lakes. The level of the plateau rises gradually from 4,500 m in the south to 5,200 m in the north. The climate is cold, arid, and quite windy. The mean annual temperature ranges between −2 and 0°C; the mean temperature of the warmest month between 6 and 10 (12)°C. During 6 to 7 months the mean temperatures remain below 0°C. The temperature is much lower northwards, and continuous permafrost is widespread. The diurnal and annual temperature ranges are very high. The annual precipitation varies between 100 and 300 mm (Figure 6-5), concentrated in the summer and decreasing from southeast to northwest.

The most extensive vegetation zone on the plateau is the steppe of *Stipa purpurea,* the centre of distribution for which is the Chiangtang Plateau. The typical high-cold steppe community of purple feathergrass is rather sparse, with plant coverage never more than 20 percent. Usually there are some cushion plants (e.g. *Arenaria musciformis, Androsace tapete, Thylacospermum rupifragum*) in the community. On different parts of the Chiangtang Plateau, the high-cold steppe of purple feathergrass shows some prominent ecological differentiation. Along the east and southeast periphery of Chiangtang, there is a transitional section between the high-cold meadow zone and the high-cold steppe zone. There, *Kobresia pygmaea* and some mesic forbs occur in the steppe communities, and the plant cover in general is somewhat more complete. Northwards, since the altitude increases, the climate becomes colder and drier and the vegetation gradually changes to

FIGURE 11. High-cold steppe of *Stipa purpurea* on the Chiangtang Plateau at 4,900 m.

high-cold desert; *Carex moorcroftii* becomes more important with increasing altitude. Finally, the high-cold desert-steppe of *Carex moorcroftii* and *Ceratoides compacta* is dominant in the northernmost part of Chiangtang. Conversely, in the southern part of Chiangtang, since the climate is a little warmer and moister, some mesothermal plant elements (e.g. *Orinus thoroldii, Pennisetum flaccidum, Artemisia wellbyi,* the shrub *Caragana versicolor*) are present. Westwards, as the climate becomes drier and warmer, in large lake basins are found steppes of *Stipa glareosa* (of the desert-steppe flora of Central Asia) and *Stipa subsessiliflora* var. *basiplumosa.* Here, the steppe vegetation is transitional toward desert. However, the plain and the lower mountains of the Plateau are still dominated by the steppe vegetation of purple feathergrass.

Most of the mountains on the Chiangtang Plateau are relatively low. Although their absolute height may be more than 6,000 to 7,000 m, their height relative to the Plateau is only between 500 and 1,000 m. The spectrum of vertical zonation of vegetation is rather simple. Usually the basic zone of high-cold steppe of purple feathergrass is replaced by high-cold meadow-steppe of *Carex moorcroftii* with increasing altitude. Therefore, there are two subzones of the high-cold steppe zone. At even higher altitudes, there exists the subnival zone with sparse alpine plants. On a few high mountains with more extensive glaciers and snow fields, there may exist some patches of alpine *Kobresia* meadow. This is also found along the northern slopes of the Gangdisi and Nyenching-Tangula ranges. Above the high-cold steppe zone there is an alpine steppe-meadow zone which is composed of *Kobresia pygmaea* and cushion plants.

Before these investigations of Chiangtang, it was thought that most of the Plateau was covered by high-cold desert. These findings have important theoretical and practical meaning for an understanding of the pattern and nature of vegetation and the physiographic zonation of Tibet.

Western Ali Mountain Desert Plateau Zone

On the western edge of Tibet, between the northwestern Himalaya and Karakoram ranges, there is a series of mountains and valleys called the Ali region. The elevation of the valleys is 3,000 m in the south and 4,300 m in the north. This region experiences the driest climate in Tibet. The centre of the summer thermal low of Tibet is located here, and this is also the hottest region on the Plateau. The July mean temperature is 15°C, but may be as low as -10°C in the winter. The annual precipitation is no more than 50-75 mm. The aridity is in the range 3.4 to 6, with a drought period of between 5 and 6 months during the growing season (Figure 6-6). Therefore, this region has a cold temperate steppe desert or desert climate.

The plateau zonal vegetation is a desert community which consists of suffrutescent *Ceratoides latens* (Tethys flora), *Ajania fruticulosa* (Central Asiatic flora), and the endemic perennial *Christolea crassifolia.* The driest core of desert is in the Bangong Mountains and the Chiangchenmo Mountains which surround Bangong Tso and Spangul Tso in the northwestern part of the region. This is a region of rocky desert with almost no vegetation; there is only a very sparse growth of *Ceratoides latens.* Above 4,500 m, some feathergrasses (*Stipa glareosa, S. subsessiliflora, S. breviflora*) enter the desert community with

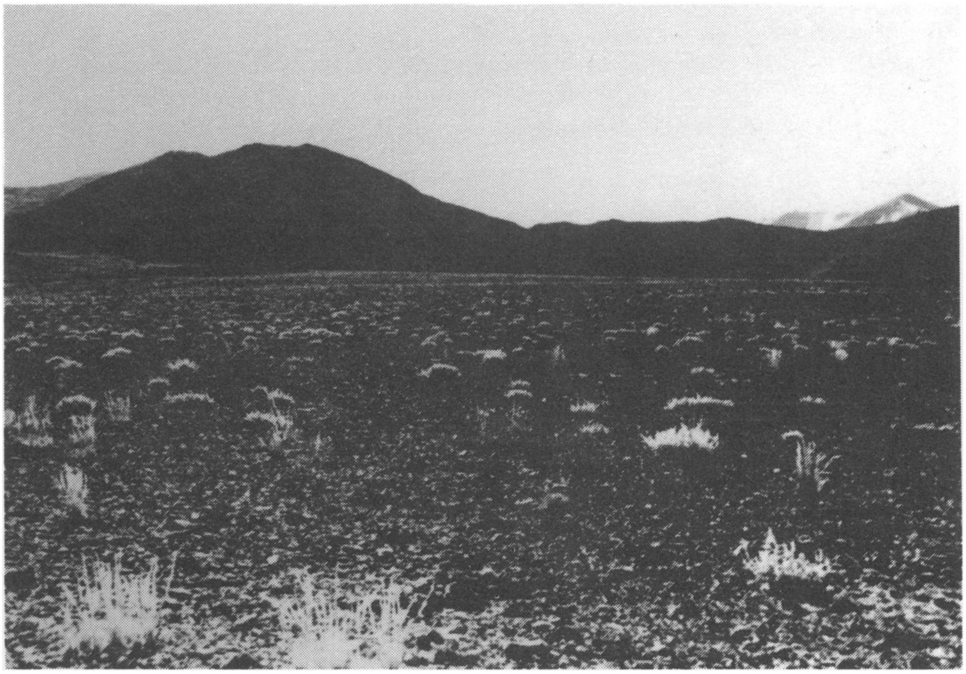

FIGURE 12. Steppe-desert of *Ceratoides latens* and *Stipa subsessiliflora* var. *basiplumosa* in the Qiangchenmo Shan, Karakorum Range, at 5,100 m.

Ceratoides latens, changing the vegetation to steppe-desert, and this community extends up to 5,200 m on Mount Chiangchenmo. This may be the world's highest desert. In south Ali, the climate is a little more moist. The Shiquanhe (Indus) River Valley, Ge'erqu River Valley, Xiangquanhe (Sutlej) River Valley, and the surrounding lower mountains are occupied by mountain steppe-desert vegetation which consists mainly of *Ceratoides latens, Ajania fruticulosa, Stipa glareosa,* and some xeric shrubs (*Ephedra gerardiana* and *Caragana versicolor*). The desert community develops vigorously there because of relatively abundant snowfall in the winter and the spring. Some ephemeral plants (*Tauscheria lasiocarpa, Koelpinia linearis*) are present in the desert.

In the southwestern corner of Ali, where the Xiangquanhe Valley falls to 2,900 m, the climate is warmer. Some Mediterranean subtropical elements such as *Colutea arborescens,* are present there. The dominants of the desert

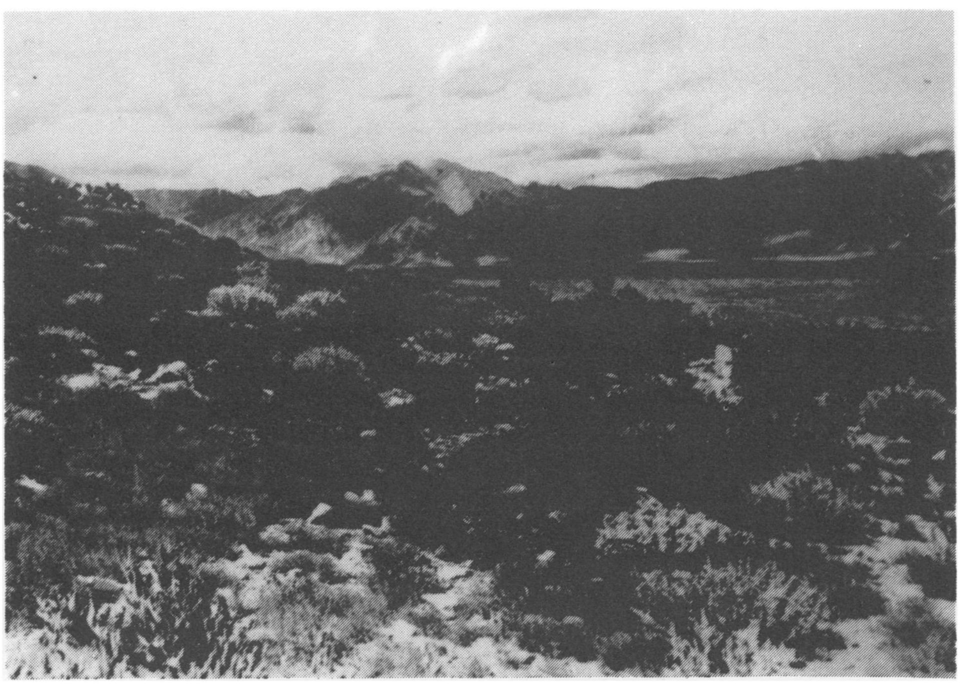

FIGURE 13. Semidesert community of *Bassia dasyphylla* and *Ceratoides latens,* Bird Island, Bangong Lake, at 4,250 m.

vegetation are species with more Tethystic and Central Asiatic affinities such as *Artemisia salsoloides*, *A. sacrorum*, *Scorzonera*, *Ceratoides latens*, *Capparis spinosa*, *Kochia*, *Polygonum paronychioides*, and *Stipa stapfii*. These reflect a change toward the subtropical desert in the Kashmir Valley.

The vertical zonation of mountain vegetation in western Ali has a spectrum of desert types, too. The structure of the vertical zones is as follows: desert or steppe-desert zone (basic zone), giving way to steppe zone, giving way to high-cold cushion plant vegetation zone, finally yielding to the subnival zone.

The mountain steppe zone can be divided into two or three subzones. The lower one is a desert-steppe subzone, which is mainly composed of *Stipa glareosa* and *Ceratoides latens*, the former being the dominant. The intermediate subzone exists only in southern mountains of the area and is formed by the conjunction of mountain shrublands (consisting of *Caragana versicolor*) and steppe communities (the dominants are *Stipa glareosa*, *S. breviflora*, and *S. purpurea*). The upper subzone is a high-cold steppe subzone which consists of *Stipa purpurea* and *Carex moorcroftii*. North of about latitude 33° in Ali, the shrubland of *Caragana versicolor* disappears, leaving the steppe zone with only the two other subzones.

The high mountains of Ali usually lack alpine meadows except for some isolated patches under moist conditions. The typical high mountain vegetation there is of sparse cushion plants, mainly *Arenaria musciformis* and *Thylacospermum caespitosum*. The upper vegetation line reaches almost to 5,600 or 5,700 m. The upper limit of the agricultural cultivation is also very high. On the southern slopes of the Karakoram Range at latitude 34° bare barley is grown to 4,780 m, and can be harvested in most years.

The finding of the mountain desert vegetation in western Ali not only completed the vegetation zonation of the Tibetan Plateau, but also expanded the known distribution of desert to new high altitudes.

Northwestern Tibetan High-Cold Desert Plateau Zone.

The northwestern part of the Chiangtang Plateau is located between the Kun Lun and Karakoram ranges. The elevation of the Plateau and lake basins is over 5,000 m. Here is the coldest and driest climate of the Plateau. The mean annual temperature is about -8 to -10°C. There are 9-10 months in which the mean monthly temperature is lower than 0°C, with no frostless season in the year. Even in the warmest part of the year, there are heavy frosts every night and an extensive permafrost horizon generally exists there. The annual and diurnal temperature ranges are rather high. The mean annual precipitation is only 20-50 mm, all in frozen forms. Eastward, the precipitation is somewhat greater, about 100-150 mm. The wind is very strong and frequent.

Because of the extremely severe ecological conditions and the shorter history of vegetation development after the uplift of the Plateau, the vegetation is very sparse and rather poor in species. Usually one is presented with a vast expanse of plateau gravel or Gobi without plants, or many bare rocky slopes and hilltops. The plateau zonal vegetation is sparse high-cold desert, which has evolved during the time since the Plateau was uplifted. It is composed of cryophytic-xeric cushionlike nano-suffruticose *Ceratoides compacta*. These plants exist on debris or gravel slopes, and especially on vast ancient lake plains formed by lake sediments. The soil contains high concentrations of salt and has permafrost. The salt in the soil may be due to the evaporation of an ancient salt lake, coupled with the low precipitation which causes continual salt accumulation.

Very low temperatures, very short or non-existent growing season, severe drought, high wind, and barren, rocky, and salty soil are typical ecological conditions for the high-cold desert plateau zone. The plant coverage of a high-cold desert community of *Ceratoides compacta* usually is never more than 8 percent, and often as little as 1-2 percent. Companion species are very few (*Pegeophyton scapiflorum*, *Hedinia tibetica*). The only woody plant in the high-cold desert zone is *Myricaria hedinii*, which grows along river beds. Its branches and trunks are entirely underground, and only its branchlets with small leaves are exposed on the ground surface. This plant forms a dense cushion, no more than 1 cm above the ground.

Eastward from longitude 80° on the Plateau, the high-cold desert vegetation prevails. The wide lake plain is occupied by high-cold desert of *Ceratoides compacta*, but the piedmont slopes and steppes are covered by high-cold desert-steppe which is dominated by *Carex moorcroftii* with some *Ceratoides compacta*. The vegetation on the mountainsides on both sides of the lake plain is more vigorous than on the plain itself. This may be caused by a persistent temperature inversion. The structure of the vertical zonal spectrum is very simple. Above the basic vegetation zone of high-cold desert and desert-steppe, there is a narrow zone of high-cold steppe consisting of *Carex moorcroftii*. Its vertical range is not wider than 200 m and its upper limit is at 5,300 m. Above this, a subnival zone with some sparse alpine herbs (such as *Saussurea gnaphaloides*, *Melandrium apetalum*, and cushion plants) is found. The snowline lies between 6,000 and 6,200 m.

GEOGRAPHIC VEGETATIONAL REGIONS OF TIBET

Statistical analysis of the Tibetan flora and a knowledge of its historical development are required to address the question of floral affinities. However, the principle and basis of regionalization of vegetation is somewhat different from that of floras. In floral regionalizations one usually considers the whole flora of the area with concern for the distributions and geographic affinities of species and higher taxa. But for description of vegetational regions, one is concerned primarily with vegetation types and their geographic relationships, and particularly the geographic distributions of the dominant species. Research on the ecological and geographical characteristics of Tibetan vegetation offers clues for interpretation of its regional relationships.

Either according to the features of the vegetation or based on the characteristic floral elements, the subtropical and tropical mountain forest vegetation zones in southeastern Tibet should be classified as Eastern Asiatic subtropical forest and Southern Asiatic tropical forest. The former passes through the Traverse Mountain Range and connects with the subtropical mountain forest in western Sichuan and northern Yünnan. They have, however, different species of forest dominants. Most of the forest dominants of eastern Tibet belong to the Sino-Himalayan floral element which is a branch of the Eastern Asiatic floral element. Therefore, the southeastern Tibetan subtropical mountain forest zone may be classified as a "subregion" of the Eastern Asiatic forest region. In the same way, the tropical mountain forest zone on the southern slopes of the Himalaya is a part of the Southern Asiatic tropical forest region.

The Plateau vegetation and its floral elements have prominent differences compared to the tropical and subtropical mountain forest vegetation of southeastern Tibet. (For this discussion the Plateau includes Chiangtang Plateau, Qinghai Plateau, and eastern Pamir.) The Plateau should then be recognized as a phytogeographic region in its own right. In 1935, 53 of the main plant species of the Plateau were classified as belonging to the Sino-Himalayan element by F.K. Ward, and he classified Tibet as a part of the Eastern Asiatic region. Grubov (1963) analyzed the geographic distribution of these species, and concluded that most of these 53 species belong to the Central Asiatic element, and so the Plateau should not have been classified with the Eastern Asiatic region. Grubov (1959, 1963), Lavrenko (1962, 1965), and Petrov (1966) considered the Tibetan Plateau to be mainly covered by high-cold desert vegetation. Therefore, they classified the Tibetan Plateau as a "province" of the Central Asiatic desert subregion in the Afro-Asian desert region. According to the viewpoint of three-dimensional zonality, the Tibetan Plateau was classified as "Tibetan Himalayas" by Schweinfurth (1957) and Troll (1972); they considered that the Plateau was a high-elevation steppe belt behind the Himalaya.

The Plateau is hardly a highly differentiated floral region because of its short history of uplift and severe climate, resulting in a lack of endemic families and genera. However, considering its vegetation types and its ecological and geographic characteristics, the Plateau is in need of a new classification.

Firstly, the vegetation types on the Plateau are a particular combination of the plateau vegetation zones. The Plateau has its own special three-dimensional zonal pattern. It can hardly be classified as belonging to any other horizontal vegetation zone or separated into parts assigned to different vertical zones.

In the second place, although there are few endemic genera (about 30) on the Plateau, the endemic species are relatively abundant. They comprise about 1,200 species, which is about one-quarter of the total number of Tibetan species. The dominants obviously are endemic species of the Plateau, and species with centres of distribution on the Plateau. For example, *Kobresia pygmaea* is strongly dominant in the high-cold meadow vegetation of Tibet. Its centre of importance is on the Plateau and from there it permeates the surrounding mountains. Some of the other species of *Kobresia* (such as *K. humilis, K. curvata, K. tibetica, K. littledalei, K. robusta, K. macranthe, K. prattii, K. royleana,* etc.) also show the same pattern as *K. pygmaea* (Ivanova, 1939; Egorova, 1967; Yang, 1976). They form a special geographic type of *Kobresia* meadow that is distinctly different from such meadows in the northern and Central Asiatic mountains. *Stipa purpurea* is still another dominant whose centre of importance is on the Plateau. Elsewhere it is present with little importance on some Central Asiatic arid mountains and alpine basins close to the Plateau. The next important dominant of the high-cold steppe, *Carex moorcroftii,* is an endemic of the Tibetan Plateau. The dominants of the Tsangpo Valley steppe (except for *Stipa bungeana* and *Pennisetum flaccidum* which are found widely in Central Asia), such as *Aristida triseta, Orinus thoroldii,* and *Trikeraia hookeri,* are also endemics of the Plateau. Dominants of the steppe shrubland (*Sophora moorcroftiana, Caragana versicolor, Ceratostigma griffithii*), and some important companion species (*Artemisia wellbyi, Astragalus malcolmii,* etc.), are also endemics of the Plateau. Two of the most important components of high-cold cushion plant vegetation (*Arenaria musciformis* and *Androsace tapete*) as well as many others belong to the Plateau endemics also.

The dominant of high-cold desert vegetation, *Ceratoides compacta,* is considered a specialized species which was formed during the process of Plateau uplift. It also is an important endemic and an example of the distinctiveness of the Plateau vegetation. Another important dominant of this genus is *Ceratoides latens* in the Ali deserts. It is a Tethystic species reflecting the intimate relation of the Plateau with the Tethystic area and not with the Central Asiatic desert region. Another widespread desert species in western Tibet is *Christolea crassifolia* which also is an endemic of the Plateau.

Based on the continental and xeric character of the plateau vegetation, and the origin and relationship of its dominant species, the Plateau should be a part of the Tethystic vegetation area. However, as a peculiar "Asiatic Plateau" steppe and desert region, parallel in part with Afro-Asian steppe and desert regions but quite distinct in its high-elevation climates and the origin of its flora and communities, it is more than just a part of the Central Asian region. Its distinctiveness has also been suggested by Schweinfurth (1972); the Tibetan Plateau is itself a region, distinct in its characteristics and diverse in its zonal vegetation.

In another article (Chang, 1978) the effects of the Tibetan Plateau on the geographic zonal pattern and vegetation types of Eastern Asia have been discussed. Here it is only pointed out that the Tibetan Plateau is situated at the conjunction of several great vegetation regions, including Eastern Asia, Southern Asia, Central Asia, and Western Asia-North Africa. Surrounding the Plateau there is a series of very distinct and different vegetation and geographic types: temperate desert in the north, tropical rain forest in the south, subtropical desert in the west, and subtropical evergreen broadleaf forest in the east. Therefore, the Plateau is the "crossroads" of vegetation in Asia, and is in fact a most important cause of the particular pattern of zonation of vegetation of Eastern Asia. Considering the great uplift of the Tibetan Plateau, the special plateau ecological conditions and communities, and the great interruption and deformation of other vegetation and geographic horizontal zones which the Plateau causes, the Tibetan Plateau should occupy its own place in the classification of the earth's vegetation.

Study of the pattern and phenomenon of Tibetan vegetation has not only provided new knowledge about Tibet itself, but has also given insight into the understanding of the zonation of vegetation in all of Eastern Asia.

APPLICATION TO NATURAL RESOURCE DEVELOPMENT

The plateau zonation of the vegetation of Tibet is a synthesis of tectonic uplift, changing atmospheric circulation, and biogeography, dating from the early Neogene. Detailed knowledge of its special adaptive characteristics and its productive capacity can provide essential guidelines for sustained use and for the introduction of cultivars and domestic animals. In this sense, therefore, knowledge of the region's vegetation becomes a principal basis for agricultural productive regionalism. Thus four agricultural zones are distinguished.

1) The southeastern tropic-subtropic montane forest zone: this is an "agro-forest" region best adapted for a mixture of crop cultivation and forest management. Tea, camellia, citrus, many other subtropical fruits, and a double rice crop are strong options. In the forest-steppe subregion of the lower Tsangpo Valley warm temperate fruit trees could be introduced, including peach, pear, chaenomeles, and walnut.
2) The southern valley temperate steppe and the western temperate desert zones: these two subregions provide the main agricultural base of Tibet. The steppe and meadow, with the surrounding mountains, could support a development of animal husbandry. The valley bottoms, especially with irrigation, are important for barley, wheat, sweet pea, potatoes, and temperate fruits. This provides a combined pastoral-agricultural region.
3) The high-cold *Kobresia* meadow zone of eastern Tibet and the vast high-cold steppe zone of the Qinghai plateau comprise the main plateau pastoral region. As for crops, only highland barley in lake basins with irrigation is possible, together with some cold-resistant and local forage grasses for supplementary winter and spring animal feed.
4) The fourth region is the high-cold desert zone of the northwest; the kingdom of the wild yak and the Tibetan pantholops. Much of this region is not suitable even for temporary pasture. An exception is the lake basin country of northern Qiangtang which can be used for short-term summer grazing for yaks and sheep.

The world's upper limit of cereal cultivation occurs on the Plateau and is closely related to the vegetation zonation. This coincides with the montane temperate steppe and temperate desert vegetation. In the western Ali region, the montane temperate steppe-desert vegetation extends to 5,000 m and barley can ripen at 4,900 m, but is subject to frequent frost damage. Thus 4,700 m is recognized as the upper limit of sustainable yield. An understanding of the relationship between the 4,700 m upper limit and the vegetation zonation can help prevent unwise over-extension of barley production. It is especially valuable to recognize that the upper limit of potential cultivation rises with increasing continentality, and that dependency on irrigation will also increase in the same manner.

Knowledge of the vegetation patterns is also valuable for the development of industry and transportation, and for the avoidance of mountain hazards. The proposed railway and the oil pipeline will prove critical for resource development and human welfare in Tibet. But these projects are faced with enormous physical obstacles including permafrost and soil creep on the Plateau and debris flows, landslides, and snow avalanches in the high mountains. Understanding the relationships between vegetation and slope stability will prove of critical importance. Similarly, rational management and protection of the montane forests of the southeast are closely allied to highway-route selection and road-bed design. Thus when a vast upland, plateau, and mountain region comes under the impact of modern resource development for the first time the need for a strong natural science research programme should be self-evident. This recognition lies behind the extensive scientific activity organized by Academia Sinica over the last twenty years.

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