PHYLOGENY OF THE LATER TERTIARY EQUIDAE IN THE LIGHT OF NEW PLIOCENE HORSES FROM CHIHUAHUA, MEXICO

Thesis by

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ABSTRACT

Phylogenetic charts currently published showing the evolution of North American Equidae indicate that species of the subgenus *Pliohippus* (*Astrohippus*) of the Hemphillian stage are in the line of ancestry of modern horses. Different opinions exist as to the ultimate fate of the typical subgenus, and as to the origin of Old World zebras.

A study of fossil horses from the Yepomera fauna of western Chihuahua, Mexico, demonstrates the presence of four species. Three of these are described, and two are regarded as new to science, namely, *Pliohippus* (*Astrohippus*) *stockii* n. sp. and *Pliohippus* (*Pliohippus*) *mexicanus*, n. sp. It is concluded from a comparison of the horses and of associated elements in the fauna with those found in related assemblages, that the Yepomera fauna is of late occurrence in the Hemphillian stage (middle Pliocene) of North America. The faunas from the Hemphill horizon of Texas, from the Alachua-Bone Valley beds of Florida, and from the Mt. Eden beds of California are believed to be older.

The two new species throw light on the phylogenetic relationships of the genus *Pliohippus sl.* The subgenus *P.* (*Astrohippus*) is removed from direct ancestry to Blancan and later horses, and *P.* (*P.*) *mexicanus* n. sp. is proposed as the most likely known ancestor of living horses, including the zebra. These new interpretations as to the phylogeny of the later Equidae are presented in a new chart.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

INTRODUCTION

Although the phylogeny of the horse has become a common textbook example demonstrating the evolution of a group of animals in geological time, differences of opinion continue to exist as to the many details involved in this development. Currently one of the most salient points of disagreement concerns the correct identity of the Pliocene ancestors of certain living horses.

Two views may be mentioned as to the line of descent of *Equus*, namely, 1) that the modern genus descended from Hipparion, and 2) that it arose from species within the genus *Pliohippus*. The opinion that *Hipparion* was ancestral to *Equus* is held by so few modern workers, and is so untenable (see, for example, Stirton, 1942; Simpson, 1944, p. 103) that it will not receive further consideration here.

It has long been recognized by most paleontologists in North America, where the historic record of the Equidae is most complete, that Recent horses can be traced back to species of the Pliocene genus *Pliohippus*. At present there seems to be general agreement that the modern Equus is descended from a particular subgenus of *Pliohippus*, namely, *P*. (*Astrohippus*) Stirton. There is, however, difference of opinion as to the ultimate fate of the typical subgenus, and as to the systematic position of the North American horses of the Blancan stage.

The geologic position of the Blancan stage still remains a matter for debate, McGrew (1944), Evans and Meade (1945), Meade (1945) and others considering it as properly belonging to the

Pleistocene, while the traditional view is that it represents the upper Pliocene. A proposal was made (Elias et. al, 1945) to hold in abeyance all definite age assignments of faunas coming from this portion of the later Cenozoic of the Great Plains. The present study does not concern itself specifically with this problem, which was the subject of a recent symposium (Colbert, 1948). The reported action taken during the meetings of the International Geological Congress in London in 1948 may result in a general recognition of the Blancan as a Pleistocene stage. However, the name as here employed conforms to the usage of the term in the Wood report (Wood, et. al, 1941), as does also the use of the Hemphillian stage.

The Blancan faunas of North America contain two genera of horses. One of these is *Nannippus*, a small, three-toed hipparion, with which obviously we are not concerned in the present discussion. The other is closely related to the living members of the Equidae, and includes species that were at times included in the genus *Equus*, *Protohippus*, or *Pliohippus*, and for which the genus *Plesippus* was erected by Matthew (1924). *Plesippus* was considered to include forms intermediate in structural characters between *Pliohippus* and *Equus*. Stirton (1936) rejected the genus and referred the included species to *Equus*, considering them as primitive members of the modern genus. McGrew (1944) concluded that the large Blancan horses of North America were properly to be referred to *Hippotigris*, the name for the living zebra, which group McGrew regards as possessing full generic rank.

Whether the Blancan stage is assigned to the Pliocene or Pleistocene, it has become increasingly apparent that a faunal discontinuity exists between the Hemphillian and Blancan faunal stages, greater than that which prevails between the Clarendonian and the Hemphillian (Matthew and Stirton, 1930; Wilson, 1937a; Schultz, 1937; McGrew, 1944, 1948; and others). A comparison of the fossil vertebrate assemblages of the Texas Panhandle demonstrates the presence in the Hemphill beds of four genera and subgenera of horses, while the younger Blanco deposits contain only two. The Blancan horse of immediate concern to the present discussion is Plesippus. Because of the time gap between the Hemphill and Blancan stages, it has not heretofore been possible to identify with certainty the Hemphillian ancestors of Plesippus. True, there is general agreement that the genus Pliohippus contains these ancestors, but their exact position within the genus is currently a subject of controversy.

Many workers have accepted Stirton's subgenus Astrohippus as including the probable ancestors of Equus (Stirton, 1940, 1942; Camp and Smith, 1942; McGrew, 1944). McGrew believes that Astrohippus gave rise to Equus, not in North America, but in the Old World after a migration from North America. If this view be accepted, the New World Blancan faunas contain no members of the genus Equus ss., but only zebras, which are placed in a separate genus by some workers, or included in a subgenus of Equus by others. The subgenus Pliohippus ss., according to McGrew, was ancestral to these New World zebras, as well as to those of the Old World, but not to the caballine horses that appear in Villafranchian and later faunas of the Old World, and Pleistocene faunas of the New World.

Stirton's published view is that species of the subgenus Astrohippus were ancestral to Equus, at least in part; that the Blancan horses of the New World are to be included in the genus Equus, which also includes all living horses, asses, and zebras;

and that the subgenus Pliohippus ss. gave rise to the South American Hippidion. Stirton (1940) concedes the possibility that some species of Equus may be descended from such forms as Pliohippus (P.) coalingensis, a vew which might be considered as tantamount to enlarging the subgenus Astrohippus, as Stirton has, indeed, suggested (Stirton, 1940; Stirton and Goeriz, 1942).

In brief, then, the problems are these. Do the zebras, including Plesippus, and the caballine (true) horses belong to separate phylogenetic lines whose trends can be traced back into the Hemphillian or earlier stages? Or is Plesippus merely a primitive member of the genus Equus s.l., which has persisted as the modern zebra, but gave rise to the caballines in post-Hemphillian time? Further, assuming the correctness of the latter view, one may ask did Plesippus descend from forms closely related to Astrohippus ansae, or from species currently referable to Pliohippus s.s.?

The final answer to these questions is, in part, dependent upon the discovery of faunas intermediate in age between those of the Hemphillian and of the Blancan stages in North America. Stirton (1947) suggests that traces of faunas of transitional type do occur in the Texas Panhandle, and Schultz and Stout (1948) report the presence of a fossil horse that may help to fill this gap in the record.

The object of the present paper is to make a comprehensive survey of three of the known fossil horses included in the Yepomera fauna of western Chihuahua, Mexico. Two of these are species new to science and appear to be more advanced than any other fossil horses known from the Hemphillian stage. One of these, because of its near approach to Plesippus, in certain characters, is of particular significance since it promotes a better understanding of the phylogeny of later Tertiary and Quaternary Equidae.

YEPOMERA FAUNA*

Collecting parties from the California Institute of Technology, Division of the Geological Sciences, have recovered vertebrate fossils from later Tertiary strata exposed in the valley of the Rio Papagochic in western Chihuahua, Mexico. A general account of the history, faunal assemblage, and nature of the occurrence has been given by Stock (1948a). Several mammals and a bird new to science have been described from the deposits (Wilson, 1937b; Drescher, 1939; Furlong, 1941; Miller, 1944; Stock, 1948b). The present study was undertaken to elucidate particularly the fossil horses in the assemblage, because these mammals comprise by far the largest number of individuals found. Moreover, the horses are the most accurate indicators of the age relationships of the fossil fauna, and in themselves yield valuable information as to the phylogenetic trends among the later Tertiary Equidae.

Since the present study is primarily paleontologic, only a brief account is given of the geological features of the region whence the fauna has come, based on the author's field work in the region during the summer of 1946. A fuller statement of the geology is being prepared by Lloyd C. Pray.

Geology

The valley in which the Yepomera fauna is found lies at an elevation of between 6000 and 7000 feet in western Chihuahua, at the eastern edge of the Sierra Madre Occidental, but west of the

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* Previously called the Rincon Fauna by authors.

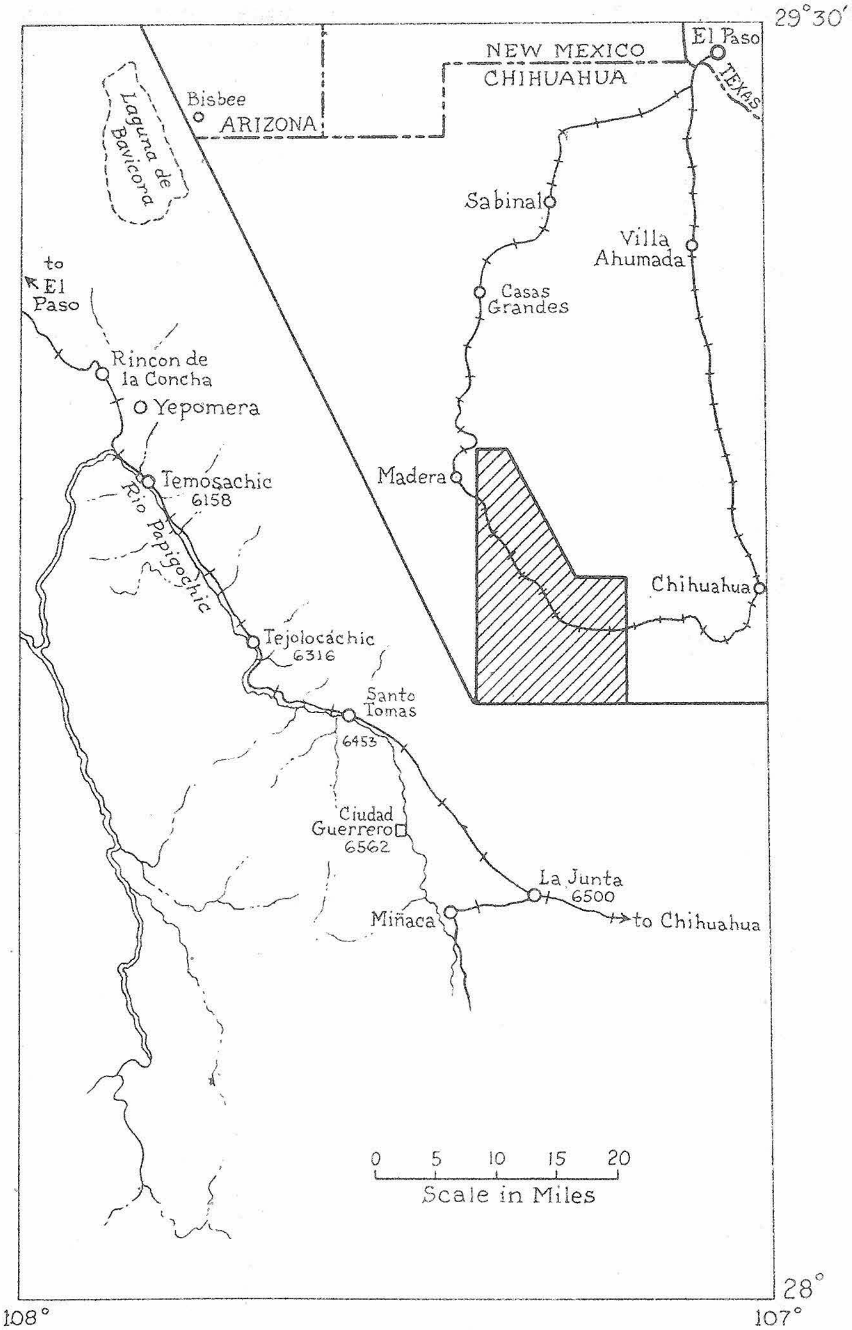

Fig. 1. Map showing location of Rio Papagochic valley.

continental divide. The region is about a hundred miles west of Chihuahua City, and approximately 200 miles south of Columbus, New Mexico. The valley is about 60 miles long, and trends roughly northwesterly. The village of Yepomera is near the north end, where the Rio Papagochic leaves the valley to cut through the Sierra Madre Occidental on its way to the Gulf of California. Near the south end of the valley are the towns of Guerrero and Miñaca. In sedimentary strata exposed near the latter community, and designated in the field the Miñaca beds, a mammalian fauna has been collected which obviously represents a later faunal stage in the Pliocene than that of the Yepomera fauna.

The Yepomera assemblage has been collected at a number of localities extending northward from near the village of Matachic (fig. 1) to near the little settlement of Rincon de la Concha, at the extreme northern end of the valley, approximately 20 miles north of Matachic. With a few possible exceptions to be noted later, the fossil localities all appear to yield essentially the same, or equivalent faunas. Most of the more prolific localities occur in the vicinity of Yepomera and Rincon, and materials from the quarries that have been opened at these sites furnish the basis of most of the observations in the present study.

The relationship of the beds in the vicinity of Rincon to those yielding the geologically younger Miñaca fauna are not known. In each area the strata appear to be flat-lying. Remains of Pleistocene mammals have been found in gravels overlying the Tertiary beds at both ends of the valley.

As intimated previously, the geological relations of the strata in the vicinity of Yepomera were investigated during the field season of 1947 by Lloyd C. Pray, and will be reported by him. Previous observations made by the author in the region are in accord with the more detailed work done by Mr. Pray (oral communication).

The fossiliferous strata consist of interbedded sands, silts, clays, and limestone. Volcanic ash is present in many horizons. Lava flows appear to interfinger with the sediments around the edges of the basin. The dominant color of the exposed fossiliferous beds is white or light gray, but green and red layers occur.

The fossils appear to be mostly in tuffaceous and calcareous clays and sands, most of which are not well indurated. The bones occur in pockets and lenses, broken and intermingled. Some of the material appears water worn, but most broken bone fragments have sharp edges, suggesting that little transportation took place after the breaking. Teeth and limb bones of horses form the bulk of the collections. Material from some localities is well-preserved by silicification, but bone from other localities is chalky, and tends to crumble and break. Calcite and quartz crystals are found filling the marrow cavities of many of the limb bones.

The nature of the fossil occurrences and the general features of the sediments suggest deposition along the flood plains of streams and in ephemeral lakes, in a flat-floored intermontaine basin. Pray states that he found no evidence of faulting around the edges of the northern part of the valley. Although the elevation of the area is relatively great, the general relief is not. An impression remains that the appearance of the valley today does not differ greatly from that which it had at the time the fossil-bearing beds were being deposited. It is believed, however, that the region stood at a much lower elevation in mid-Pliocene time, and through-flowing drainage probably did not exist.

Some light is thrown on the probable history of the area by a study made by King (1939), largely in the region to the west. Yepomera lies at the eastern margin of the plateau section of the Sierra Madre Occidental. West of this, trending north-south, is the barranca portion of the Sierra, where westerly flowing drainage has incised deep gorges. King (1939, p. 1699) states, "Early Tertiary volcanic rocks spread out over the whole surface of the Sierra Madre Occidental. In the plateau section of this province, the underlying Mesozoic rocks are probably greatly deformed....... The later, or post-volcanic deformations strongly expressed to the west, have, however, scarcely affected this region. Over wide areas the volcanic rocks are flat or gently tilted...... After its formation the surface must have been raised thousands of feet by epeirogenic rather than by orogenic movements, as an ancient erosion surface developed to maturity extends over its surface and is now deeply dissected by the present cycle of erosion."

In the vicinity of Yepomera, erosion surfaces cut on Quaternary gravels now stand one to two hundred feet above the present level of the river. Although not enough evidence is available at present to reconstruct the history of the drainage, it appears not improbable that the present drainage pattern is of relatively late origin. The basin now occupied by the Rio Papagochic may have been closed, and filled to a greater depth with sediments before it was added to the Papagochic-Rio de Maros-Rio Yaqui drainage system. The pattern of drainage in the valley as a whole, as shown on recent U. S. Army Air Force charts compiled from aerial photographs suggests that the region may have drained toward the south end of the valley in an earlier time, with, or, more probably, without an outlet.

As an example of the lithology of one of the fossil localities, the following section is given from a small pit excavated in 1946 at C. I. T. Locality 286, near the village of Yepomera. Limestone beds occur in the immediate vicinity, both above and below the horizon of the pit.

1'3"	Topsoil, brown to black, grading into
2'	light brown, sandy silt, with caliche. Sand grains fine, sub-rounded. Grades into
1'1"	very soft, light brown silty sandstone, with very fine angular to sub-rounded grains of quartz, some of which are red, pink, or brown, and poorly to moderately well sorted. No large fragments or coarse sand.
6'	Streamer of calcareous clay, persistent for 15 or 20 feet around pit, but grading laterally and vertically. Contains small calcareous concretions.
4'6"	Light brown to brownish gray silty sandstone, soft in general, but with hard lenses. Contains 2 to 6 inch lenses of more silty material, caliche nodules, and calcareous patches. Sand is very fine-grained quartz sand, poorly to moderately well-sorted, with about 20 per cent clay.

In the pit described, the lower four and one half feet of silty sand yielded most of the fossils, although a few occurred at higher levels. The lithology graded laterally and vertically. The fossils were found in small pockets, with most of the bones broken. A horse limb bone might be found pressed tightly against the jaw of a camel. The accumulation appears to be typical of an occurrence along a flood plain or margin of a playa.

Field work done by Pray (oral communication) has demonstrated that the strata at locality 286 are a hundred feet or more higher in the section than those of localities 276 and 275, from which the bulk of the material in the present study came. The lower beds contain greenish clays and silts, less sand, and few or no limestone horizons. Localities in the vicinity of the Rincon are stratigraphically higher than locality 286, contain few limestone beds, and consist mostly of white and light gray silts.

Faunal List and Correlation

Wilson (1937b) and Stock (1948a) have stated that the Yepomera fauna shows closest affiliations to the Hemphill fauna from the Texas Panhandle. This is doubtless true, but the study of the fossil horses has also revealed relationships to Pliocene faunas known from the Atlantic coast and Pacific coast provinces. A detailed faunal study of the Mexican material would be necessary to completely evaluate these relationships. This has not been attempted, but sufficient information is available to give a partial faunal list for comparison with the three faunal assemblages believed to be most pertinant to the present problem.

Table 1 gives the list of Yepomera forms as they are now known, and comparisons with the Hemphill, Alachua-Bone Valley, and Mt. Eden faunas. Identification of the Yepomera fauna is based in part on published statements and on identifications made by Dr. Stock and by the author. Comparison with forms in related faunas has been facilitated by descriptions placed on record by Frick (1921), Stirton (1937), Simpson (1930), and others.

It will be seen from Table 1 that the Yepomera assemblage shares several genera and some species or closely related species with the Hemphill fauna. Additional work on the Mexican collection will probably add to the list. No attempt is made here to describe the material other than the horses, but a statement concerning some of the forms identified in the Mexican fauna may help to better explain the relationships.

TABLE 1

COMPARISON OF PLIOCENE VERTEBRATE FAUNAS

YEPOMERA	HEMPHILL	ALACHUA-BONE VALLEY	MT. EDEN
CARNIVORA			
Agriotherium cf *schneideri*	**	**	**
Taxidea mexicana	**		
Machaerodus catacopis	**		
Vulpes ?	*		*
Osteoborus ? sp.	*		
Metailurus ? sp.			
Canid (coyote?)			
LAGAMORPHA			
Notolagus velox			
PROBOSCIDIA			
cf *Stegomastodon*			
PERISSODACTYLA			
Pliohippus (*A.*) *stockii* n. sp.	*		
Pliohippus (*P.*) *mexicanus* n. sp.			**
Nannippus cf *minor*		**	
Neohipparion cf *phosphorum*		**	
Rhinocerotid			
ARTIODACTYLA			
Hexabelomeryx fricki		*?	
Prosthennops	*	*	*
Megatylopus ?	*	*?	*?

*Represented by same genus

**Represented by same or closely related species

Agriotherium is regarded as a guide fossil of the Hemphillian stage in the North American Pliocene. The type locality of *A. schneideri* is the Bone Valley formation of Florida. *A. gregorii* from the Mt. Eden horizon of California is a closely related species. *A. schneideri* is found in the Hemphill fauna. Thus, all four faunas being compared are characterized by the presence of the same or of similar species of this large bear.

Of additional carnivores, only two require any special comment. Drescher (1939) described remains of a new species of badger (*Taxidea mexicana*) from the Yepomera Pliocene, and compared some of the teeth of this form with material from Optima, Oklahoma and from the Hemphill horizon of Texas. He concluded from the comparisons that the resemblances were very close. The Optima fauna, which is now quite well known, is apparently nearly identical with that from the Texas Panhandle Middle Pliocene.

Osteoborus is reported somewhat doubtfully from the Yepomera fauna. Careful search of the entire collection for material which might be referred to this genus resulted in the identification of two upper and one lower carnassial teeth, possibly associated. In this individual P4 has a parastyle, and closely resembles the equivalent tooth of a referred specimen of *Osteoborus cynoides* from the Coffee Ranch quarry, Texas, except for its smaller size and relatively smaller transverse diameter of crown. The same relationships hold for the lower carnassials. A few additional teeth from other localities may represent *Osteoborus*, but no further upper sectorial teeth have been found.

Among artiodactyls in the Yepomera fauna, a peccary and several types of camels are not well enough known to be of much value at present in establishing correlations. A large camel referred tentatively to Megatylopus, and two, or possibly three smaller species are present. Of much greater interest is the presence in the Mexican fauna of a curious antelope with six horns, Hexabelomeryx Furlong. Shortly after this animal in the Yepomera fauna had been described by E. L. Furlong (1941), T. E. White (1941) placed on record a six-horned antilocaprid from the Bone Valley beds of Florida, under the name of Hexameryx. It is of considerable interest to note that these genera are quite similar, probably identical, and that six-horned antilocaprids have not been reported from any other Tertiary localities known to the author.

The horses, which are the particular object of the present study, show interesting relationships among the four faunas. The details will be made clear in later sections of the present report. It may be stated that the horses suggest that the Yepomera is the most advanced of the four assemblages, and no other mammals in any of the faunas contradict this, except that the Osteoborus? from Yepomera might be considered more primitive than the Hemphill species. Dr. Stock, who has investigated Neohipparion from Mexico, states (oral communication) that the species represented at the Chihuahua localities is advanced over the Hemphill species. Pliohippus (Astrohippus) stockii, n. sp. is decidedly precocious and more advanced than P. (A.) ansae from the Texas Panhandle, which it resembles more closely than it does any other known species. P. (Pliohippus) mexicanus, n. sp. resembles more closely P. osborni of the Mt. Eden horizon, California, than it does P. interpolatus from the Hemphill. It is considerably more advanced than the species from Texas, and is regarded as slightly more so than the California horse.

Nannippus cf. minor from Yepomera, although resembling N. lenticularis from the Hemphill, is a decidedly smaller species. N. Minor from Florida is known from very scanty material, but the small hipparion from Mexico is definitely to be compared with the Florida species. Nothing can as yet be said as to the age relations between the Mexico and Florida sites based upon the Nannippus material, except that the presence of this horse at the former locality further emphasizes the broader relationships of the two faunal provinces, and is in line with the evidence previously indicated.

The presence of Agriotherium, rhinoceros, the advanced nature of several additional species, as well as absence of known Blancan genera, place the Yepomera fauna as a correlative of North American mammalian assemblages now assigned to the Hemphillian stage (Wood, 1941). The advanced characteristics displayed by some of the horses suggest that the Mexican fauna is possibly one of the latest known mammalian stages within the Hemphillian.

In terms of the geologic position of the successive vertebrate faunal stages of the Tertiary time scale, the Hemphillian is considered to represent the Middle Pliocene by conventional standards (Wood, 1941). There is, however, a growing tendency in North America to consider the Blancan faunas as representing Pleistocene time. Reports not yet published indicate that action taken by delegates to the 1948 International Geological Congress in London will doubtless result in a reference of Blancan assemblages to the Pleistocene. Be this as it may, it can still be safely stated that the Yepomera fauna belongs to the Hemphillian stage of the North American Pliocene.

DESCRIPTION OF MATERIAL

Plichippus (*Astrohippus*) *stockii* n. sp.

Type.- C.I.T. No. 3576, palate with right P2-M2 and anterior part of M3, and left P2-M2.

Referred Material.- Numerous skull and jaw fragments, isolated teeth, limb and foot material.

Type Locality.- C.I.T. Loc. 276. Referred material from same locality and others at approximately same stratigraphic level. Valley of the Rio Papagochic, western Chihuahua, Mexico.

Fauna.- Yepomera.

Diagnosis.- Size smaller than *Astrohippus ansae*, cheek teeth higher crowned. Upper cheek teeth with crowns slightly curved or straight. Protocone relatively large, elongate, with well-developed anterior projection and usually pronounced lingual groove, reniform in some specimens. Protocone approaches shape seen in some species of *Equus*. Posterior end of protocone tends to be directed toward lingual side of tooth. Lower cheek teeth with metaconid and metastylid attenuated, with parallel borders, widely separated to base of crown, with U-shaped groove. Parastylid and hypostylid on lower milk molars present or absent. Protoconid and hypoconid walls flattened.

Description.-

Upper Cheek Teeth

The upper cheek teeth resemble those of *Pliohippus* (*Astrohippus*) *ansae* in some respects, but the total range of characters indicates a form much more advanced than the species from the Panhandle of Texas. The variability complex in hypsodont horse teeth caused by individual variation, tooth position, and stage of wear has been remarked upon by many workers. These variations make difficult a comparison of isolated teeth of different species as to size and pattern. However, an examination of a large series of teeth in all stages of wear makes it possible to present the characteristics which make the new species distinctive.

The upper cheek teeth of *P. stockii* are small, the smallest being only slightly larger than some teeth of *Callippus regulus*, and the largest overlapping the size range of *P. (A.) ansae* teeth. The actual size range is exaggerated by factors related to tooth position and stage of wear. Many of the teeth are greatly expanded in an antero-posterior direction in the upper few millimeters, tapering more uniformly toward the base below this expansion. Some specimens taper sharply toward the base throughout the length of the crown, resemblihg in this feature teeth of *Pliohippus leardi* Drescher. In general the teeth of *P. stockii* have smaller occlusal surfaces than corresponding teeth in *P. ansae*, a few are absolutely longer-crowned than those of *ansae* examined, and all are relatively more hypsodont. A vestigial P1 is present or absent.

The enamel pattern is simple. A slight complication in the enamel of the fossette borders disappears within a few millimeters of the top of the tooth. The presence of a pli caballin fold is variable; where present it is usually lost by the time the tooth is about one-half worn. M1 seems least prone to have or to retain this fold. The hypoconal groove is not open after two-thirds of the tooth is worn, and is absent in some slightly worn teeth. Some third molars show an isolation of the tip of the hypoconal groove in the form of a small lake.

As an example of the influence of stage of wear on certain details of tooth pattern, the results of a study of 34 examples of molar $\underline{3}$ from locality 276 are given. Of the thirty-four teeth, five are more than one-half worn, and the remainder less than half-worn. The five most-worn teeth show neither a hypoconal lake nor a pli caballin. The twenty-nine remaining teeth were divided into two groups, those with a slightly complex enamel pattern of the fossette borders, which means that they are less than approximately one-fourth worn, and those with a simple pattern, indicating a stage of wear estimated to be between one-fourth and one-half.

Considering all the teeth, the pli caballin was present in seventeen and absent in seventeen, while the hypoconal lake was absent in twenty-four and present in ten. Of the twenty-nine teeth less than one-half worn, eleven have a complex pattern, all eleven have the pli caballin, and nine have no hypoconal lakes. Of the eighteen teeth with simple patterns, six display pli caballin folds, while twelve lacked them. The hypoconal lake is present in eight and absent in ten of the eighteen.

The above figures suggest that in the particular tooth under examination, the pli caballin is likely to be present in most instances in early stages of wear, but is lost by the time the tooth is about one-half worn. The hypoconal lake is not likely to be present at all, and when it does appear, it becomes apparent at about the time the pli caballin is disappearing, and the lake itself disappears after the tooth is more than one-half worn. $M\underline{3}$ was used because it is so readily and positively identified. Other teeth in the series do not show a hypoconal lake, but many show a pli caballin, which appears to follow about the same pattern as seen in the third molar. The example illustrates the danger of using a character such as a pli caballin for diagnostic purposes without careful consideration of stage of wear of teeth.

Again considering the upper cheek teeth as a group, the post-protoconal valley is deep, in some teeth it is a narrow inlet with parallel sides, and in others expanding sharply at the closed end, with or without a pli caballin. The pre-protoconal groove is well-developed and is farther from the lingual border of the tooth. It is directed more in a posterior direction than in *A. ansae*. Even in extremely worn teeth of *A. stockii* (fig. 3,d), the groove is still persistant enough to outline a distinct heel on the protocone. It is never reduced to the simple lingual notch seen in *A. ansae* and in most other species of *Pliohippus*.

The fossette borders are simple except in very early stages of wear, when they become slightly complicated. The fossettes in general are very similar to those seen in *A. ansae*.

The protocone presents the most striking characteristic of the new species, being quite *Equus*-like in many specimens. The shape of the protocone varies from oval or elongate oval to kidney-shaped, or from a shape somewhat like that seen in *A. ansae* to one like that characteristic of some species of *Plesippus* and *Equus*. The majority of teeth have the more advanced form of protocone. The protocone in teeth of *A. stockii* is relatively longer than in *A. ansae*, and has a decidedly greater anterior projection. This projection combines with the pre-protoconal groove to produce a distinct "heel". A connection of the protocone to the hyposelene has not been seen even in extremely worn teeth.

The lingual side of the protocone in most specimens is either flattened or grooved, a character which is usually persistent to the base of the tooth. In early stages of wear the protocone may have sharply-pointed anterior and posterior ends, which disappear at

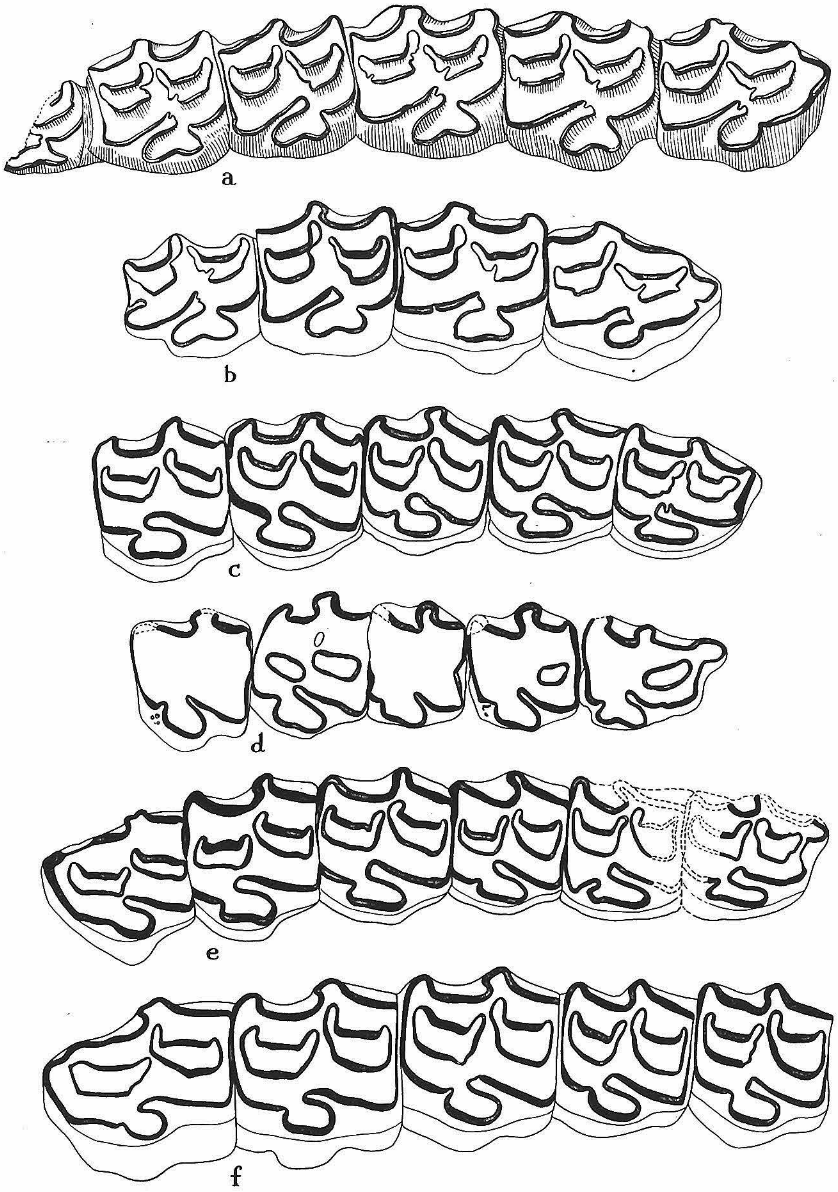

Fig. 2. *Pliohippus* (*Astrohippus*) *stockii*, n. sp. Upper cheek-tooth series. a. No. 3576, right side of type, C.I.T. Loc. 276; b. No. 3617, C.I.T. Loc. 289; c. No. 3573, C.I.T. Loc. 276; d. No. 3618, C.I.T. Loc. 289; e. No. 3621, C.I.T. Loc. 276; f. No. 3619, C.I.T. Loc. 275; No. 3618 extremely worn. All others moderately worn. All figures natural size. Calif. Inst. Tech. Vert. Paleont. Coll., Yepomera Pliocene, Chihuahua, Mexico.

about the same time as the crenulations of the fossette borders. Figures 2a to 2f illustrate the differences in enamel pattern caused by individual variation, tooth position, and stage of wear. Besides the extremely precocious characteristics shown by some features, the teeth are also notable for their general simplicity of appearance. This simplicity, and the postero-lingual trend of the protocone in some teeth, are reminiscent of teeth referred to the genus *Calippus*.

The styles of the upper cheek teeth are not particularly distinctive. They tend to be pinched, and flattened externally. In some small teeth the styles are rather delicate, somewhat as in *Calippus*, but do not differ appreciably from those of *A. ansae* in most specimens. The usual difference in character of styles on premolar and molar teeth is seen.

As has been noted, the teeth are quite hypsodont. Slightly worn teeth attain a height of crown of 55 millimeters, measured along the protocone. The curvature of the entire crown is not great, but in some specimens approaches that seen in *A. ansae*. Most teeth are less curved than this, however, and some are quite straight (Plate I). This advanced character, combined with the precocious enamel pattern, makes many individual teeth closely resemble small *Equus* teeth.

Deciduous Upper Cheek Teeth

Upper milk cheek teeth have a simple enamel pattern, with few plications of the fossette borders, and a pli caballin that is variable in occurrence. The protocone is more primitive than in the permanent teeth; the pre-protoconal groove is situated more lingually, and the lingual wall of the protocone is more prone to be rounded, although it is flattened or grooved in some specimens.

Figures 3g to 3k and 6b illustrate some of the features of the upper milk molars.

Milk teeth are generally thought of as tending to display atavistic characters reminiscent of those found in the dentition of ancestral types, and indeed, in some cases can be shown to do this. They are certainly more primitive in most characters than the permanent cheek teeth, both molars and premolars, which is strange in view of the possibility that they may belong to the same series as the true molars. However, the variability complex in milk teeth, particularly in the case of the uppers, seems to be so much greater than that displayed in the permanent teeth that one would hesitate to go very far in attempting to trace any phylogenies through them.

Nevertheless, it would be well to point out two characters which seem to distinguish upper milk teeth of A. stockii from those of A. ansae. These relate to the protocone in stockii and are (1) the tendency of this cusp to project farther lingually beyond the line of the protoconule, and (2) the tendency of the long axis of the protocone to project inward as well as backward. In these respects milk teeth of A. stockii somewhat resemble both milk and permanent teeth of Calippus regulus.

Lower Cheek Teeth

The lower cheek teeth of A. stockii, like the uppers, are in general smaller than those in A. ansae, but somewhat resemble them in pattern. The metaconid and metastylid of A. stockii are narrow and elongated, widely separated, the separation extending to the base of the tooth. In most teeth the metaconid in contrast to the metastylid tends to be more elongate and to have parallel sides. The

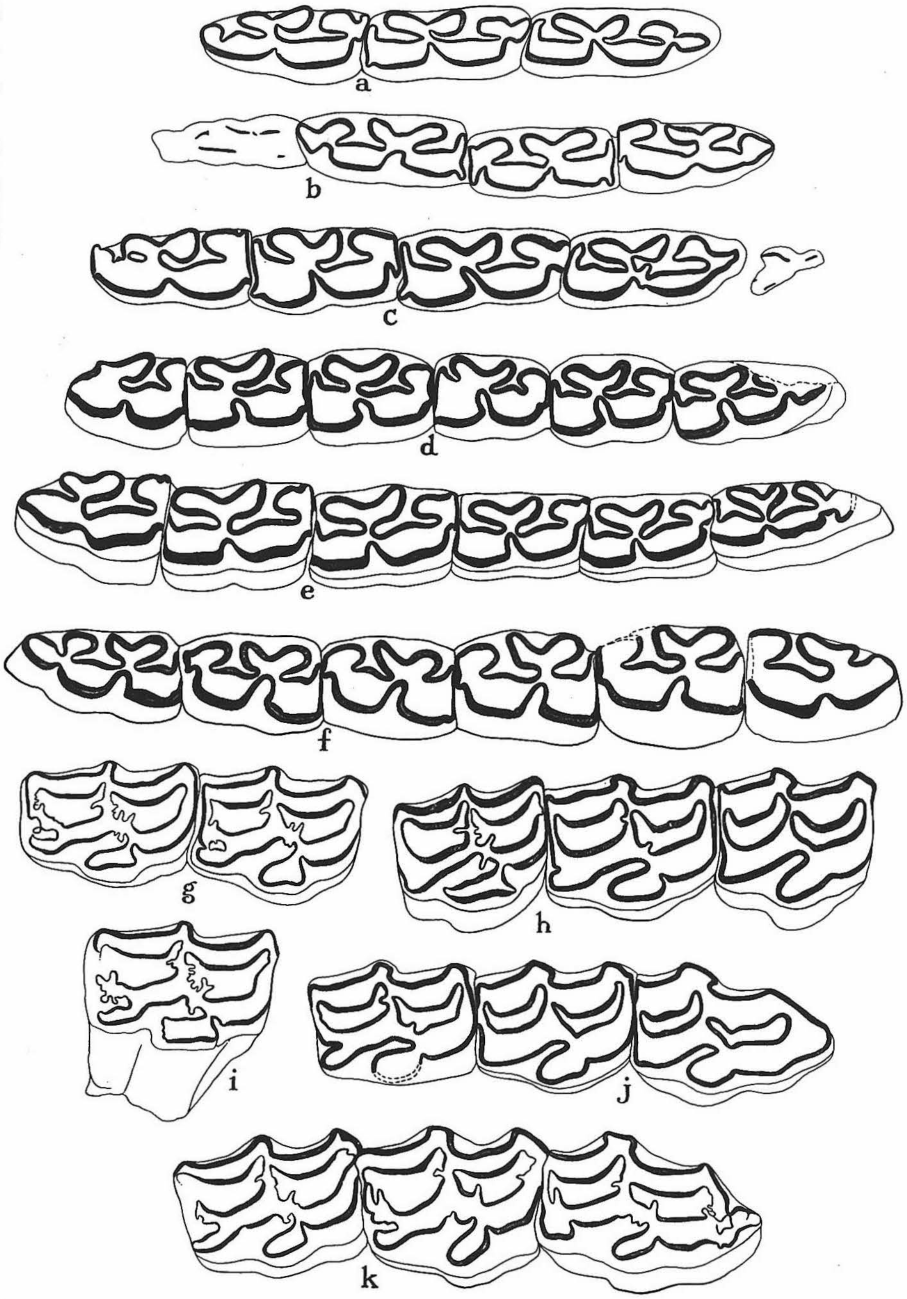

Fig. 3. *Pliohippus* (*Astrohippus*) *stockii*, n. sp. Permanent and deciduous cheek teeth. a. No. 3622, deciduous lower molars, C.I.T. Loc. 289; b. No. 3624, deciduous lower molars, C.I.T. Loc. 289; c. No. 3623, deciduous lower molars with first molar, C.I.T. Loc. 289; d. No. 3680, lower cheek tooth series, C.I.T. Loc. 276; e. No. 3579, lower cheek tooth series, C.I.T. Loc. 289; f. No. 3650, lower cheek tooth series, C.I.T. Loc. 275; g. No. 3696, upper deciduous third and fourth molars, C.I.T. Loc. 289; h. No. 3620, upper deciduous third and fourth molars, first molar, C.I.T. Loc. 276; i. No. 3731, upper deciduous third or fourth molar, C.I.T. Loc. 289; j. No. 3695, upper deciduous molars, C.I.T. Loc. 276; k. No. 3580, upper deciduous molars, C.I.T. Loc. 281. All figures natural size. Calif. Inst. Tech. Vert. Paleont. Coll., Yepomera Pliocene, Chihuahua, Mexico.

reverse, however, is sometimes true.

The groove or gutter between the metaconid and metastylid is a broad, open U, with the sides usually concave internally, and rarely with a V-shaped notch. This feature is generally considered to be characteristic of *Equus*, and is one of the characters considered valid by McGrew (1944, p. 61) in separating the zebras and the caballines. Because *A. ansae* displays this character somewhat, as does *A. stockii*, McGrew concurred with Stirton (1940) in placing *A. ansae* near the line of ancestry of the caballine horses.

Much as the metaconid-metastylid gutter of *A. stockii* resembles that seen in advanced species of *Equus*, the two cusps themselves do not closely resemble those seen in either the primitive or advanced species of that genus, nor those of typical *Pliohippus*. In *A. stockii* the metaconid and metastylid are attenuated, diverging from the point of juncture of the two cusps with nearly parallel walls, except in slightly worn teeth. In the other forms that are being compared, the cusps are constricted near the point of juncture of the two cusps, swelling out into rounded, or in some cases angular shapes. In *A. stockii*, the pattern of the two cusps as a whole is reniform, while in *Equus s. l.* and *Pliohippus s. s.*, the pattern is somewhat like a dumbbell, with the cross bar bent.

There are exceptions to the above statements, but the differences are fairly consistent in all the specimens and figures of the forms that have been discussed. Figures 3d to 3f, and 9 show the range of characters displayed in the metaconid and metastylid of *A. stockii*. These may be compared with illustrations of the lower teeth of *Equus* from Rancho La Brea (Merriam, 1913, figs. 5, 6, 10, 11), *Plesippus*, various species (Schultz, 1936, fig. 2; Plate 1), and various additional species and genera (McGrew, 1944, fig. 21). It may be noted that the hipparions tend also to show the rounded character of metaconid and metastylid, even in the case of Neohipparion, in which form the two cusps are widely divergent, even more so than in *A. stockii.*

The lingual wall of a lower tooth of *A. stockii* shows three prominent ridges (Pl. II, fig.2). The anterior one is the metaconid, and is broadly rounded. It is separated from the narrower, more sharply rounded metastylid column by a broadly open valley. The metastylid is separated by a fairly sharp groove from the column formed by the entoconid and hypoconulid. This posterior column tends to be flattened, is intermediate in width between the metastylid and metaconid, and sometimes shows a faint groove indicating the notch between the entoconid and hypoconulid.

The external walls of the protoconid and hypoconid are flattened in *A. stockii*, even more so than in some specimens referred to *Plesippus.* A pli caballinid is slightly developed in a few teeth in early stages of wear. The same feature has been observed in teeth of the Rancho La Brea *Equus.* In *A. stockii* there are occasionally a few extra folds on the internal walls of the protoconid and hypoconid. Stirton (1941, p.444) states that these are of rare occurrence in *Pliohippus* and *Equus*, and common in the hipparions. *A. stockii* also shows a faintly developed parastylid in permanent teeth in a very few specimens.

Deciduous Lower Cheek Teeth

The lower deciduous molars of *A. stockii* differ in a few details from the permanent teeth. The metaconid and metastylid are in general more attenuated, and more divergent than in the permanent teeth, with consequently a more broadly open gutter between. The labial walls of protoconid and hypoconid tend to be straight.

A parastylid is present on DP$\overline{\overline{3}}$ and DP$\overline{\overline{4}}$ in all specimens examined. More variable is the development of a hypostylid. A weak hypostylid is present usually on DP$\overline{\overline{2}}$. This structure is strongly developed on DP$\overline{\overline{3}}$ in some specimens, and weak to absent on others (figs. 3a to 3c). The degree of development of the hypostylid appears to be subject to individual variation, and not so much to stage of wear of tooth crown. This is demonstrated by its variable presence or absence in teeth of various ages. A moderately worn DP$\overline{\overline{3}}$ with no hypostylid was sectioned about half-way down the crown. At this level a moderately strong hypostylid occurs, but it is by no means so well-developed as in some slightly worn teeth.

Facial Fossae

Some workers have considered the pre-orbital fossae of fossil horses to be of diagnostic value. Stirton (1942, p.636) however, has pointed out that if the differences in facial fossae be used as criteria of generic rank, it would be possible to erect five or more genera from known species of *Pliohippus*. Portions of the face are preserved in several specimens referred to *A. stockii*, but no very clear statements can be made as to the exact nature of the fossae because most of the material is crushed or incomplete. The impression remains that the facial fossae exhibit quite a range of characters due to sexual or individual variation, or both.

Specimen 3620 resembles in extent that portion of the face seen in the type of *Astrohippus ansae*, but in 3620 the anterior opening of the infra-orbital canal can also be seen. The type of *A. ansae* shows a wide, deep malar fossa, with the zygomatic ridge reduced to a thin crest. In 3620 the malar fossa is like a very shallow thumb print in front of the orbit, on the malar bone, above the posterior end of the first molar. The zygomatic ridge is sharp, but not thin, as in *A. ansae.* In fact, the malar ridge in 3620 does not differ appreciably from that in several skulls of recent horses and zebras with which it has been compared. In several additional skull fragments a similar malar fossa and zygomatic ridge can be seen. Specimen 3708, which is a crushed skull with the anterior and posterior ends gone, but complete across the posterior end of the nasals, shows a slightly deeper malar fossa. In front of this, above M1, is a deeper fossa, corresponding approximately to the anterior malar fossa in a skull of *P. fossulatus* illustrated by Stirton and Chamberlain (1939). Except for depth, the fossae that can be seen in specimen 3708 correspond well with those in the skull of the *P. fossulatus.* There is a moderately deep lachrymal fossa, but not pocketed as in the Clarendon skull, and with a smaller elongated depression below the posterior end and postero-dorsal to the anterior malar fossa, which itself lies along the malar-maxillary suture. In front of the infraorbital foramen is a small maxillary fossa.

Portions of skulls available from the Mexican localities demonstrate the presence of the fossae seen in 3708. On the other hand, some skulls show clearly that these fossae are not found in all individuals, and that where present, their development is quite variable. Also demonstrably variable are two deep depressions with sharp ridge between, situated immediately above P2 and P3. These might correspond to the so-called sub-nasal branch of the lachrymal and the posterior part of a buccinator fossae. They do not appear to correspond exactly to anything illustrated by Gregory (1920).

Another feature seen in some of the skull fragments should be mentioned. This is the V-shaped anterior extension of the frontal bones along the median line of the skull at their junction with the nasals. The projection as seen in the fossil specimens is much like that in skulls of zebras and caballine horses, whereas in the modern ass the V-shaped projection is lacking.

Limb Bones

Since the Yepomera fauna contains four species of horses, and since practically no material has been found in association, it is difficult or impossible to identify certain skeletal elements as belonging definitely to a particular species. However, the metapodials can be readily segregated. Metapodials of the large *Pliohippus* and of *Neohipparion* are similar in size, but can be distinguished on the basis of morphological features. Those of *Astrohippus stockii* are similar to the metapodials of the larger *Pliohippus*, but fall into a distinctly smaller size range, while specimens of the diminutive *Nannippus* are recognizable by their very small size, slender proportions, and morphological similarities to those of *Neohipparion.*

The metacarpals of *A. stockii* are quite similar in appearance to those of *A. ansae*, except that they are in general smaller, and relatively more slender. The same relationships hold for the metatarsals. Metapodials of the two species overlap in size range. No consistent differences other than size appear to distinguish the metapodials of *A. stockii* from the larger *Pliohippus* in the Yepomera fauna.

In segregating the metapodials of the Yepomera horses, and in an attempt to evaluate the degree of monodactylism of the two species of *Pliohippus*, detailed measurements and comparisons were made. Some of these will be presented in a later section on size and proportions of the several horse species of the fauna.

Observations made on metapodials of all the horses from the fauna have resulted in some interesting discoveries. The metapodials of

Astrohippus, although morphologically similar to those of the typical *Pliohippus*, are relatively much more slender. Those of *A. stockii* are relatively more slender than those of *A. ansae*, suggesting that a progressive feature in the astrohippine line was the increasing slenderness in the lower limbs.

It is well known that feet of the hipparion-like horses differ from those of their contemporaries assignable to the genus *Pliohippus* in the retention of side toes. This tridactylism is displayed by metapodials of *Neohipparion* and *Nannippus* in two obvious ways. One is the continuation of the rugose surface for articulation of metapodials II and IV down the sides of metapodial III to the distal end. The other is the forward displacement of the lateral processes above the trochlea of metapodial III. The processes are situated anteriorly, in front of a fossa which represents the most distal portion of attachment of the lateral metapodials.

Another distinctive feature pointed out by Matthew and Stirton (1930) is the greater sharpness of the distal keel in the metapodials of *Neohipparion* and *Nannippus* as compared with *Pliohippus*. These authors also noted the greater relative slenderness of the metapodials in the hipparion-like horses.

Study of the limb material from Yepomera indicates diagnostic features at the proximal ends of the metacarpals. When the metacarpal of *Pliohippus* or *Astrohippus* is viewed normal to the proximal articulating surface, the volar edge of the facet for the magnum is seen to be terminated in a more or less straight line, which is approximately parallel to the transverse axis of the bone and to the dorsal margin. The situation is much as it is found in the modern horse. Only rarely will a projection of any sort be seen on the volar surface of the bone, below the proximal facet.

In *Neohipparion* and in *Nannippus*, the posterior ventral margin of the proximal surface trends externally and posteriorly, making the lateral side of the facet for the magnum have a greater antero-posterior length than the medial side. This is quite pronounced in some instances. Just below the proximal surface, on the volar side of the metapodial, is the region for attachment of the suspensory ligament. *Neohipparion* and *Nannippus* show a decided boss-like protuberance in this area. This protuberance is centrally located with reference to the transverse diameter, and is readily visible when the bone is viewed normal to the proximal surface (Pl. IV).

Another feature which assists in distinguishing the proximal ends of the median metacarpals of *Neohipparion* and *Nannippus* is the shape and character of the unciform facet. In both subgenera of *Pliohippus* (*Pliohippus* *s.s.* and *Astrohippus*), available material shows that the facet slopes outward and downward at an angle approximating 45°. It is narrower at the back, and the larger front portion is usually separated from the smaller area in the back by a distinct notch. This notch corresponds to a space formed by grooves in the magnum and unciform. Sisson (1927, p.223) says, "Two interosseous ligaments pass downward from the interosseous ligaments of the distal row (of carpal elements) to end in depressions of the opposed surfaces of the proximal ends of the metacarpal bones." This apparently describes the function of the notches observed.

In *Neohipparion* and *Nannippus*, the facet for the unciform is not usually so wide transversely as in *Astrohippus* and *Pliohippus* *s.s.*, it does not slope down at such a sharp angle, and frequently does not have a notch at all, or at most only a very slight one. In a large number of metacarpals examined, representing material referred to various species of Pleistocene and Recent *Equus*, the notch in the unciform facet was found to be reduced in many cases much as in

Neohipparion. The facet for the unciform takes up a greater portion of the proximal surface of the bone in Equus, however.

Examination of metacarpals of Neohipparion leptode from the Thousand Creek, and of Nannippus from the Miñaca fauna of Chihuahua indicates that the two features of volar protuberance below the proximal end and reduction in size or lack of the notch in the facet for the unciform are probably persistent in the later Tertiary three-toed horses, at least.

An attempt was made to find diagnostic values in the angle at which the unciform facet slopes outward and downward. It was thought that the degree of the angle might be of help in separating metacarpal elements, and may prove to be different in the two species of Pliohippus in the fauna. Examination of a large number of bones from several species indicates that the angle is of limited use in generic identification. It can be stated, for instance, that in Pliohippus mexicanus and in Astrohippus stockii, the unciform facet is likely to be inclined to the horizontal at an angle of approximately 45°, and that in those three-toed horses that have been studied, as well as in Equus, the angle is usually not so great. However, specimens were found in the last two groups with rather sharply inclined facets for the unciform. No consistent differences were observed in the nature of these facets between P. mexicanus and A. stockii.

Furthermore, it should be mentioned that in the course of the detailed examinations, the author was impressed with some of the individual variations found in shape and nature of facets of carpal and tarsal elements and metapodials. When those characters that appeared to be significant were found, they were checked against a large series of material belonging to Pleistocene Equus and available from San Josecito cave, Mexico, all of which almost certainly represents a single species. A single example of these variations will be given.

A study of a large series of specimens representing the magnum in the Yepomera collection disclosed a striking variation in the distal facet articulating with the trapezoid. A double facet, in place of a single articulating surface, exists in some specimens, one of which is directed upward and inward and articulates with the trapezoid, while a second lower facet, separated by a sharp corner from the first, is directed inward and slightly downward, to articulate with a corresponding facet on metacarpal II. In other cases the distal facet for the trapezoid is parallel to the proximal articulation, and is almost vertical in position, with no facet for the splint. In the latter specimen the facet for the trapezoid meets the distal surface of the magnum at almost 90°.

Examination of Recent horse material, and of the fossil series from San Josecito cave series indicates that the facets described are variable, and that both types of facet development occur in *Equus*. However, that of the first type described in the fossil material from Yepomera is more common in *Equus*. Judging from the diagram presented by Matthew (1926, p. 144, fig. 4), the second type of articulation would seem to be the more advanced.

Two nearly complete humeri, a femur, several radii, and tibiae, as well as broken portions of all these bones appear to represent *A. stockii* in the collections. The femur, and more particularly the humeri, are quite short in comparison to the ratios of similar elements to metapodials found in most pliohippine horses. The possibility that the humeri might belong to *Nannippus* has been considered, but is believed to be unlikely, in view of the sparse representation of other *Nannippus* material in the collections. Furthermore, many incomplete fragments in the collections show that a number of individual specimens of this element are of approximately the same size range.

The proximal limb elements, and the tibia show no noteworthy features, other than size. It is different in the case of the radius. Radii in the collections fall into three definite size groups, representing *A. stockii*, *P. mexicanus*, and *Neohipparion*, the elements of the last being intermediate in size between the other two. The radii of the two species of *Pliohippus* are quite similar, except in size, and show a fusion of the ulna much as in modern horses. The shaft of the ulna is reduced to a thin sliver, and in most instances terminates abruptly about half way down the shaft of the radius.

In the radii referred to *Neohipparion*, the shaft of the ulna is reduced and fused, but can be traced as a distinct crest on the postero-external portion of the radius all the way to the distal end. A comparison of the bone with radii of *Neohipparion leptode* from Thousand Creek shows that the reduction and fusion is more complete in specimens from Mexico than in the Thousand Creek form. A greater development of the ridges on the front of the distal portion of the radius appears to be another way in which *Neohipparion* differs from the other two forms.

Measurements and proportions of *A. stockii* are presented in a later section.

Comparisons and Affinities

P. (*A.*) *stockii* resembles *P.* (*A.*) *ansae* from the Hemphill beds of Texas in several ways. Some of the features in which these two forms differ have been mentioned, but will be re-emphasized here. Upper cheek teeth of *A. stockii* differ from those of the Texas horse in being slightly smaller and more slender, straighter-crowned, and in possessing a much more advanced protocone with anterior projection and lingual groove. Lower teeth of *A. stockii* differ from those of *A. ansae* in having more flattened external walls on protoconid and hypoconid, more divergent and attenuated metaconid and metastylid, and deeper and more broadly rounded gutter between metaconid and metastylid.

A. stockii also has smaller and more slender metapodials than *A. ansae*. In all features considered to be progressive in equid evolution, *A. stockii* is more advanced than *A. ansae*. Size is the only exception. Because of this, and likewise because of the relationships of the associated horses in the assemblage, the Yepomera fauna is thought to represent a later zone in the Hemphillian stage than the type Hemphill of Texas. Nevertheless, it does not appear probable that *A. stockii* is directly descended from *A. ansae*. Judging from the degree of similarity between the Hemphill and Mexican faunas it is difficult to postulate the necessary amount of time and evolution required to explain the dissimilarities between the two horses in question.

R. A. Stirton (oral communication) called the author's attention to a fossil species of horse from the Christian Ranch fauna of Texas that is likewise clearly advanced beyond *A. ansae*, and is apparently from deposits younger than the Hemphill formation. This *Astrohippus* from the Christian Ranch is much nearer *A. ansae* than it is to *A. stockii*, being not nearly so precocious as the latter. *A. stockii* would thus appear, from these considerations, to be an offshoot at an early stage from the line leading from *A. martini* through *A. ansae* to the Christian Ranch form.

One other small horse of the Central American Pliocene should be compared with *A. stockii*. This is the species, *Pliohippus hondurensis* Olson and McGrew (1941), from the Rancho Lobo locality in the Gracias formation of Honduras. The Gracias contains a fauna considered to be approximately equivalent to the Clarendonian faunas of North America.

Examination of the fossil material from Honduras shows that *A. stockii* differs noticeably from *P. hondurensis*. Measurements indicate that the Central American form is distinctly smaller than *A. stockii*, in fact, it is the smallest known horse assigned to the genus *Pliohippus*. *P. hondurensis* further differs from *A. stockii* in possessing upper teeth with greater longitudinal curvature of crowns and more primitive, rounded protocones. The lower teeth have rounded metaconids and metastylids, suggesting a greater resemblance to teeth of *N.* cf. *minor* of the Yepomera beds than to *A. stockii*.

From the foregoing it would appear that *A. stockii* is definitely a distinctive species. The characters in both upper and lower dentition are the most advanced of any seen in pre-Blancan horses excepting the hipparions. The horse is smaller than any described Hemphillian species, again excepting those of the hipparion group. Its probable position in the uppermost part of the Hemphillian stage and its precocious characteristics would seem to remove it from the line of ancestry of any known later Equidae. The reasons for this contention are:

1.) The disparity in size between *A. stockii* and known species of *Plesippus* is too great to allow the former to be considered ancestral to the latter, particularly since one specialization of *A. stockii* seems to be a decrease in size. Even *A. ansae*, a larger form, was thought by Stirton (1940) to be the possible ancestor of such small, geologically later horses as *Equus tau*. Evidence against the latter view is the lack of intermediate Blancan forms, with possible exception of *Plesippus cumminsii*. The latter species, however, may be a small variant of *P. simplicidens* (Meade, 1945).

2.) In addition, features seen in the dentition of *A. stockii*, as for example, shape of protocone, flattening of protoconid and hypoconid walls, metaconid-metastylid groove, and the shape of the individual cusps of metaconid and metastylid are too highly specialized to support the view that *A. stockii* is ancestral to known species of *Plesippus*. The latter are generally more primitive themselves in the characters mentioned. McGrew's (1944) view that *A. ansae* might be ancestral to Pleistocene and Recent *Equus*, through unknown Asiatic forms, would not seem to be probable in the case of *A. stockii* because of features pointed out in the lower cheek teeth. These include the shape of metaconid and metastylid, and the persistent development of parastylids and hypostylids on deciduous lower cheek teeth.

3.) It is significant that a type of horse associated with *A. stockii* in the Yepomera fauna, namely, *Pliohippus* (*Pliohippus*) *mexicanus*, n. sp. possesses characteristics in which it more nearly approaches the ancestor of the plesippine horses, and of most modern forms as well.

It thus appears probably that *A. stockii* is not near the direct line of ancestry of any later horses. The question of its antecedants is less clear. The assignment to the subgenus *Astrohippus* is based on certain morphological similarities to *A. ansae*. This would suggest that the species has branched from the phylogenetic stem advocated by Stirton (1940) which includes *Merychippus* (*Protohippus*) *perditus*, *Pliohippus* (*Astrohippus*) *martini*, and *P.* (*A.*) *ansae*. This is not, however, the only logical possibility.

The straightness of crown in upper teeth, general simplicity of enamel pattern, small size and lingually directed protocone in some specimens suggested early in the present study that ~~wo~~ two similar species might be represented by the material, namely, one here referred to *A. stockii* and definitely related to *A. ansae*, and the other, an advanced species of the genus *Calippus*, now known by two species from the Clarendonian.

A brief summary of what is known about the genus *Calippus* will help to explain the possible relationships. Matthew and Stirton (1930) proposed the name as a subgenus of *Protohippus*, designating *Protohippus placidus* as the subgenotype. Stirton (1935, 1936) raised *Calippus* to generic rank, and referred to it certain species formerly assigned to *Protohippus*, then believed to be in the direct line of ancestry of *Equus*. *Protohippus* was designated a subgenus of *Merychippus*. *Protohippus ansae* thus became *Calippus ansae*. Hesse (1936) described *Calippus martini* from the Lavern zone of the Ogallala, considering it to be intermediate in structural features between *Merychippus* (*Protohippus*) *perditus* and *Calippus ansae*. Johnston (1937) described *Calippus regulus* from the Clarendon beds of Texas.

In the light of the new forms, Stirton (1940) removed *ansae* the genus *Calippus*, leaving two species, namely, *C. placidus* and *C. regulus* in the genus. He erected the subgenus *Pliohippus* (*Astrohippus*) and referred to it various species with advanced characteristics. The two species of *Calippus* are horses with hypsodont cheek-teeth of small size. The teeth are straight-crowned.

This brief summary emphasizes the similarity that exists between certain of the horses now referred to *Astrohippus* and those retained under the genus *Calippus*. A similarity of *Calippus* to certain nannippine forms from the Clarendonian has been noted by Stirton (oral communication), and is at present the basis of a study being conducted at the University of California.

The only known Tertiary horses that may be regarded as descendants of described *Calippus* species, other than those formerly referred to the genus, are *Pliohippus hondurensis* and *P.* (*A.*) *stockii*. Olson and McGrew (1941) suggest that the extreme curvature reported in the upper teeth of *P. hondurensis* seem to remove it from relationship to the *Calippus* group.

Considering the time relationships involved, a species of *Calippus* could well be in the line of ancestry of *A. stockii*, since no species are known through the the Hemphillian stage. Comparisons of *A. stockii* with teeth of *C. regulus* Johnston show several similarities, in spite of the obvious differences in size and in general stage of evolution of the two forms.

The most outstanding similarity is in the straightness of crown in the upper teeth of both species. Teeth of *A. stockii* are somewhat straighter, but those of *C. regulus* are straighter than in most species of *Pliohippus*. A second point of similarity is seen in the simplicity of the enamel pattern. Although the protocone in *C. regulus* is primitive in some respects, it is quite elongate, relatively, and in some teeth forms a buttress projecting inward beyond the hypocone. The separation of the posterior tip of the protocone from the hypocone gives rise to the inward slant of the protocone that has been used to characterize the genus (Stirton, 1940). This feature is seen in many teeth of *A. stockii*, particularly in the smaller, well-worn teeth.

Although the teeth of *Calippus* in general have been described as having delicate styles (Stirton, 1940, p. 188), Johnston (1937) describes them as "well developed". The styles are more commonly delicate than not, but some teeth from the Clarendon beds of Donley County, Texas, show styles that are relatively as heavy as those in some species of *Pliohippus*. The styles are usually pointed externally, but are slightly flattened in teeth with heavier styles.

One important difference between A. stockii and C. regulus is the frequency with which the protocone in teeth of the latter become connected with the hyposelene in later stages of wear. This connection has not been observed in several hundred teeth of A. stockii that were examined. Absence of this posterior connection of the protocone is listed by Stirton(1940) as characteristic of the subgenus Astrohippus. It occurs in many teeth of Pliohippus s.s.

In the lower teeth of C. regulus, the metaconid and metastylid are generally rounded, but in some cases are narrowed, and diverge in a manner somewhat like that seen in A. stockii, and to a lesser extent in A. ansae. The groove between the two cusps varies in shape from a rather sharp V to an open U. In segeral specimens of C. regulus from West Texas the metaconid and metastylid are rather widely separated to the base of the tooth.

The upper teeth of A. stockii may be derived from those of C. regulus with the following changes: 1) increase in size; 2) slight increase in relative size of protocone with development of "heel" and grooving of lingual border; 3) development of slight complication of enamel pattern near crown of tooth; 4) slight relative strengthening of styles; and 5) complete loss of connection between protocone and hyposelene. Morphological changes in the lower teeth would include loss of parastylid on permanent teeth, further attenuation of metaconid and metasylid, and broadening and deepening of the groove between.

Derivation of A. stockii directly from A. ansae would require the following changes in upper cheek teeth of the latter species: 1) decrease in size, with increase in relative hypsodonty; 2) slight straightening of crown; 3) modification of protocone by strengthening of incipient "heel" and lingual groove, and lengthening of cusp. The major changes in the lower dentition would consist of: 1) further attenuation and divergence of metaconid and metastylid; 2) greater separation of metaconid and metastylid; and 3) flattening of protoconid and hypoconid.

Derivation of *A. stockii* from an ancestral form somewhere intermediate between *A. martini* of the Clarendonian stage and *A. ansae* would perhaps be simpler. *A. martini* is slightly larger than *A. ansae*, and nearer in general size to *A. stockii* than is *C. regulus*. It is more primitive in hypsodonty and curvature of crown of upper teeth than *C. regulus*. The lower teeth figured by Hesse (1936, fig.2) show some development of the attenuation of metaconid and metastylid. However, Stirton (1940, p. 190) states that the teeth referred to *A. martini* may belong to *Mannipus gratus*.

The above discussion appears to indicate that the problem of the ancestry, and thus generic assignment of *A. stockii*, is open to doubt. As the total range of variation in teeth of the small advanced form from Yepomera became apparent, it was realized that only one species is present, and that it shows greatest morphological affinities to *A. ansae*, although differing from it in many characters. It is probable that the similarity of smaller teeth from the Mexican collection to *Calippus* is more or less fortuitous. A certain degree of resemblance in some characters among all of the forms mentioned above might be expected, in view of certain basic similarities, as indicated by the rather complex history of the nomenclature applied to certain species, some having been assigned at various times to both groups considered as containing possible ancestors of *A. stockii*.

The new species is thus assigned to the subgenus *Pliohippus* (*Astrohippus*) on the basis of what is considered good evidence, but with the realization that such assignment is possibly open to debate. The shape of the metaconid and of the metastylid in lower cheek teeth is considered one of the strongest bits of evidence. It should be mentioned here that the new species assigned to *Astrohippus* requires certain modifications in the definition of that subgenus. This will be discussed later, following description of another new species that throws some light on the subgeneric groups within the genus *Pliohippus*.

Pliohippus (*Pliohippus*) *mexicanus* n. sp.

Type.- C.I.T. No. 3697, a portion of a left maxillary, with P2-M3, and anterior portion of zygomatic ridge.

Referred Material.- Several skull and jaw fragments, isolated teeth, and limb and foot material.

Type Locality.- C.I.T. Loc. 286. Referred material from same locality and others at approximately same stratigraphic level.

Fauna.- Yepomera, western Chihuahua, Mexico.

Diagnosis.- Size approximately same as *P. osborni* and *P. interpolatus*. Upper cheek teeth with crowns slightly to moderately curved. Curvature less than in *P. interpolatus*, about as in *P. osborni*. Protocone usually large and elongated, with well-developed anterior projection, usually with faint to pronounced lingual groove. Protocone much as in species of *Plesippus*. Styles of moderate to heavy development. Fossettes more crescentic than in *P. osborni*, with moderate degree of crenulation of fossette borders in upper half of crown. Pli protoloph, pli protoconule, pli hypostyle usually present. Post-protoconal valley deep, with or without pli caballin. Lower cheek teeth with rounded metaconid, round to angular metastylid. Metaconid-metastylid widely separated to base of crown, with V-shaped groove. Protoconid and hypoconid with flattened walls. Pli caballinid sometimes present in early stages of wear. Parastylid and metastylid present or absent on lower milk molars.

Description.-

Upper Cheek Teeth:

The upper cheek teeth of *Pliohippus mexicanus* n. sp. are of particular interest because of the near approach of some specimens to teeth referred to species of *Plesippus* from the Blancan stage. In straightness of crown, form of protocone, and general enamel pattern, some teeth from the Yepomera fauna approximate closely teeth of a plesippine horse from the Miñaca fauna. In their smaller size, degree of curvature of some specimens, and more primitive appearance of protocone in some individuals, teeth of *P. mexicanus* show clearly their pliohippine affinities. Nevertheless, *P. mexicanus* appears to be more closely related to the Blancan *Plesippus* than any other known species of horse from the North American Hemphillian stage.

In size, teeth of *P. mexicanus* are about like those of *P. interpolatus* and *P. osborni*. The last named species from the Eden Pliocene of California is not well known, but available material suggests that *P. osborni* differs appreciably in size from the two compared with it. Small teeth of *P. mexicanus*, usually well-worn molars, approach in occlusal dimensions the larger, unworn teeth of *P.* (*A.*) *stockii*, n. sp. At the other extreme, teeth are found that are almost as large in cross section, but not in height of crown, as teeth of the Miñaca *Plesippus*, and that are fully as large as, or larger than, teeth of *Equus* from the San Josecito cave Pleistocene of Mexico.

In relative hypsodonty, or height of crown relative to cross sectional dimensions, teeth of *P. mexicanus* slightly exceed those of *P. interpolatus*, and are about equal to those of *P. osborni*, as well as can be judged from material examined. They are greatly exceeded in this character by teeth of *P.* (*Astrohippus*) *stockii*. The teeth of the latter horse are fully as high crowned as are those of the larger horse from the same fauna, but they are much more slender.

The exaggerated degree of taper in antero-posterior length relative to height of tooth crown, as observed in *Astrohippus stockii* and Pliohippus leardi is not observed in P. mexicanus. The teeth do taper somewhat, but only slightly. A vestigial first premolar is present or absent.

In enamel pattern of occlusal surface, upper cheek teeth of P. mexicanus display the most Equus-like characters seen in pre-Blancan horses, with the exception of Astrohippus stockii. The protocone shows considerable variation in shape, but characteristically has a well developed anterior projection and lingual groove. Some individual teeth, and a few associated tooth-series show protocones of a small and primitive shape, and some protocones with an anterior projection are not lingually grooved. By far the greatest number of teeth in the collection, however, have protocones that approximate the shape seen in species referred to Plesippus, or in modern species of Equus.

In some stages of wear, the pattern on the occlusal surface is practically identical with that seen in Astrohippus stockii. The teeth are separable from those of the latter on the basis of size and relative hypsodonty, however. It may be remarked that it has been found easier to segregate teeth of the two pliohippine forms from the Yepomera fauna than to distinguish between some individuals of Astrohippus ansae and P. interpolatus in the Hemphill collections.

The protocone in the Mexican species ranges in shape from round to elongate-oval, being in some cases reniform, because of the anterior projection and the lingual groove (fig. 4). J. R. Schultz (1936, fig.1, and Plate 2, fig. 2), illustrates upper cheek tooth-series from several species of Plesippus. In some of those illustrated the protocone shows characters less advanced than in many teeth of the Mexican Pliohippus.

A pli caballin is present or absent. The post-protoconal valley tends to be wide, and to extend far into the tooth. In some teeth

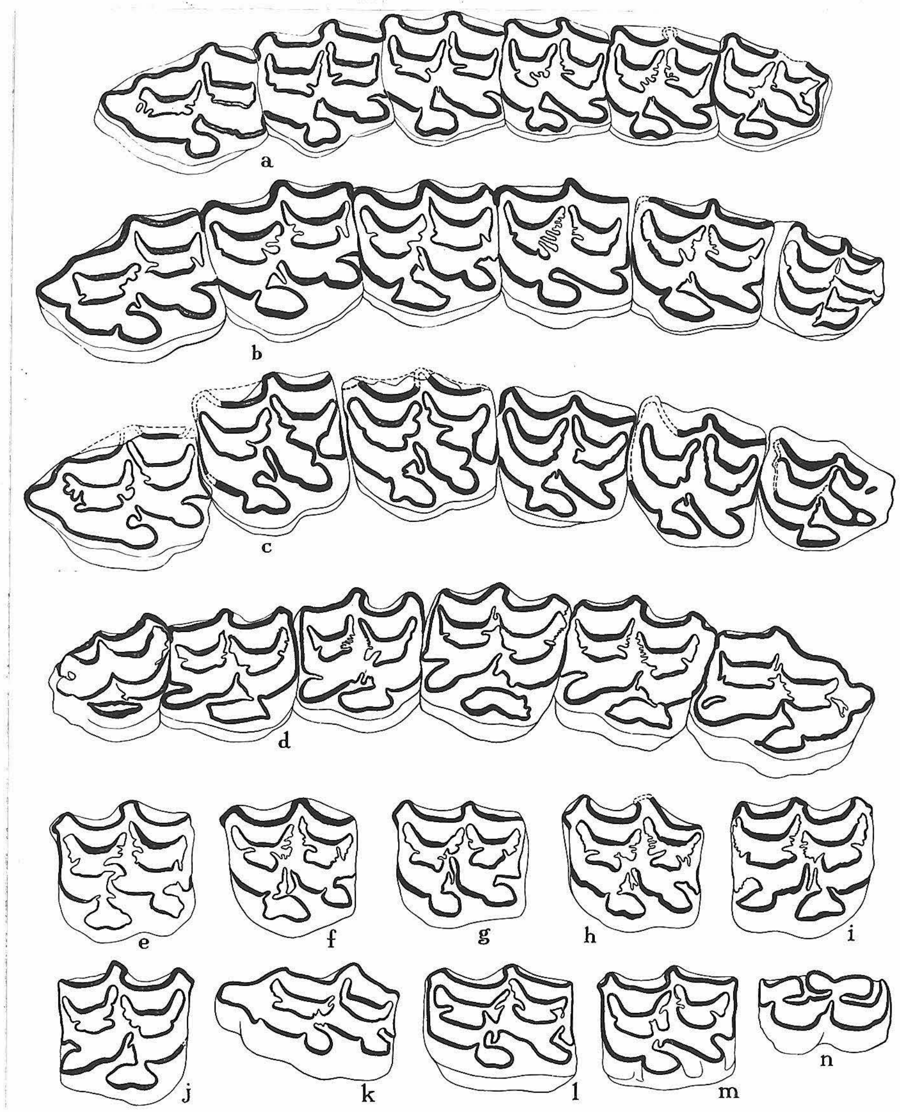

Fig. 4. Pliohippus (Pliohippus) mexicanus, n. sp. Permanent and deciduous cheek teeth. a. No. 3697, type, upper cheek tooth series, C.I.T. Loc. 286; b. No. 3701, upper cheek tooth series, C.I.T. Loc. 275; c. No. 3703, upper cheek tooth series, C.I.T. Loc. 291; d. No. 3705, upper cheek tooth series, C.I.T. Loc. 275; e. No. 3728, upper third premolar, C.I.T. Loc. 275; f. No. 3727, upper fourth premolar, C.I.T. Loc. 276; g. No. 3734, upper third premolar, C.I.T. Loc. 289; h. No. 3726, upper third premolar, C.I.T. Loc. 289; i. No. 3736, upper third premolar, C.I.T. Loc. 276; j. No. 3729, upper fourth premolar, C.I.T. Loc. 275; k. No. 3724, upper deciduous second molar, C.I.T. Loc. 275; l. No. 3730, upper deciduous third molar, C.I.T. Loc. 289; m. No. 3725, upper deciduous fourth molar, C.I.T. Loc. 289; n. No. 3733, lower deciduous third (?) molar, C.I.T. Loc. 275. All figures two-thirds natural size. Calif. Inst. Tech. Paleont. Coll., Yepomera Pliocene, Chihuahua, Mexico.

where this valley is very deep, the pli caballin is developed to a marked degree, and may even be bifurcate. A deepening of the post-protoconal valley is mentioned by Stirton as a progressive feature found in *Equus* and some other horses, particularly in some teeth of *P. interpolatus* (Stirton, 1941, p. 438).

The pre-protoconal groove is much as in *Astrohippus stockii*, and is one factor in bringing about the similarity of shape of protocone in some tee6h of both species. As in the smaller form, this groove is placed farther from the lingual border of the tooth than in most species of *Pliohippus*, is deeper, and is directed more posteriorly than externally, even in some well-worn teeth. A similar feature is seen in the few known teeth referable to *P. osborni*, but not in the teeth from the Mt. Eden locality referred to *P. edensis*. In *P. interpolatus*, the groove is more likely to be a notch, nearer the lingual border of the tooth, and pointing in the direction of the mesostyle. Some teeth of *P. interpolatus*, are, however, moderately advanced in this, as in other features. The depth of the pre-protoconal groove in *P. mexicanus* contributes to the characteristic narrowness of the isthmus between the protocone and protoselene, a feature which is persistent to some degree even in later stages of wear.

In addition to a somewhat more advanced type of protocone, upper cheek teeth of *P. mexicanus* exhibit another detail in the enamel pattern that seems to mark them as being more progressive than those of *P. osborni*. This feature is the moderately-developed complexity of the fossette borders, a feature that is developed to a high degree in *Hipparion* and in some species of *Equus*. This crenulation of the fossette borders varies with stage of wear, position in the tooth series, and from individual to individual. However, with very few exceptions, teeth of the Mexican horse exhibit a certain degree of this complexity in teeth that are less than one-half worn, and in some teeth that show greater wear.

The opposed borders of the fossettes are moderately plicated in most specimens that are less than one-half worn, and even well-worn teeth usually exhibit a pli-protoconule and a plication at the antero-internal corner of the post-fossette. Most teeth also exhibit a pli-hypostyle and a pli protoloph, which may disappear before the pli protoconule does. The slight complexity in the enamel pattern of teeth belonging to Astrohippus stockii disappears after the crown has been worn a few millimeters in depth.

In teeth of P. osborni and P. edensis from Mt. Eden, the pli protoconule is the only fold in the fossette borders that appears to occur with any degree of regularity, and it disappears at an early stage of wear (Frick, 1921, figs. 103a-103f).

A slight fold at the antero-internal corner of the post-fossette is present in a few of the Mt. Eden teeth, and one specimen, UCMVP No. 24039 (Frick, 1921, figs. 119a-119c), a slightly worn premolar referred to P. edensis, subform A, Pliohippus spectans-like, has crenulations in the fossette borders somewhat as in some teeth of P. mexicanus. No. 24039 is a large, straight-crowned tooth, with a primitive protocone. It respresents a second premolar, and is probably referable to the same species as the type of P. osborni.

Styles on upper cheek teeth of P. mexicanus are moderately to heavily developed. They overlap in this character the range of variation seen in P. osborni, but many teeth of the Mexican horse show styles much stronger than any seen in teeth from Mt. Eden. There is, of course, no large series of P. osborni available on which basis one might demonstrate to what extent these characters equal those seen in *P. mexicanus*. The heavier styles on teeth of *P. mexicanus* are flattened externally, and some are grooved. These are progressive features.

Although some teeth of *P. mexicanus* are rather strongly curved, the majority of them are only slightly curved, no more so than many teeth assigned to species of *Plesippus*. The degree of curvature is slightly greater than that seen in *Astrohippus stockii*, less than that in most teeth of *P. interpolatus*, and about equal to that in *P. osborni*. Plate II illustrates the range of curvature.

Deciduous Upper Cheek Teeth

The upper milk teeth of *P. mexicanus* are relatively more primitive than those of *A. stockii*. A lingual groove is not present in most milk molars of the former species, although some teeth, always deciduous molars three and four, show a pronounced anterior projection on the protocone. In this respect they are much more advanced than milk molars of *P. interpolatus*. The enamel pattern shows more complication than in the permanent cheek teeth. The protocone progresses in length of tooth crown toward the posterior end of the row. Upper milk molars of *P. osborni* seem to display more lingual grooving of the protocone than is seen in the Mexican species, but this may be due to stage of wear of specimens examined, since the feature appears to be at its maximum development in intermediate stages of wear. The complication of enamel is much less in the Mt. Eden species.

Figures 4k to 4m, 5a, and 5b illustrate the characters displayed by milk molars of the new species from Mexico. These teeth may be compared with corresponding parts of the dentition of *Plesippus francescana*, identified in the Coso fauna of California (Schultz, 1936, plate 2, figs. 3 and 4), and of *Pliohippus interpolatus* in the Hemphill fauna of Texas (Matthew and Stirton, 1930, plate 48, fig. 2, and plate 49, fig. 2) to show the advanced evolutionary stage represented by the Mexican material.

Lower Cheek Teeth

The lower cheek tooth-series of *P. mexicanus* displays advanced characteristics that are in keeping with those of the upper teeth. The metaconid and metastylid are widely separated to the base of the crown by a groove which is generally V-shaped, but which opens out slightly in extreme stages of wear. The metaconid is usually larger than the metastylid, a feature noted in most species of *Pliohippus*, *Plesippus*, and *Equus* available for comparison, but which is in contrast to the situation observed in *A. stockii*, in which the cusps tend to be sub-equal in size.

The metaconid is round to oval in shape, and the metastylid is round or oval to angular. The groove separating the columns is readily discernible on the lingual side of the tooth, extending to the base (Pl. II). Three prominent columns are visible in this view of the tooth, all broadly rounded or flattened, with sharp ridges at the anterior and posterior edges, the last two representing respectively the paralophid and hypoconulid. The sub-equal columns represent the metaconid, metastylid, and entoconid. In *A. stockii*, the metastylid is seen as a sharper and narrower column than the other two, and the anterior and posterior ridges are only faintly seen, if at all. The difference in the two species is not related to relative sizes of metaconid and metastylid, but to the shape and degree of lingual divergence of these cusps.

In occlusal view the metaconid-metastylid column looks somewhat like a figure eight, with the two portions of unequal development, but more or less in line with the longitudinal axis of the tooth, while in A. stockii, as noted under the description of that form, the two cusps diverge medially from their point of juncture.

The entoflexid is more developed than in A. stockii, and has an expansion at the anterior end, which accounts to a great extent for the differences observed in the shape of the metastylids in the two forms. The same relationships hold for the posterior end of the metaflexid and metaconid. Accessory folds appear on the internal walls of the metaconid and hypoconid.

A pli caballinid is developed in the earliest stages of wear in some teeth. A parastylid is also occasionally observed, usually in the lower portion of the crown, although it may be present throughout most of the length of the crown.

The external walls of the protoconid and hypoconid are flattened, the teeth being quite Equus-like in this character. Figures 5g to 5i illustrate the characteristics displayed by the lower cheek teeth of the new species. It may be observed that there is a considerable range of variation in some characters which have been considered occasionally as of diagnostic value in describing isolated specimens. This is particularly evident in the character of transverse thickness of the crown. A tiny first premolar is seen in one mandible containing deciduous teeth. Gazin reports this tooth as usually occurring in young individuals of Plesippus from Hagerman (Gazin, 1936, p.302).

Deciduous Lower Cheek Teeth

Lower milk molars of P. mexicanus are shorter crowned and narrower than the permanent teeth, as is to be expected. They also differ in several structural features. External walls of protoconid and hypoconid are more rounded than in the permanent teeth, but may be moderately flattened. A small parastylid is present on all teeth examined. This structure becomes strongly developed in some instances, usually toward the base of the crown. Some teeth in early stages of wear do not show the parastylid on the occlusal surface, but it is to be seen on the sides of such teeth (Figs. 5c to 5f, 6a).

A hypostylid is present in most teeth examined, but does not appear to be strongly developed. It is best seen on DP$\overline{3}$, and in some instances the external tip is isolated. Like the parastylid, the hypostylid frequently is not apparent until later stages of wear. A faintly developed pli caballinid is seen in some teeth in early stages of wear.

The metaconid, which is larger than the metastylid, tends to be elongate, with parallel sides, somewhat as in the teeth of *A. stockii*, although it is more rounded in some individuals. The metastylid is oval. The two cusps diverge from their point of juncture in early stages of wear, but are usually aligned nearly parallel to the long axis of the tooth in later stages. Both cusps, even the attenuated examples of the metaconid, are constricted near the point of juncture. The metaconid-metastylid varies with wear from an open V to a very shallow U shape. In some well-worn teeth, the notch is little more than a small, rounded inflection.

The lower milk teeth of *Pliohippus* from the Mt. Eden beds and illustrated by Frick (1921, figs. 157a-157c) compare rather closely with slightly worn teeth of the deciduous series in *P. mexicanus*. U.C. Nos. 23510 and 23286 are described as representing P$\overline{4}$ to M$\overline{3}$ and P$\overline{2}$, P$\overline{3}$, and M$\overline{1}$ respectively (Frick, 1921, figs. 131 and 130). 23510 is a mandibular fragment with apparently deciduous third and fourth

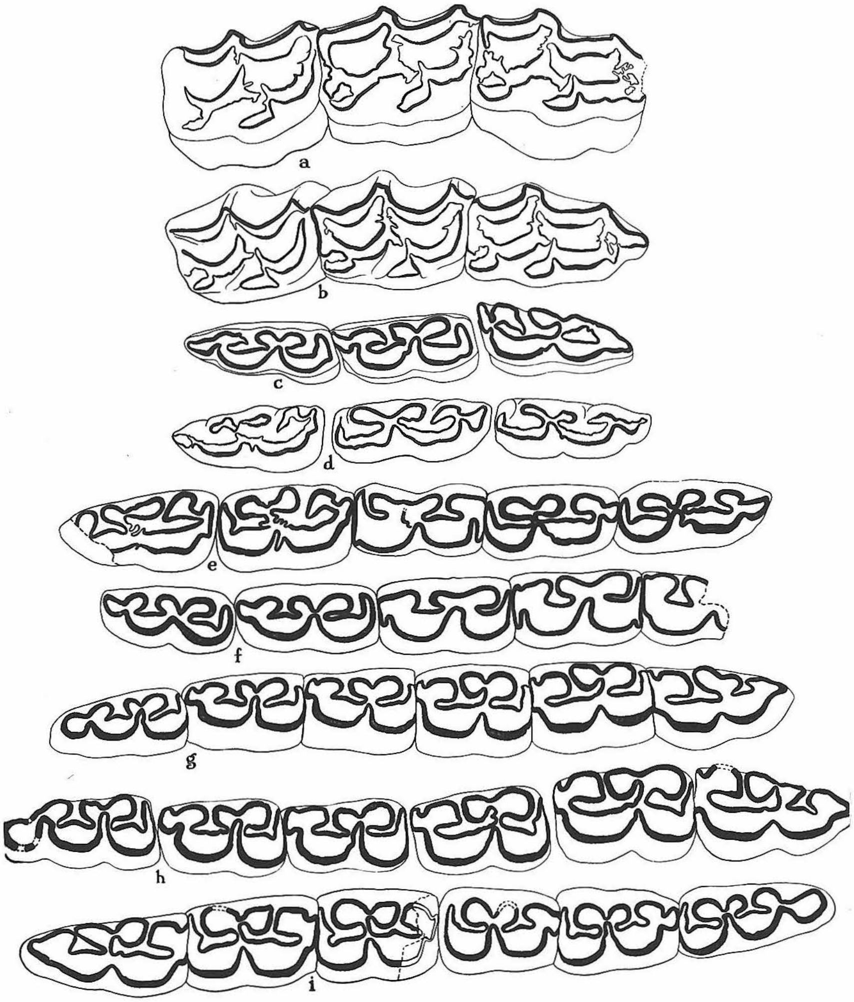

Fig. 5. *Pliohippus* (*Pliohippus*) *mexicanus*, n. sp. Permanent and deciduous cheek teeth. a. No. 3721, upper deciduous molars, slightly worn, C.I.T. Loc. 275; b. No. 3720, upper deciduous molars, slightly worn, C.I.T. Loc. 275; c. No. 3702, lower deciduous molars, moderately worn, C.I.T. Loc. 275; d. No. 3716, lower deciduous molars, slightly worn, C.I.T. Loc. 275; e. No. 3710, lower deciduous molars, first and second molars, C.I.T. Loc. 276; f. No. 3719, lower deciduous molars, first and second molars, C.I.T. Loc. 275; g. No. 3698, lower cheek tooth series, moderately worn, C.I.T. Loc. 275; h. No. 3699, lower cheek tooth series, moderately worn, C.I.T. Loc. 275; i. No. 3700, lower cheek tooth series, moderately worn, C.I.T. Loc. 276. All figures two-thirds natural size. Calif. Inst. Tech. Vert. Paleont. Coll., Yepomera Pliocene, Chihuahua, Mexico.

molars, and an associated deciduous molar two. No. 23286 displays the three lower milk molars, with the first true molar slightly worn. The pronounced development of parastylids and hypostylids, as well as the straightening of the internal walls of the metaconid-metastylid give support to this identification based on an examination of the original material. These teeth were tentatively referred by Frick to *P. osborni*, subform A.

A comparison of lower milk molars of *P. mexicanus* with the Mt. Eden specimens just mentioned shows that no appreciable difference is to be found between the two groups of teeth. This emphasizes the close relationship existing between the Mexican and Californian species, and also confirms Frick's tentative reference of the Mt. Eden material to the same species as the type of *P. osborni*. Lower milk molars of *P. interpolatus* that have been examined, seem not to differ in any material way from those of *P. mexicanus* and *P. osborni*. Parastylids and hypostylids are present in the teeth from the Texas Panhandle.

Facial Fossae

A distorted anterior portion of the skull pf *P. mexicanus* is represented by C.I.T. No. 3723. This specimen shows a zygomatic ridge that appears to be not unlike that seen in *A. stockii* and more recent equine skulls. Above the zygomatic ridge is a shallow, elongate malar fossa. The skull is distorted on both sides in this region, but the fossa appears to extend from just in front of the orbit to a point above the posterior margin of the first molar. A moderately deep lachrymal fossa is present. This appears to be slightly shallower than that seen in *P. interpolatus* (Matthew and Stirton, 1930, plate 46). It is slightly deeper, particularly at the posterior end, than the corresponding fossa in a skull of Plesippus francescana, C.I.T. No. 2020, from the Coso Mountain deposits, California of Blancan age.

A shallow groove on the side of the face leads down from the anterior end of the lachrymal fossa to a point above the roots of the first premolar. The skull is broken in front of the groove, and the nature of the buccinator fossa, if present, is not known. The frontal bones project forward in a V between the nasals along the mid-line of the top of the skull, as noted in A. stockii.

Limb Bones

The metapodials of P. mexicanus do not differ in any discernible way from those of A. stockii except in size. The characters by which the metapodials of the pliohippine horses in the collection may be distinguished from those of the hipparion types have been described above. Several radii are referred to P. mexicanus with some certainty because of size and the nature of the reduction of the ulna, as explained under the description of A. stockii.

A nearly complete femur, and several fragments probably represent P. mexicanus. The femur, although slender, is less so than that of Neohipparion leptode from the Thousand Creek, which form is a little larger, but slightly more primitive than the Mexican Neohipparion. A calculation of the ratio between metatarsals and the femur referred to P. mexicanus approximates closely similar ratios calculated from measurements given of material referred to Plesippus shoshonensis from Hagerman, data on a skeleton of Equus prezwalskii in the Moscow museum, and from a composite skeleton of Equus from San Josecito Cave, Mexico.

No complete humeri were found. Measurements on available material, and calculations of proportions of *P. mexicanus* will be given in later sections.

Three metapodials from locality 295 present an interesting problem. A metatarsal 310 mm. long, and two metacarpals, one 257 and one 271 mm. in length fall completely outside the range observed in the rest of the collection. Additional metapodial material from this locality falls into the size range observed in material from all the localities. It may be observed that when these giant bones are excluded, the metapodials from all localities approximate normal distributions, with a coefficient of variation of 3.1 for the metacarpals and of 2.8 for the metatarsals.

These aberrant bones are shown in Plate V, with more typical metapodials from Loc. 295 for comparison. That more than one individual is represented is apparent from the dissimilar proportions of the two metacarpals, and from the fact that both belong to the left side. Nothing in the remainder of the material from Loc. 295 throws any light on the relationships of the giant metapodials. They have been excluded from the statistical calculations, and are considered as abnormal examples. The bones show more resemblance to corresponding elements of *P. mexicanus* than they do to the three-toed horses. The spongy nature of the distal end of the shaft of the metatarsal suggests that this element did not belong to a fully adult individual.

Comparisons and Affinities

The only known species of Pliohippus that resemble to any extent *P. mexicanus* n. sp. are *P. osborni* and *P. interpolatus*. Of these, the Mexican species more closely approaches in its characters those seen in *P. osborni*. It is separated from the latter by the moderate complication of enamel in upper cheek teeth, larger and more advanced protocone, shape of fossettes, and development of heavier and flattened styles. P. mexicanus is readily distinguished from P. interpolatus by the straightness of crown and advanced protocone in upper cheek teeth and by flattening of protoconid and hypoconid in the lowers.

An examination of original material from the Mt. Eden Pliocene suggests that most, if not all of the fossil horse teeth occurring at that locality might be assigned to a single species. Certain teeth referred by Frick (1921) to various subforms of P. edensis are primitive in their development of protocone, as well as in some additional features. Although the material is fragmentary, these teeth all appear to be rather straight-crowned, insofar as the upper dentition is concerned. Teeth referred to P. mexicanus from Yepomera appear to demonstrate a range of individual variation as large as that seen in the total collection from Mt. Eden. A similar gange of variation is seen in the collection of upper molars of P. interpolatus from Hemphill, in which most of the teeth show protocones of primitive shape, but some have an incipient anterior projection.

Because of the scanty material from Mt. Eden, and the lack of specimens showing all stages of intergradation from primitive to advanced features, as are available from Yepomera, no attempt is made to propose synonymy for the Mt. Eden species. However, it is suggested that certain teeth referred to P. edensis, as for example U.C. Nos. 24039, 23207, and 23234 (Frick, 1921, fig. 119a-119c, fig. 117, and fig. 122b), among others might well belong to the same species as the type of P. osborni.

Regardless of the status of P. edensis, the new species of Pliohippus from Mexico appears to represent a form more advanced than P. osborni, as described originally. P. osborni shows characters which indicate that it is very likely near the line of descent leading to the Blancan horses of North America. This was recognized by Frick (1921) and later by Stirton (1940) when he assigned it to the subgenus *Astrohippus*. The discovery of *P. mexicanus* provides an intermediate form, nearer the plesippine group.

Thus, *P. mexicanus* is seen to be closely related to a fossil horse that was considered by Stirton in 1940 to represent a typical member of the subgenus *Astrohippus*. On the other hand, *P. mexicanus* shows certain similarities to *P. interpolatus*, which Stirton (1940) recognized as an advanced species of the subgenus *Pliohippus s.s.*, probably in the line leading to the South American horses. The degree of resemblance is not great, but *P. mexicanus* is closer to *P. interpolatus* than it is to *P. (A.) ansae* or *P. (A.) stockii*. This question will be discussed later.

Mention should be made of certain pecularities in the enamel pattern of upper cheek teeth of *P. mexicanus*. A fourth premolar, in an early stage of wear, displays an isolated protocone in one specimen (Fig. 4d). It is evident from the remaining teeth in the skull that the protocone becomes connected with protoselene as a result of a slight amount of additional wear. The specimen well illustrates the advanced nature of the protocone in the new form, including the narrowness of the isthmus connecting the protocone to the protoselene. *P. supremus* and *Equus fraternus* are reported as displaying an isolation of this cusp in early stages of wear (Stirton, 1941). A tooth of the latter horse from Florida became the type of *Hipparion princeps* (Leidy) because of this feature (Osborn, 1918; Simpson, 1930).

No particular significance is attached to the feature mentioned above, nor to another anomaly which suggests an atavistic tendency. C.I.T. No. 3703, representing complete right and left upper cheek tooth-series referred to *P. mexicanus*, shows three teeth, in early stages of wear, with open post-fossettes. The hypostyles of right P4 and left P3 and P4 have not joined the metalophs to close the fossettes, although M3 on each side has been worn to a fairly flat occlusal surface(Fig. 4c).

These two variations are mentioned here to illustrate the extremes in characters that may be expected when a large series of teeth of any species is examined. In any population, certain individuals may show a reversion to more primitive characters, while other individuals may foreshadow some character which might be of selective value, or linked to a character of selective value, in the evolution of the race. Isolation of protocone may be considered a progressive feature not attained by *Equus*, but one in which the hipparion group was more advanced than the modern horses.

Nannippus cf. *minor*(Sellards)

Teeth and limb elements in the Yepomera collection represent a species of *Nannippus* smaller than *N. lenticularis* from the Hemphill beds of Texas. A comparison with figures of specimens reproduced in Osborn's iconographic type revision of the Equidae (Osborn, H. F., Mem. Amer. Mus. Nat. Hist., n.s. vol. 2, p. 193, fig. 158, 1918), and in the original description (Sellards, 1916) indicates that the Mexican material cannot be distinguished at present from *N. minor* Sellards from the Bone Valley and Alachua of Florida. *N. minor* is known from a single tooth from the Bone Valley formation and from two referred teeth and referred limb elements from the Alachua.

Description of Material

Upper Cheek Teeth

In his description of the type tooth of *N. minor*, Sellards (1916, pp. 96-97, pl. 11, fig. 10, pl. 13, figs. 7 and 8) characterized the species as being of miniature size, with much complicated cement lake borders, and with an ellipsoidal protocone. Simpson (1930, p. 188) states that the complication of enamel pattern and shape of protocone are well within the range of variation observed in teeth of *N. ingenuus* and *Hipparion plicatile* found in the same formations, but that the size appears to be distinctive.

The range of variation observed in *Nannippus* teeth from Mexico includes all the characters attributed to the species from Florida. A great deal of the variation seen in proportions and in enamel pattern of the occlusal surface can be shown to be related to stage of wear.

Teeth of *N.* cf. *minor* are high crowned, with small cross sectional areas. The teeth taper from top of crown to the base so rapidly that the antero-posterior diameter near the base is little more than two-thirds that at the top of little-worn teeth. There is a less abrupt flaring out in this dimension near the occlusal surface than is sometimes seen in Astrohippus stockii. The taper in the Nannippus teeth is much more uniform as a rule, although the antero-posterior diameter of tooth crown diminishes more rapidly to a point about one-fourth of the way down the crown (Pl. I). Teeth less than approximately one-half worn are elongated, while those in a greater stage of wear are almost square in cross-section. There seems to be no great difference between molars and premolars in the degree to which this is true.

Little worn teeth are moderately curved, while those worn down below the middle point are slightly curved to straight. The curvature is thus in that portion of the tooth that also displays the greatest degree of change in length of occlusal surface.

The styles are thin and delicate, frequently pinched internally, expanding externally, and sometimes recurved toward the back of the tooth. The styles sometimes thicken slightly near the roots. Styles in premolars are only slightly heavier than those of the molars, and the greater relative degree of development of the parastyle usually seen in hypsodont horse teeth in the premolar portion of the dentition is not pronounced. This makes it necessary to rely largely on the factor of angle of occlusal surface in assigning isolated teeth to their position in the cheek tooth series.

The shape of the protocone varies within wide limits (Figs. 6c to 6f). Not enough information is available from the material in the collection to demonstrate definitely how much of this is due to position in the cheek tooth series, but apparently the protocone tends to lengthen slightly toward the back of the row. Most of the

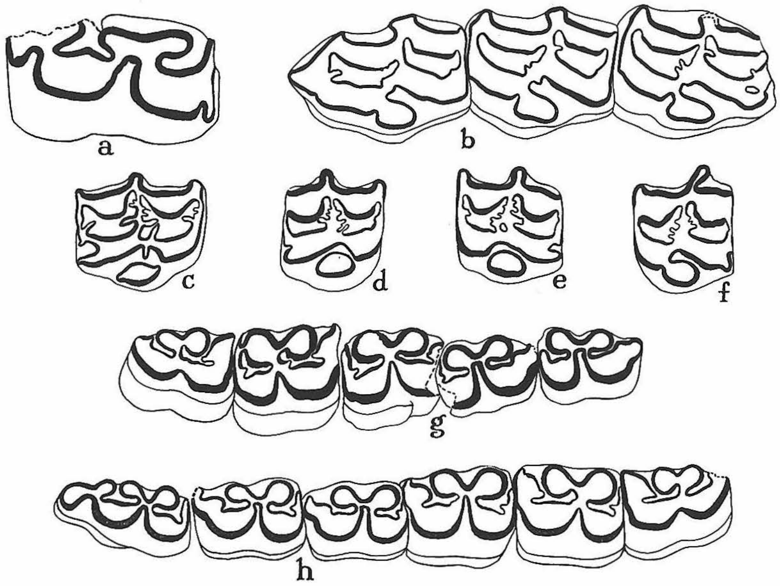

Fig. 6. Cheek teeth of Yepomera Pliocene Horses.

Pliohippus (*Pliohippus*)*mexicanus*. a. No. 3732, lower deciduous third(?) molar, C.I.T. Loc. 275.

Pliohippus (*Astrohippus*) *stockii*. b. No. 3694, upper deciduous molars, C.I.T. Loc. 289.

Nannippus cf. *minor*. c. No. 3758, upper first molar, slightly worn, C.I.T. Loc. 275; d. No. 3760, upper first molar, moderately worn, C.I.T. Loc. 275; e. No. 3922, upper second (?) molar, moderately worn, C.I.T. Loc. 275; f. No. 3923, upper third premolar, well worn, C.I.T. Loc. 275; g. No. 3752, lower premolars, first and second molars, moderately worn, C.I.T. Loc. 275; h. No. 3751, lower cheek tooth series, slightly worn, C.I.T. Loc. 275. All specimens natural size. Calif. Inst. Tech. Vert. Paleort. Coll., Yepomera Pliocene, Chihuahua, Mexico.

variation in size and shape, however, is directly dependent upon stage of wear. In little worn teeth the protocone is greatly elongated, almost spindle shaped, with pointed ends. The anterior end is bent outward toward the protoselene. With increasing wear the protocone becomes an oval and loses the points at the ends and the angular inflection seen at the center of the external side in earlier stages. In developing into an oval, some protocones are almost diamond-shaped at one stage.

During the latter half of wear of the crown, the protocone changes from an elongate oval to one less elongate, becoming almost circular in some teeth. The protocone becomes connected to the protoselene after approximately three-fourths of the crown is worn away in some teeth.

The fossette borders are moderately complex, tending to become more simple with increasing wear. A loop at the internal posterior corner of the pre-fossette is frequently isolated as a small lake in some stages of wear. The increasing simplicity of enamel pattern with wear, and the connection of the protocone with the protoselene causes some specimens in late stages of wear to resemble well-worn teeth of *A. stockii*, except for size.

A pli caballin is present or absent. The hypoconal lake, so frequently observed in members of the *N. gratum* group, has not been observed in the teeth from Mexico.

Most of the statements made concerning the characters seen in upper cheek teeth of *N.* cf. *minor* from Yepomera appear to apply in a qualitiative way to teeth of *N. lenticularis* from the Texas Panhandle. Comparisons of the Mexican material with a series of teeth of *N. lenticularis* from U.C. Loc. 20, Texas, and with casts of the type teeth indicate that upper molars of *N.* cf. *minor* have quite similar proportions in all stages of wear, but are smaller, and taper more rapidly toward the base. Certain teeth of the two species are found to have almost identical occlusal lengths, but in such cases the comparison is made between little worn teeth of the Mexican horse and half-worn teeth of N. lenticularis.

Lower Cheek Teeth

Lower cheek teeth of N. cf. minor are characterized by their small size, well rounded metaconid and metastylid, and rounded external protoconid and hypoconid walls. Metaconid and metastylid are subequal to equal in size, the anterior cusp being slightly larger in some instances. The two cusps are widely separated to the base of the crown by a broadly open, U-shaped gutter. The lingual side of the tooth shows two prominent, well-rounded columns separated by a wide, rounded valley (Pl. II). Just in front of the column representing the metaconid is a narrow groove, disappearing immediately above the base of the crown. In front of the groove, forming the antero-internal corner of the tooth is a thin ridge representing the paralophid. Posterior to the metastylid column is a broad, flat valley, sloping up to the ridge formed by the hypoconulid. This ridge is heavier than the one at the anterior corner. The entoconid does not show as a ridge or column on the lingual side of the tooth as is the case in the two horses described previously. This results from the fact that the hypoconulid extends farther lingually than the entoconid.

The external walls of protoconid and hypoconid are well-rounded. In most details of enamel pattern of occlusal surface, teeth of N. cf. minor resemble closely those of specimens referred to N. lenticularis (Figs. 6g, 6h). Both forms show a fairly constant development of a small posteriorly-directed fold at the anterior end of the metaflexid.

A small fold frequently seen opposite the entrance to the entoflexid in teeth of *N. lenticularis* has not been observed in those of *N.* cf. *minor*. A more important detail in which lower teeth of the two species differ is the presence of a parastylid in most teeth of *N. lenticularis*, and its absence in most teeth of the Mexican form. The style is best seen in isolated teeth as a small ridge. It usually extends from within 10 millimeters of the bottom of the tooth to a point somewhere in the upper half, sometimes almost to the top of the crown. The ridge is sometimes persistent to the base of the crown, but usually merges with the enamel wall of the protoconid a short distance above the base. This style is developed on only a very few teeth of the Mexican species, and then only very faintly.

Limb Bones

The morphology of the metapodials of *Nannippus* cf. *minor* has been considered under the description of *A. stockii*. Only two complete metatarsals and one metacarpal are available for study, but several broken proximal and distal ends suggest that the complete bones are typical in their proportions. This is also suggested by carpal and tarsal elements and phalanges, referred to the species on the basis of size, and agreeing in proportions with the referred metapodials.

The metapodials of *N.* cf. *minor* are distinctive for their extreme slenderness. A comparison with limb bones referred to *N. lenticularis* emphasizes the smaller size, and probably more slender proportions of the Mexican horse. Unfortunately no upper limb elements that could be referred with any degree of certainty to *N.* cf. *minor* were found in the collection. The phalanges that were referred to this species are separated on the basis of size. A tiny ungual phalanx of a side toe agrees in general shape and in proportions to comparable elements referred to Neohipparion cf. phosphorium. Plate III shows the character of the more distal portions of the limbs.

Comparisons

As previously pointed out, the type and referred specimens of N. cf. minor Sellards appear to show characters that fall within the range of variation observed in Nannippus material in the Mexican collections. No comparison on the basis of lower cheek teeth is possible. Sellards (1916, p. 97) describes a metacarpal which he believes might be referable to either N. ingenuus or N. minor. This element is stated to have the following dimensions: length, 185 mm., width of proximal articular face, 23 mm., width distal articular face, 24 mm. The single complete metacarpal in the Mexican collection is only 154 mm. in length, and much more slender. The Florida specimen exceeds in length the two metatarsals referred to N. cf. minor in the Yepomera assemblage. The bone from Florida is probably referable to N. ingenuus. A second metacarpal from Florida is described merely as being smaller than the first, with a proximal transverse width of 21 mm. This element is apparently smaller than the Mexican metacarpal.

Relationships of N. cf. minor to N. lenticularis have already been discussed. The two forms are probably closely related, the size and degree of development of parastylid being the only significant differences observed in the teeth. Metapodials of the Mexican horse are much smaller and relatively more slender. In view of the probable time relationships between the deposits in which the two species occur, it is thought unlikely that N. lenticularis is diredtly ancestral to N. cf. minor.

Comparisons with casts of types of additional species of Nannippus reveal that the small size of *N.* cf. *minor* is distinctive. *N. gratum* is larger in occlusal dimensions in teeth of corresponding height, and is itself distinctive along with *N. retrusus*, in the frequent development of a hypoconal lake. *N. ingenuus* teeth resemble those of *N.* cf. *minor* in most characters, but appear to be of significantly larger size.

The only other species at all similar to *N.* cf. *minor* are *N. montezumae* and *N. peninsulatus* from Mexico, and *N. venustus* from South Carolina. These three forms are all known from very little material. The species, *N. minor* from Florida, *N.* cf. *minor* from Yepomera, and small teeth from the Upper Snake Creek (Matthew, 1924) may represent the same species or, more probably, a closely related group of species.

A cast of the type of *montezumae* shows that this form approaches *N. lenticularis* more closely in dimensions than it does *N.* cf. *minor*. The protocone of the Lacualtipan tooth is more elongate, as in the neohipparions. *N. peninsulatus* is from a locality not widely separated geographically from the type locality of *N. montezumae*, and was considered to be synonymous with it by Gidley (1907). Illustrations of the type tooth of the Tehuichila form (Osborn, 1918, fig. 163) shows certain similarities to C.I.T. No. 3758, in height of crown, dimensions of occlusal surface, and general enamel pattern. No. 3758 is straighter-crowned, slightly smaller in area of occlusal surface, and has a shorter and more lenticular protocone. The figured tooth appears to be almost identical in height with No. 3758. The former gives practically no suggestion of a tapering in longitudinal diameter, so apparent in all little worn teeth of *N.* cf. *minor*.

Figures of teeth of *N. venustus* (Osborn, 1918, fig. 165) suggest that this little-known form is larger than N. cf. minor and has teeth of slightly different proportions.

A single tooth from the Upper Snake Creek, Nebraska, and in the paleontological collections of the Webb School, Claremont, California, corresponds to the description by Matthew (1924) of small teeth from this fauna. It clearly falls within the range of variation observed in the Mexican teeth. This might not be true if a less worn specimen were available. However, on the basis of present evidence, it is not possible to determine any specific differences when the Snake Creek tooth, N. minor of Florida, and teeth in the Yepomera collection are compared.

MEASUREMENTS

Measurements of teeth in the present study follow the methods outlined by Merriam (1913), unless otherwise specified. Calculations of various statistical data follow procedures explained in Simpson and Roe (1940), and by Simpson (1941).

Stage of wear of teeth causes a considerable variation in measurements in occlusal dimensions. This is particularly true of teeth which change rapidly in antero-posterior length with wear, as is the case with A. stockii and Nannippus cf. minor. In these species, measurements on teeth about one-half worn seem most satisfactory. Publication of the raw measurement data for each individual in such cases would facilitate comparisons, but is impractical. For this reason, measurements of some individuals are given in the present paper, and some data are grouped and treated statistically. Measurements of lower jaw material of A. stockii and P. mexicanus are considered together and treated statistically. Slightly worn and extremely worn specimens are excluded, but the relatively high coefficients of variation seen in some of these data reflect variations due to sex, stage of wear, and possibly other factors, as well as individual variation.

Lengths given for metapodials are greatest over-all lengths. For all other limb bones, the length given is taken between articulating facets along the lateral side of the bone.

One feature of considerable interest results from a study of the measurement data. This is the difference in size displayed by individuals of Astrohippus stockii from different field localities. The differences may be seen readily by examining the measurements, length of metapodials and length of lower molar series, of individuals from localities 275 and 276 (Tables 3, 5, 6).

These comparisons were made after preliminary examination of the fossil material suggested that the astrohippine teeth from locality 275 were in general larger than those from locality 276. Measurements of several variants indicated that the difference in size is such as to be statistically significant. This means that the odds are prohibitive that the two samples being compared came from the same population. Material from locality 289 is intermediate in size.

A careful inspection of the teeth of Astrohippus from the two localities shows no difference by which the two groups can be distinguished, other than by size. Field evidence available (L.C.Pray, oral communication) indicates that the two localities are within 50 feet of each other stratigraphically. They are separated geographically by approximately two miles. No evidence of channeling in the deposits was observed by the author or by Mr. Pray.

The difference in size may be related in large measure to a physical and biotic environment, one group having lived under more favorable conditions than the other. The geographic proximity of the localities is such as to obviate the possibility of different geographical races living at approximately the same time. The time separation is not believed to be great in view of the small stratigraphic interval between the horizons represented by the localities, and in view of the general unity of the faunas from all of the fossil sites.

Possibly the interval represents a long enough span of time which when combined with a difference in climate and topography permitted optimum conditions of food supply at locality 275 while the deposits were accumulating at this site. It is perhaps significant that the smaller horses occur in the younger beds, at locality 276. It may be recalled that *A. stockii* in general is smaller than *A. ansae*, which in turn is smaller than *A. martini*.

If the measurements of one of the variant of *A. ansae* are compared with those of the groups from the two Mexican localities, it may be possible to postulate the direction of a chronocline, varying in time, somewhat as geographical subspecies vary in space (Simpson, 1944). The Yepomera horses, however, are too closely similar in their morphological characteristics to permit the recognition of several subspecies and clearly represent a group specifically distinct from *A. ansae*. Perhaps it is possible to interpret this information as an indication of a rather rapid rate of evolution, with decrease in size preceeding extinction. Geographic isolation for the entire Yepomera fauna may also be postulated, but the character of the mammals associated with the horses does not support this view.

The present evidence is not interpreted as indicating more than slightly varying climatic conditions or similar influences between the time of deposition of the two fossil occurrences. These factors apparently acted selectively in the direction of reduction of size in this particular group of animals. The difference in size is not regarded as of sufficient value to warrant any taxonomic distinctions.

TABLE 1

MEASUREMENTS OF UPPER TEETH OF ASTROHIPPUS STOCKII

	1	2	3	4	5	6	7	8
P2-L	21.1	22.6	21.5	20.5	21.4	25.2	--	--
W	17.3	17.2	18.4	17.6	21.0	20.2	--	--
P3-L	19.0	18.7	18.3	17.8	18.8	21.2	--	15.5
W	18.7	18.3	19.0	20.2	22.4	21.3	--	16.8
P4-L	18.0	18.2	18.3	17.9	18.9	20.3	17.7	14.9
W	18.0	17.3	19.6	19.6	21.9	21.4	20.5	18.4
M1-L	16.2	15.8	16.1	15.7	16.6	17.6	15.3	12.3
W	16.7	16.1	18.0	18.8	20.2	19.2	18.5	16.5
M2-L	16.6	16.5	15.7	16.3	16.9	18.2	15.8	14.1
W	16.2	15.8*	18.2	18.2	19.9	19.7	18.6	16.9
M3-L	--	--	--	17.5	19.3	--	17.1	15.0
W	--	--	--	16.9	17.6	--	15.2	13.7
P2-P4	59.3	59.9	57.8	57.0	59.0	67.9	--	45.3
M1-M3	--	--	--	50.9	53.2	--	48.8	--
P2-M3	110*	--	--	108.2	111.2	--	--	

1. No. 3576, about one-fourth worn, right side.
2. Same as 1, left side.
3. No. 3574, about one-half worn, right side.
4. Same as 3, left side.
5. No. 3578, about three-fourths worn, left side.
6. No. 3619, about one-half worn, left side.
7. No. 3577, about three-fourths worn, right side.
8. No. 3618, extremely worn, most of fossettes gone, left side.

L, Length
W, Width
*, estimated

TABLE 2

MEASUREMENTS OF UPPER DECIDUOUS TEETH OF ASTROHIPPUS STOCKII

	1	2	3	4	5
dP2-L	28.0	--	--	27.0	23.7
W	16.4	--	--	16.3	15.3
dP3-L	22.7	20.2	20.7	20.5	19.3
W	18.2	15.2	17.7	16.8	15.3
dP4-L	23.2	21.8	21.9	22.0	20.9
W	16.0	13.9	17.0	--	14.4
dP2-dP4	73.5	--	--	69.6	65.2

---

1. No. 3580, practically unworn.
2. No. 3696, slightly worn.
3. No. 3620, slightly worn.
4. No. 3695, slightly worn.
5. No. 3694, moderately worn.

TABLE 3

STATISTICAL DATA ON LOWER TEETH OF ASTROHIPPUS STOCKII

	N	O.R.	S.R.	Mean	S.D.	V
1.	37	18	29	57.1± .7	4.5	7.9
2.	40	16	27	55.9± .7	4.1	7.3
3.	29	25	47	114.5±1.4	7.3	6.3
4.	21	7	13	59.0± .4	1.9	3.3
5.	11	9	18	51.7± .8	2.8	5.4

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1. Length $P\overline{2}$-$P\overline{4}$, all localities grouped.
2. Length $M\overline{1}$-$M\overline{3}$, all localities grouped.
3. Length $P\overline{2}$-$M\overline{3}$, all localities grouped.
4. Length $M\overline{1}$-$M\overline{3}$, Loc. 275.
5. Length $M\overline{1}$-$M\overline{3}$, Loc. 276.

TABLE 4

MEASUREMENTS OF LENGTHS OF LOWER DECIDUOUS TEETH OF ASTROHIPPUS STOCKII

	1	2	3	4	5
Dp$\overline{2}$	20.4	20.9	20.9	20.0	21.6
Dp$\overline{3}$	19.1	19.5	20.6	19.6	21.0
Dp$\overline{4}$	20.9	22.8	23.4	20.8	22.9
Dp$\overline{2}$-Dp$\overline{4}$	61.7	64.1	65.1	61.8	65.9

---

1. No. 3623, moderately worn.
2. No. 3624, moderately worn.
3. No. 3622, moderately worn.
4. No. 3905, moderately worn.
5. No. 3906, moderately worn.

TABLE 5

STATISTICAL DATA ON MAXIMUM LENGTH OF METACARPAL III OF ASTROHIPPUS STOCKII FROM VARIOUS LOCALITIES

	N	O.R.	S.R.	Mean	S.D.	V.
1.	131	37	57	169.4 ± .8	8.8	5.2
2.	36	19	31	179.4 ± .8	4.8	2.7
3.	31	23	35	162.2 ± 1.0	5.4	3.3
4.	31	20	31	166.5 ± .9	4.7	2.8

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1. Data from all localities, including that of 2, 3, and 4.
2. Data from locality No. 275.
3. Data from locality No. 276.
4. Data from locality No. 289.

TABLE 6

STATISTICAL DATA ON MAXIMUM LENGTH OF METATARSAL III OF ASTROHIPPUS STOCKII FROM VARIOUS LOCALITIES

	N	O.R.	S.R.	Mean	S.D.	V.
1.	90	33	45	196.4 ± .7	6.9	3.5
2.	14	16	33	205.1 ±1.3	5.0	2.5
3.	17	25	42	192.9 ±1.6	6.5	3.4
4.	43	31	41	194.9 ±1.0	6.4	3.3

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1. Data from all localities, including that of 2, 3, and 4.
2. Data from locality No. 275.
3. Data from locality No. 276.
4. Data from locality No. 289.

TABLE 7

ARTICULAR LENGTHS OF LONG LIMB BONES

OF ASTROHIPPUS STOCKII

	N	O.R.	S.R.	Mean	S.D.	V
1.	2	1		161.5		
2.	25	24	38	211.8 ± 1.2	5.9	2.8
3.	1			229		
4.	5	23	59	243.8 ± 4.1	9.18	3.8

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1. Mean of two humeri, both from Loc. 289.
2. Radii from several localities.
3. Femur from Loc. 289.
4. Tibiae, all from Loc. 289.

TABLE 8

MEASUREMENTS OF UPPER TEETH OF PLIOHIPPUS MEXICANUS

	1	2	3	4	5	6	7	8	9
P2-L	31.8	35.5	35.1	33.5	33.7	33.9	33.9	32.7	32.6
W	23.9	25.7	--	23.8	24.0	25.8	26.3	24.1	24.6
Prot.	7.1	6.9	7.1	7.0	7.1	7.8	7.8	6.9	6.6
P3-L	26.1	27.4	28.5	27.4	26.6	28.0	27.3	24.1	24.5
W	26.6	26.9	26.5	26.2	26.0	27.7	28.5	28.1	27.8
Prot.	7.9	7.5	9.0	9.8	9.1	9.9	9.4	7.8	8.0
P4-L	24.1	26.0	28.4	25.7	26.1	26.0	26.1	23.3	23.3
W	26.3*	26.3	--	24.5	24.4	27.4	27.5	26.7	26.3
Prot.	8.8	8.3	8.9	10.3	9.9	10.6	10.2	7.4	7.6
M1-L	21.8	24.6	24.7	24.4	24.4	23.4	23.2	21.0	20.9
W	24.4	25.0	24.8	25.1	25.1	26.8	26.7	25.4	25.8
Prot.	8.9	9.9	10.4	8.4	8.4	9.8	9.4	7.4	7.4
M2-L	22.2	24.3	24.7	23.6	23.6	23.7	23.3	22.2	22.1
W	--	25.9	25.6	23.3	23.4	26.3	26.3	25.3	25.2
Prot.	8.8	8.3	8.6	10.0	10.0	11.8	11.5	8.6	8.9
M3-L	22.2	23.7	24.1	23.8	23.2	23.3	24.4	21.6	21.3
W	--	19.3	19.8	17.6	18.1	20.9	21.5	21.2	21.0
Prot.	9.0	9.3	9.3	9.9	9.8	10.9	11.0	8.7	9.1
P2-P4	82.0	91.8	92.5	87.8	86.9	87.8	87.9	80.5	81.2
M1-M3	66.2	73.9	74.2	71.3	71.6	72.3	72.1	65.7	65.5
P2-M3	147.2	164.4	165.3	158.1	158.4	160.0	159.1	145.9	146.8

1. No. 3697, type, moderately worn, left side.
2. No. 3703, moderately worn, right side.
3. Same as 2, left side.
4. No. 3717, slightly worn, right side.
5. Same as 4, left side.
6. No. 3746, moderately worn, right side.
7. Same as 6, left side.
8. No. 3747, moderately worn, right side.
9. Same as 8, left side.

L, Length
W, Width
Prot., Protocone length
*, estimated

TABLE 9

MEASUREMENTS OF UPPER DECIDUOUS TEETH OF PLIOHIPPUS MEXICANUS

	1	2	3	4	5	6
Dp$\underline{2}$-L	35.9	--	33.4	--	34.2*	35.0
W	21.5	21.0	19.8	--	21.0	20.0
Dp$\underline{3}$-L	28.4	28.8	24.4	23.3	27.6	27.9
W	20.5	20.3	22.2	21.9	20.8	20.9
Dp$\underline{4}$-L	26.9	26.8	26.2	25.2	28.0	28.4
W	19.3	20.0	21.8	21.9	19.3	19.8
Dp$\underline{2}$-Dp$\underline{4}$	95.2	--	83.8	--	94.0*	94.0

1. No. 3722, slightly worn, right side.
2. Same as 1, left side.
3. No. 3723, moderately worn, M$\underline{2}$ in occlusion, right side.
4. Same as 3, left side.
5. No. 3721, slightly worn, left side.
6. No. 3720, slightly worn, right side.

TABLE 10

STATISTICAL DATA ON LOWER TEETH OF PLIOHIPPUS MEXICANUS FROM VARIOUS LOCALITIES

	N	O.R.	S.R.	Mean	S.D.	V
P$\overline{2}$-P$\overline{4}$	18	11	22	78.2± .8	3.34	4.3
M$\overline{1}$-M$\overline{3}$	14	8	15	72.6± .6	2.38	3.1
P$\overline{2}$-M$\overline{3}$	13	16	28	150.5-1.2	4.28	2.8

TABLE 11

MEASUREMENTS OF LENGTHS OF LOWER DECIDUOUS TEETH OF PLIOHIPPUS MEXICANUS

	1	2	3	4	5
$Dp\overline{2}$	29.9	30.0	27.9	27.5	--
$Dp\overline{3}$	26.1	27.0	27.4	24.8	24.5
$Dp\overline{4}$	28.9	30.7	27.6	25.5	25.9
$Dp\overline{2}$-$Dp\overline{4}$	84*	88.2	89.1	78.2	--

---

1. No. 3702, moderately worn.
2. No. 3907, moderately worn.
3. No. 3716, slightly worn.
4. No. 3706, well worn.
5. No. 3719, well worn.

TABLE 12

STATISTICAL DATA ON LIMB BONES OF PLIOHIPPUS MEXICANUS

	N	O.R.	S.R.	Mean	S.D.	V
1.	1			313		
2.	37	22	45	240.9±1.1	6.9	2.8
3.	3			296		
4.	3			291		
5.	40	30	44	216.2±1.1	6.7	3.1

---

1. No. 3828, femur, loc. 289.
2. Metatarsal III, several localities.
4. Radii, Locs. 276, 286, 297.
3. Tibiae, Loc. 276.
5. Metatacarpal III, several localities.

TABLE 13

MEASUREMENTS OF ILLUSTRATED UPPER TEETH OF NANNIPPUS CF MINOR

	1	2	3	4
Length	16.6	13.4	12.9	13.5
Width	14.7	14.3	15.7	14.4
Prot. length	6.1	5.3	4.9	5.2
Height crown	42	25	17	24

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1. No. 3758, M$\underline{1}$?
2. No. 3760, P$\underline{4}$?
3. No. 3922, M$\underline{2}$?
4. No. 3923, P$\underline{3}$

TABLE 14

STATISTICAL AND MEASUREMENT DATA ON UPPER TEETH OF NANNIPPUS CF MINOR ACCORDING TO TWO WEAR STAGES

	N	O.R.	S.R.	Mean	S.D.	V
1.	18	3.5	6.5	15.6± .3	1.00	6.4
2.	26	3.9	5.8	13.7± .2	.90	6.6

1. Occlusal length, isolated non-terminal upper teeth, less than three-fourths worn, heights of crown 32-47 mm. inclusive.

2. Occlusal length, isolated non-terminal upper teeth, three-fourths worn to well-worn, heights of crown 13-31 mm. inclusive

TABLE 15

MEASUREMENT OF ILLUSTRATED LOWER TEETH OF NANNIPPUS CF MINOR

	1	2
$P\overline{4}$-L	14.0	
W	9.8	9.9
$M\overline{1}$-L	13.2	13.2
W	7.6	8.7
$P\overline{2}$-$P\overline{4}$	42.7	41.5
$M\overline{1}$-$M\overline{3}$	46.4	
$P\overline{2}$-$M\overline{3}$	89	

---

1. No. 3751
2. No. 3752

TABLE 16

MEASUREMENTS OF METAPODIALS OF NANNIPPUS CF MINOR

	1	2	3
Max. length	154	181	174
Prox. width	22.7	24.3	22.3
Min. width	13.2	14.2	13.9
Dist. width	19.3	19.4	19.5

---

1. No. 3778, metacarpal III.
2. No. 3772, metatarsal III.
3. No. 3766, metatarsal III.

STATURE AND PROPORTIONS OF FOSSIL HORSES FROM YEPOMERA

In his studies of living and fossil horses, David P. Willoughby, Scientific Illustrator of the Division of the Geological Sciences, California Institute of Technology, has compiled data which serve in estimating the stature and proportions of horses from limb-bone measurements. Certain assumptions are necessary in some cases, most of these being based on the probable analogous proportions of similar types of horses, living under similar environmental conditions. The results of the application of these methods to the fossil species of horses from Yepomera are seen in figure 7, presenting the relative stature of the horses, as computed by Willoughby.

The hypothetical restorations of Neohipparion and Nannippus are based on the assumption that they are comparable in proportions to Neohipparion leptode from the Thousand Creek Pliocene of Nevada, a complete mounted skeleton of which is available (Stock, 1945). Of Nannippus, only two metatarsals and one metacarpal are available. The stature of Neohipparion cf. phosphorum is based on measurements of 21 metacarpals, 16 metatarsals, and 3 radii. The ratio of average length of metacarpal III to average length of radius of the Mexican neohipparion is .85, while the corresponding ratio for the Thousand Creek specimen is .86, a degree of correspondence suggesting that the assumption of generally similar proportions for these two forms is valid.

The relative stature of Pliohippus mexicanus as shown is based on measurements of metapodials, radii, and a femur, as given in Table 12. The assumption is made that the proportions are similar to those of Plesippus and the living zebras. This is regarded as

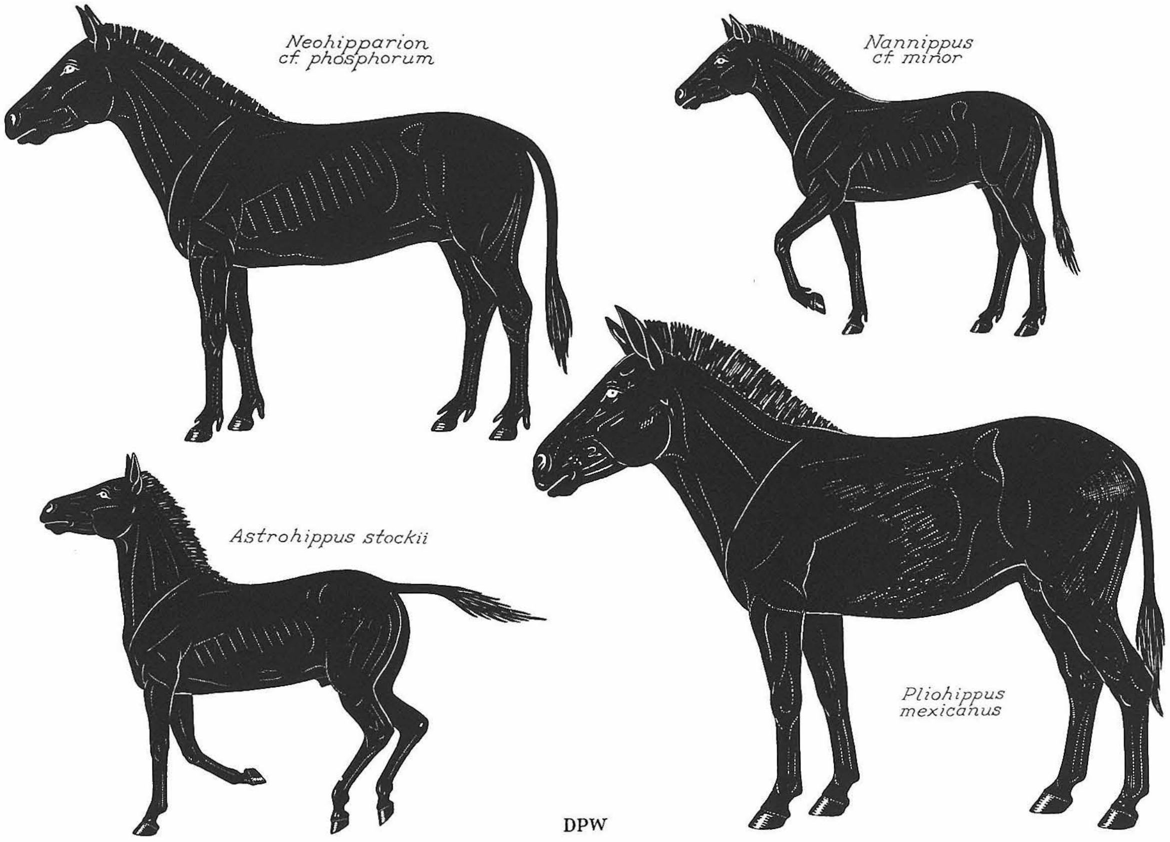

Fig. 7. Hypothetical restorations of fossil horses from Yepomera, showing relative sizes.

likely in view of the close similarity between P. mexicanus and Plesippus in several important structural respects. The comparison of ratios of the Mexican material available with that of the zebra skeleton on which the sketch in figure 7 is based indicates that the assumption is valid.

An attempt to compare the proportions of Astrohippus stockii with those of any of the living groups of horses breaks down. To eliminate the problem arising from the known size discrepancies between members of the species from the different localities, material was used from only one locality, namely, Loc. 289. Only one femur is available, but additional fragments indicate that the specimen is of approximately the same size as that indicated by several partially preserved femora. Sufficient material of the humerus is available to demonstrate that the two complete specimens measured are typical. Measurements of 5 tibiae, 13 radii, 31 metacarpals, and 43 metatarsals are available from Loc. 289.

These measurements show that A. stockii is a horse of slender proportions, and that the distal portions of the limbs are greatly elongated. A. stockii must have been a fleet, almost gazelle-like animal, and in this respect offers further evidence that it is not directly related to living Equidae. It may be noted that the humerus is extremely short relative to the most distal elements of the fore limb. In general proportions of limb elements, A. stockii shows more similarity to the three-toed horses than to P. mexicanus.

Figure 8 illustrates the proportions of the Yepomera horses as compared with other forms, and indicates the known degree of validity of the method used in making the reconstructions shown in figure 7. Figure 8 is a ratio diagram of the type devised by Simpson (1941). The variates plotted are the differences between

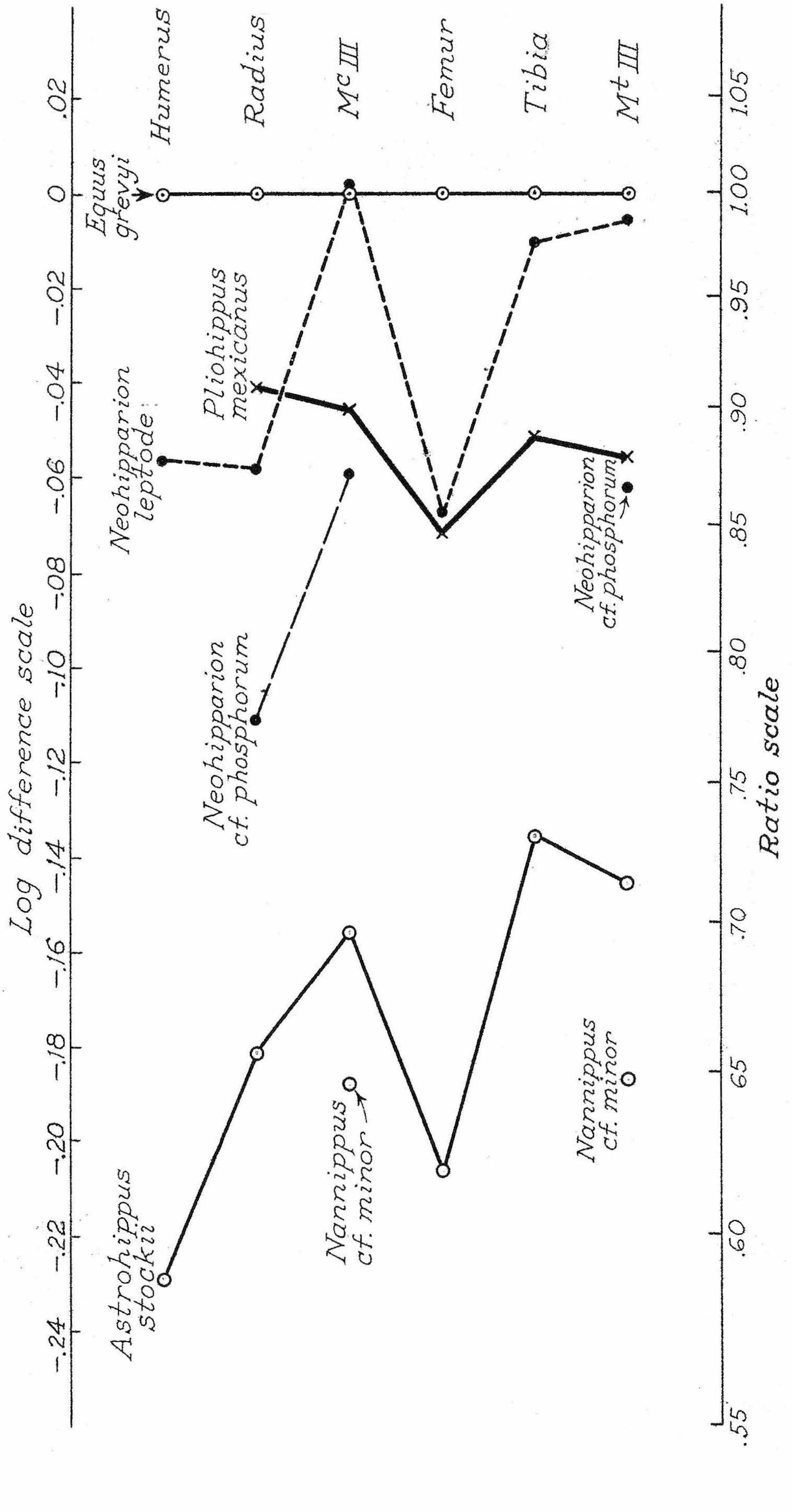

Fig. 8. Ratio diagram of limb bone measurements of various species of horses. For explanation, see text.

the logarithms of absolute measurements of a given element and the logarithm of the corresponding measurement on one form taken as a standard of reference, in this case, a skeleton of the living zebra, *E. grevyi*.

The variates for the standard of reference are placed in a vertical line, and thus, the proportions of the fossil horses can be compared directly with those of the zebra by inspection. The closer the limb proportions of one of the fossil horses approach those of the example used for reference, the more nearly will the plotted variates approach vertical alignment. The ratios between the various horses for any given limb element can be measured by means of the ratio scale at the bottom of the figure. This does not, however, apply to ratios between limb elements of a given horse. For example, the radius of *A. stockii* is absolutely longer than metacarpal III; what is shown is the ratio of each of these bones to the corresponding elements of *E. grevyi*, and to those of other forms as well.

The points plotted for the Mexican horses are based on the measurements previously mentioned, some of these representing means, and others single observations. Data for *A. stockii* are all from Loc. 289. The figures for *E. grevyi* have been furnished by Willoughby, and reppesent measurements of American Museum specimen, No. 82037. Willoughby has also furnished the measurements of *E. przewalskii*, from a specimen in Moscow, and of *Neohipparion leptode*, from an articulated skeleton in the collections of the California Institute of Technology.

It may be recognized from the figure that the proportions of *P. mexicanus* more nearly approach those of the two specimens of living horses than do those of *A. stockii*. The latter shows more similarity to the proportions of Neohipparion. In the relative reduction of the length of the humerus, *A. stockii* is unique among the forms compared.

The general validity of the restoration of *Neohipparion* cf. *phosphorum* in its similarity to *N. leptode* is strongly suggested by the arrangement of the three points plotted for available limb elements, which arrangement is quite like the position of corresponding points for *N. leptode*.

STATUS OF PLESIPPUS

Some of the problems involved in determining the systematic status of Plesippus of the North American Blancan deposits have been mentioned in the introductory section of this report. The present investigation has not included the examination of a sufficiently large enough collection of horse material from Blancan, Pleistocene, and Recent horizons to add much information to a discussion which is partly, at least, taxonomic. However, an opinion, based on observations and study of the literature may be expressed.

It seems reasonably certain that Schultz (1936), McGrew (1944), and others are correct in recognizing relationships among the plesippine horses of the North American Blancan, Equus stenonis of Europe, and the modern zebra. It is questionable, however, that this group collectively is worthy of full generic rank. In the present paper the name Plesippus is employed primarily as a matter of convenience, but with the understanding that it should be definitely regarded as a subgenus of Equus.

The central problem is one of determining the phylogenetic relationships of living horses. A demonstration of presence of two lines of equine evolution in the Hemphillian, one clearly leading to the caballines, and the other to the zebrines, would justify the elevation of the latter group to generic rank. Such a situation was thought to be indicated by McGrew (1944), when he concurred with Stirton (1940) in recognizing the subgenus Astrohippus as a probable ancestor of Equus, McGrew considering it to be ancestral to Equus s.s., while Stirton regarded it as ancestral to all the living horses. McGrew considered the typical subgenus of Pliohippus in line of descent of the zebras, while Stirton looked upon this group as one related to the South American horses.

A study of the fossil material from Yepomera throws some light on the subject, at least indirectly, for, as will be discussed more fully later, *Astrohippus* as originally defined can no longer be considered an ancestor of *Equus* in any sense. A species here referred to *Pliohippus* *s.s.*, namely, *P. mexicanus*, is shown to be the most likely ancestor of *Plesippus*, and, in the absence of evidence to the contrary, of *Equus* *s.l.* as well.

It should be strongly emphasized that the apparent elimination of the subgenus *Astrohippus* as an ancestor of *Equus* by no means invalidates McGrew's argument. It merely takes away one of the strong supporting points. The theory that *Equus* *s.s.* arose in the Old World and migrated to North America in Pleistocene time to replace the plesippine group already existing here is based on the reported presence of both caballine and zebrine horses in Villafranchian deposits of the Old World, and the absence of caballine types in Blancan deposits of the New World.

This is an interesting question, and it may well be that the horses occurring in North American Pleistocene deposits are, indeed, migrants from the Old World. Further evidence is needed on that point. However, the author believes that the new species described from Mexico, namely, *Pliohippus mexicanus*, occupies a position ancestral to *Equus* *s.l.* At any rate, it is clear that *P. mexicanus* is the most closely related known ancestor of *Plesippus*, which remark may or may not mean the same thing.

SUBGENERA OF PLIOHIPPUS

R. A. Stirton (1940) based the subgenus *Pliohippus* (*Astrohippus*) on *Protohippus* *ansae* Matthew and Stirton (1936) from the Hemphill beds of Texas. A number of subgeneric characters were listed, among which the most important were those that appeared to be *Equus*-like, as for example the straightness of crown and advanced protocone in the upper teeth and wide separation of metaconid and metastylid in the lowers. To this subgenus Stirton referred those species that appeared to show a pre-*Equus* type of dentition.

Because of its small size, *A. ansae* was considered by Stirton to be a possible ancestor of *E. tau* and similar small forms, while *Pliohippus osborni* was referred to the new subgenus (*Astrohippus*) as the ancestor of the larger species of the North American Blancan and Pleistocene. Certain even less-known species, were retained only tentatively in the typical subgenus.

Characters found in the dentition of the two new horses described in the present paper display evidence that requires a reconsideration of the subgeneric assignment of species to *Pliohippus*. The new information also appears to throw light on the phylogeny of later Tertiary Equidae, within the limits defined in the preceeding section. It may be noted that an independent study of either of these two new horses could lead to approximately the same conclusions.

The two new Yepomera species have the most *Equus*-like characters in the upper dentition yet found in horses from the Hemphillian stage. A comparison of figures 2 and 4 will emphasize certain similarities. However, differences in the character of the lower teeth suggest that the two species are not so closely related as might at first appear.

Even before these characters in the lower teeth were fully evaluated, a comparison of the Mexican material with *A. ansae*, *P. interpolatus*, and *P. osborni* led to the conclusion that the advanced

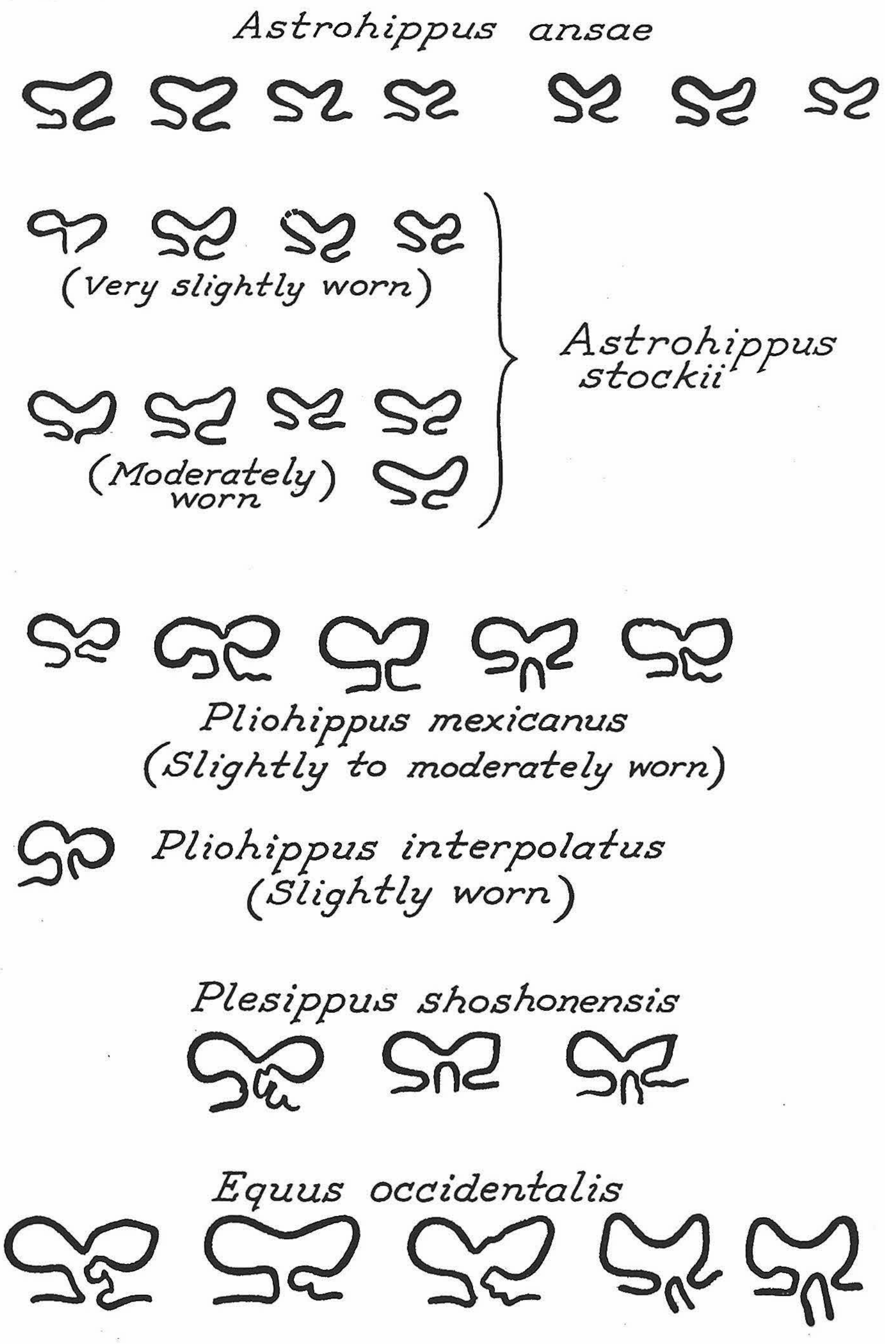

Fig. 9. Shape of metaconid and metastylid in various species of fossil horses.

form from the Mt. Eden Pliocene was more properly to be referred to Pliohippus s.s., rather than to the subgenus Astrohippus, where it had been placed by Stirton (1940). This followed largely from the fact that P. mexicanus, undoubtedly related to P. osborni, seemed to be a more fitting ancestor to Equus than A. ansae, and yet showed certain affinities to species of Pliohippus s.s.

Removing P. osborni from the subgenus Astrohippus, however, presented further problems. It meant, for example, the inclusion of horses with Equus-like characters in both subgenera of Pliohippus, with little but size remaining in distinguishing advanced species of the two groups.

An analysis of characters seen in the lower teeth of the species involved led to the discovery of a feature which is here considered as diagnostic in defining the subgenera of Pliohippus, and which seems to have phylogenetic value as well. This character relates to the shape of the metaconid and metastylid.

To the subgeneric characters for Astrohippus listed by Stirton (1940) may now be added the feature of attenuated rather than rounded metaconid and metastylid. This character must be used with due cognizance of the stage of wear of the tooth considered. For example, the specimen illustrated by Stirton (1940, fig. 48) is a slightly worn lower tooth of A. ansae. The same shape of metaconid and metastylid is seen in slightly worn teeth of A. stockii (fig. 9). For more typical illustrations of worn teeth of A. ansae, see figure 9 in this paper, in Matthew and Stirton (1936, pl. 54, fig. 1), and in McGrew (1944, fig. 21).

A single tooth may not always be sufficient to demonstrate this character, but a few moderately worn lower teeth should serve to separate advanced species of the two subgenera of Pliohippus.

Figure 9 Illustrates shape of metaconid and metastylid in various species. Milk teeth in species of *Pliohippus* *s. s.* sometimes show metaconid and matastylid attenuated, and only slightly constricted at the point of juncture. *Calippus* seems to foreshadow the *Astrohippus* type of metaconid and metastylid. As stated, the lower teeth of *A. martini* are not certainly known. However, the lower teeth illustrated by Hesse (1936, fig. 2) seem to display the character in question.

Pliohippus *coalingensis* was only tentatively referred to the typical subgenus in 1940 (Stirton, 1940), and later was suggested as possibly belonging in the *Astrohippus* group (Stirton and Goeriz, 1942). Because of its apparent relationship to *P.* *osborni*, this horse is probably better considered a member of the typical subgenus.

As re-defined in the present study, the subgenus *Pliohippus* *s. s.* appears to include species in the line of ancestry of the modern horse. The characters found in the most advanced species extend considerably the range of features usually considered as diagnostic of the group. In some characters, *P.* *mexicanus* closely approximates *Plesippus*. Bode (1934) and other workers have recognized that the intergradation of species and genera is inevitable with more complete representations of the fossil record.

The parastylid on lower milk teeth of *P.* *mexicanus* and the hypostylid on some milk teeth, patently DP$\overline{3}$, are not so strongly developed as in specimens of *Plesippus* *shoshonensis* and *P.* *franciscana* examined, but appear to be trending toward the plesippine type. The character appears sufficiently variable to indicate a form intermediate between the zebras and caballines in this respect.

The assignment of the larger of the new species from Mexico to the genus *Pliohippus* removes some of the distinctions between advanced members of Pliohippus and primitive members of Plesippus. The latter group may still be recognized on the basis of greater size and lesser degree of curvature in the upper teeth.

The subgenus Astrohippus, as defined in the present study, includes horses with remarkably Equus-like characters in the upper dentition of advanced species, but with certain unique features in the lower teeth. Small size also appears to be of some value as a diagnostic character. It seems probable that Astrohippus did not give rise to any known forms later than the Hemphillian in North America.

The foregoing considerations imply a considerable degree of parallelism in the development of certain phylogenetic lines. That increasing hypsodonty was a progressive feature in several later Tertiary groups of animals is well known (see Stirton, 1948). In the case of the horse, increase in height of crown of cheek teeth is displayed in the hipparion group as well as in forms nearer the line of descent of modern horses.

Increasing hypsodonty in horse teeth requires certain structural modifications for increased strength. Increase in complication of the triturating surface is also a development leading to a more efficient masticatory apparatus suitable for the conditions under which modern horses live. It is not remarkable that different phyla of horses should show parallelism in developing characters to meet these similar requirements.

For example, in the instance of strengthening a high-crowned tooth, it seems likely that the strong curvature seen in earlier species of Pliohippus became one solution in acquiring the desired result. Further increase in height of crown imposed the necessity of modifications in the structure of the skull, and required a straightening of the teeth. The acquisition of a straight crown required in turn changes, as for example, increase in heaviness of styles on the outside walls of the upper teeth and greater development of metaconid and metastylid in the lower teeth.

Elongation of metaconid-metastylid column, elongation of the protocone, deepening of the post-protoconal valley, and development of crenulations on fossette borders are all factors increasing the efficiency of the triturating surfaces of the teeth. Flattening and grooving of the styles of the upper teeth, and development of a lingual groove in the protocone are factors which lend strength. The same is true of styles on the external sides of lower teeth, but these have been largely eliminated in living forms. The crescentic shape seen in some of the hipparions with elongate protocones is doubtless a similar strengthening feature.

The point is then that progressive species in different groups are likely to show similar structural modifications, particularly if the basic pattern of tooth construction is similar. This is believed to account for the great similarity observed in upper teeth of advanced species of both subgenera of Pliohippus.

PHYLOGENY OF LATER TERTIARY EQUIDAE

Evidence presented in preceeding pages seems to indicate that certain changes can be proposed to the current concept of phylogenetic lines of later Tertiary Equidae in North America. The basic phylogenetic scheme is that advocated by R. A. Stirton (1940), with such changes as the present information seems to warrant.

Stirton (oral communication) concurs in the proposed removal of *P. osborni* from the subgenus *Astrohippus*, and the removal of *Astrohippus* from the direct line leading to *Equus*, having arrived at these conclusions by other lines of reasoning. The views of the present author and those of Stirton do not agree, however, on the generic assignment of *Astrohippus stockii*. Only those trends in evolution that are of immediate concern to the present study are shown (fig. 10).

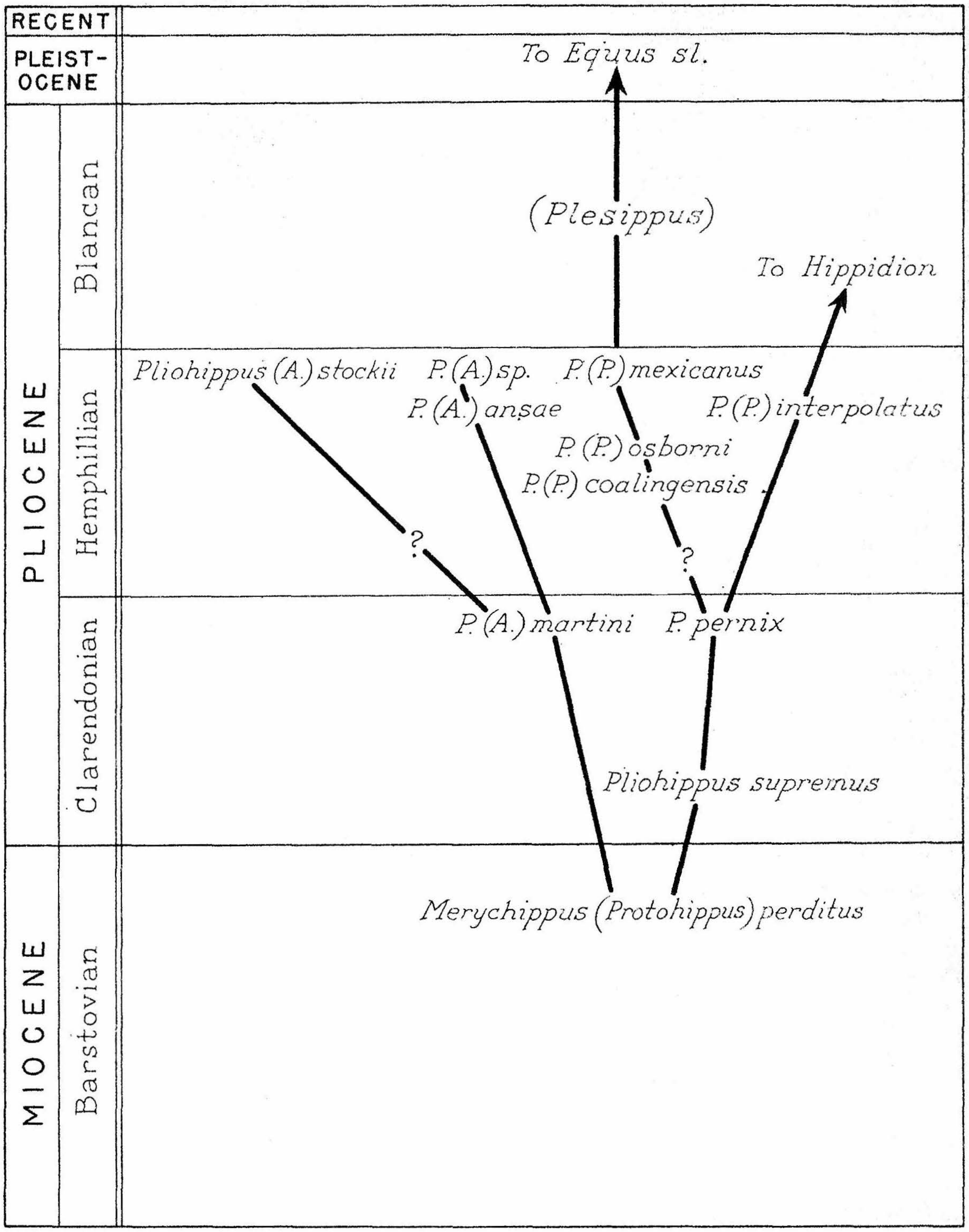

Fig. 10. Chart showing probable phylogenetic relationships of some later Tertiary equidae.

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EXPLANATION OF PLATES

Plate I

Nannippus cf. *minor*. Fig. 1, No. 3758, upper first molar, lingual view, slightly worn, C.I.T. Loc. 275. Fig. 2, No. 3760, upper first or second molar, lingual view, one-half worn, C.I.T. Loc. 275.

Pliohippus (*Astrohippus*) *stockii*. Upper molars and premolars, showing curvature. Fig. 3, No. 3737, $P\underline{4}$, C.I.T. Loc. 275. Fig. 4, No. 3740, $P\underline{3}$, C.I.T. Loc. 276. Fig. 5, No. 3742, $M\underline{1}$, C.I.T. Loc. 289. Fig. 6, No. 3738, $M\underline{1}$, C.I.T. Loc. 275. Fig. 7, No. 3739, $M\underline{2}$, C.I.T. Loc. 275. Fig. 8, No. 3741, $P\underline{3}$, C.I.T. Loc. 275.

All figures natural size.

Plate II

Pliohippus (*Pliohippus*) *mexicanus*. Fig. 1, No. 3744, $M\overline{1}$?, C.I.T. Loc. 275. Fig. 4, No. 3734, $P\underline{3}$, C.I.T. Loc. 289. Fig. 5, No. 3726, $P\underline{2}$, C.I.T. Loc. 289. Fig. 6, No. 3727, $P\underline{4}$, C.I.T. Loc. 276.

Pliohippus (*Astrohippus*) *stockii*. Fig. 2, No. 3743, $P\overline{4}$?, C.I.T. Loc. 275.

Nannippus cf. *minor*. Fig. 3, No. 3745, $M\overline{2}$, C.I.T. Loc. 275.

All figures natural size.

Plate III

Pliohippus (*Pliohippus*) *mexicanus*. Fig. 1, left composite tarsus and matatarsal III, No. 3806; phalanges Nos. 3807, 3808, 3810, all from C.I.T. Loc. 275. Fig. 2, left composite carpus and metacarpal III, No. 3801; phalanges Nos. 3802, 3803, 3805, all from C.I.T. Loc. 275.

Pliohippus (*Astrohippus*) *stockii*. Fig. 3, left composite tarsus and metatarsal III, No. 3796; phalanges Nos. 3797, 3798, 3800, all from C.I.T. Loc. 275. Fig. 4, right composite carpus and metacarpal III, No. 3791; phalanges Nos. 3792, 3793, 3795, all from C.I.T. Loc. 275.

Nannippus cf. *minor*. Fig. 5, left ectocuneiform, navicular, metatarsal III, No. 3766; phalanges Nos. 3768, 3769, 3770, 3771, all from C.I.T. Loc. 275. Fig. 6, left metacarpal III, No. 3778; phalanx No. 3779, both from C.I.T. Loc. 287; ungual phalanx No. 3780, C.I.T. Loc. 275.

All figures approximately one-fourth natural size.

Plate IV

Third left metacarpals, proximal and lateral views.

Pliohippus (*Pliohippus*) *mexicanus*. Fig. 1, No. 3811, C.I.T. Loc. 295.

Neohipparion cf. *phosphorum*. Fig. 2, No. 3814, C.I.T. Loc. 276.

Pliohippus (*Astrohippus*) *stockii*. Fig. 3, No. 3812, C.I.T. Loc. 289.

Nannippus cf. *minor*. Fig. 4, No. 3778, C.I.T. Loc. 287.

Lateral views three-seventh natural size. Proximal views eleven - sixteenths natural size.

Plate V

Pliohippus (Pliohippus) mexicanus. Abnormal and normal specimens of metatarsal III and metacarpal III from C.I.T. Loc. 295. Fig. 1, metatarsal III, No. 3910. Fig. 2, left metacarpal III, No. 3908. Fig. 3, left metacarpal III, No. 3909. Fig. 4, right metatarsal III, No. 3912. Fig. 5, left metacarpal III, No. 3913.

All figures approximately one-fourth natural size.

PLATE I

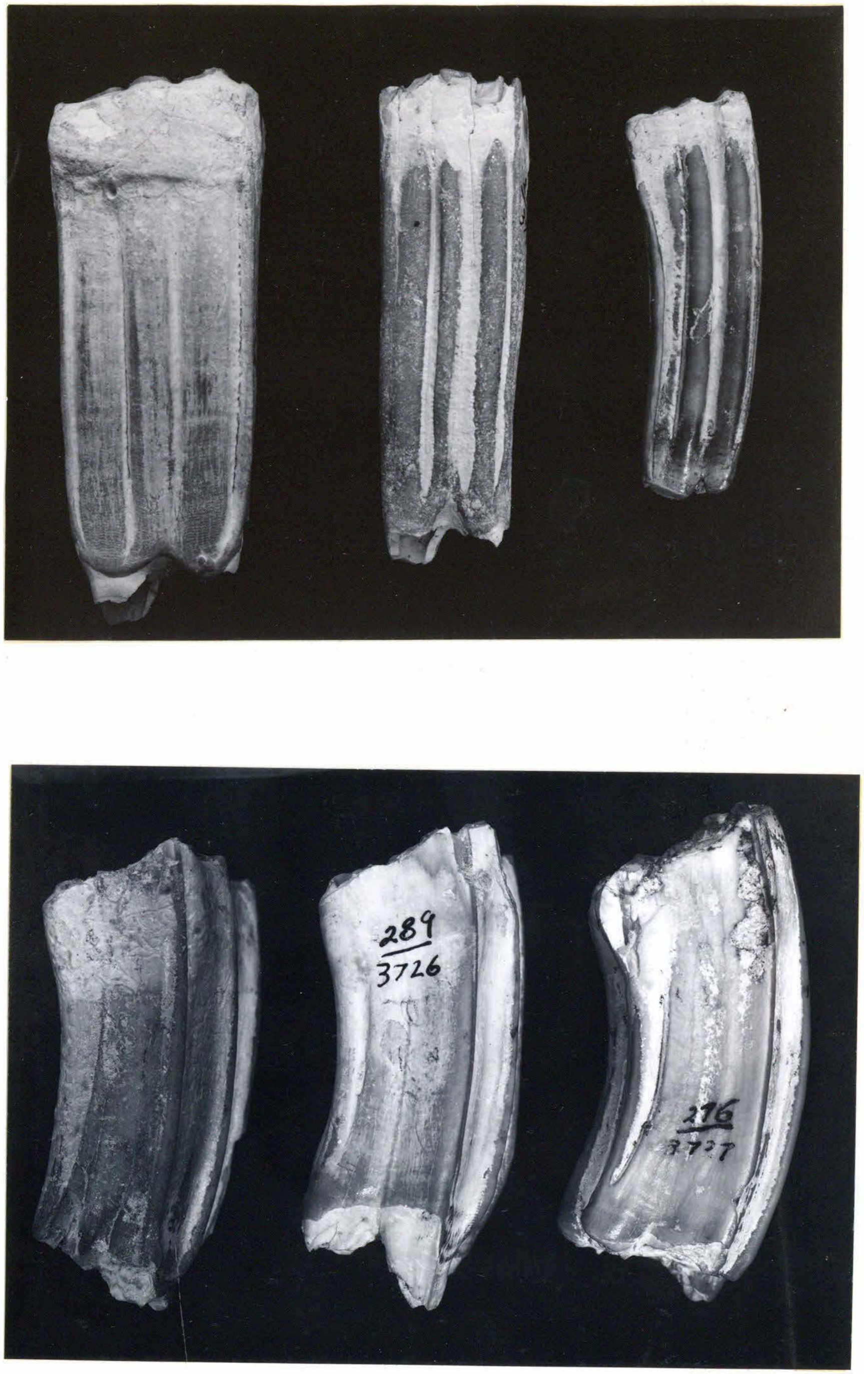

PLATE II

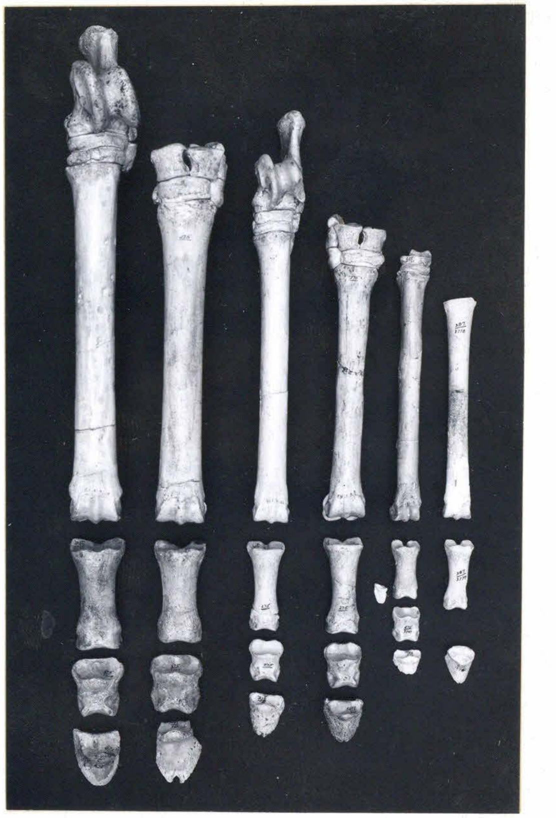

PLATE III

PLATE IV

PLATE V

ORIGIN OF THE PIONEER
PYROPHYLLITE DEPOSIT,
SAN DIEGO COUNTY,
CALIFORNIA

Thesis by

John Franklin Lance

In Partial Fulfillment of the Requirements
For the Degree of
Doctor of Philosophy

California Institute of Technology
Pasadena, California
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TABLE OF CONTENTS

ABSTRACT

Pyrophyllite, a hydrous aluminum silicate with properties and uses similar to those of talc, is abundant at the Pioneer deposit near Escondido, San Diego County, California. The mineral occurs in lenticular bodies in the Santiago Peak volcanics of approximate Jurassic age. The deposit is approximately on a Tertiary(?) erosion surface that has probably been exhumed.

A study of field, petrographic, and chemical data indicates that the pyrophyllite was developed by replacement of volcanic flows and breccias of original andesitic and latitic composition. These volcanic rocks had been previously folded and sheared, and subjected to mild regional metamorphism and accompanying propylitic alteration. Silicification in part preceded the formation of pyrophyllite. Development of pyrophyllite is known to be complete or nearly so in only one body, which is being quarried at the present time.

The solutions forming the deposit appear to have followed shear zones, and lithologic control evidently was not important in localizing the mineralization. The solutions were of hydrothermal origin, and possibly were associated with the emplacement of the Peninsular batholith of southern California. They were of intermediate temperature and acid in nature. Silica and possibly alumina were added to the rocks by these solutions, and other elements were removed. Moderate stresses produced a schistosity in the pyrophyllite, probably during mineralization.

LIST OF ILLUSTRATIONS

INTRODUCTION

The present study was undertaken in an attempt to determine the conditions governing the formation of a pyrophyllite deposit in San Diego County, California. This deposit is near the San Dieguito river, about 8 miles southwest of Escondido (Fig. 1). Because of a name used by a company formed to exploit the occurrence, it is known as the Pioneer pyrophyllite deposit.

About 15 days was spent in the field at various times during 1947 and 1948. A plane table map, on a scale of 20 feet to the inch was made of the pyrophyllite quarry and vicinity by R. H. Jahns and the author (Pl. 1), and a less detailed map was made by Jahns on an areal photograph covering the general vicinity of the deposit (Pl. 2). The author mapped a small area of good exposure on a scale of 4 feet to the inch to show some detailed relationships between the pyrophyllitized rocks and those of the surrounding region (Pl. 3). Petrographic studies of approximately 30 thin sections of rocks in the vicinity of the quarry were made by the author.

The only known published discussion of the pyrophyllite deposit considered in this report is a short note on the properties of the material from the standpoint of its possible utilization in the ceramics industry (Richard, 1935). Most of the available information on the geology of the region is of a very general nature.

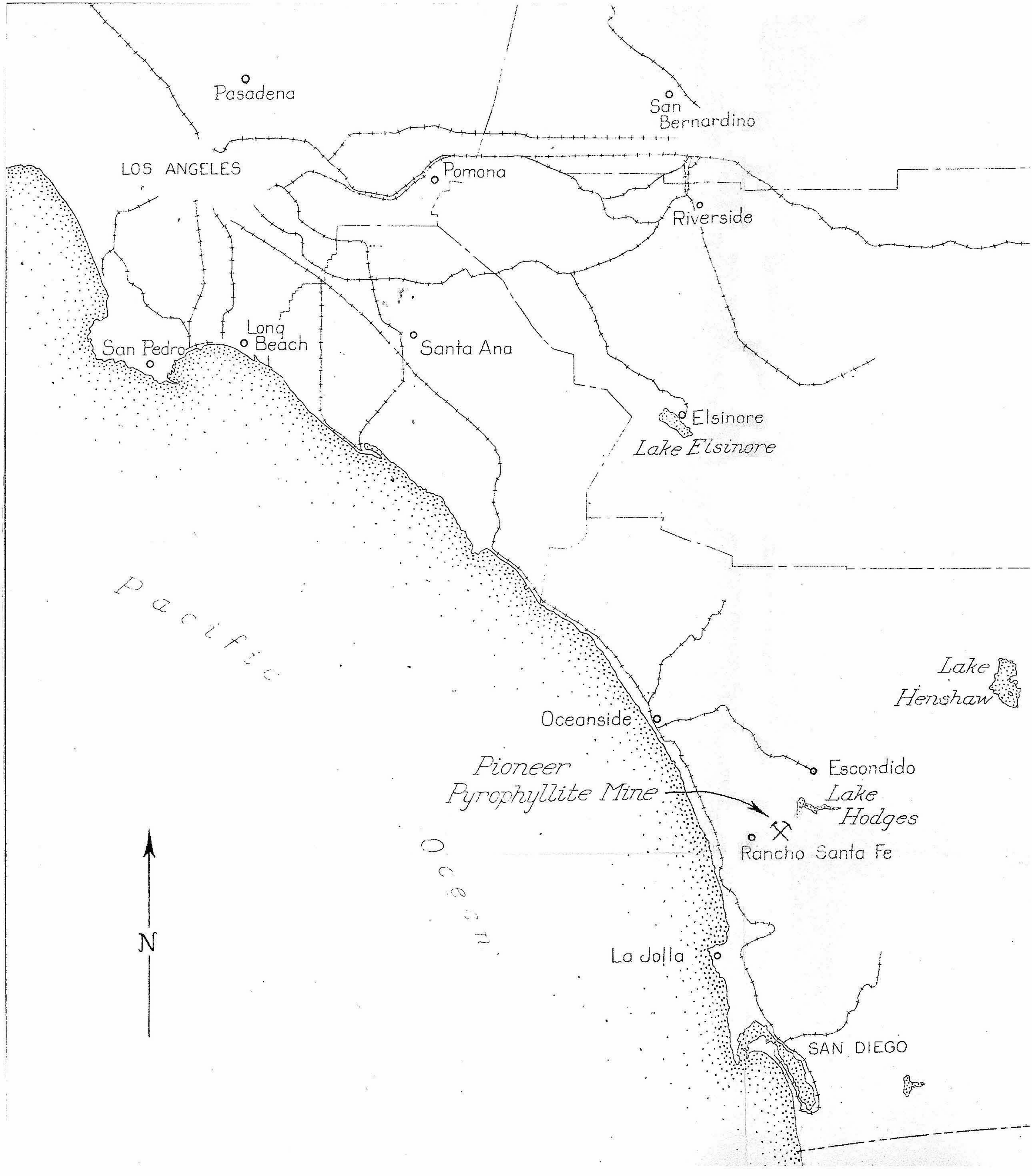

Fig. 1. Index map of a part of southern California, showing location of Pioneer pyrophyllite deposit.

Fig. 2. Pioneer pyrophyllite quarry, looking slightly east of north, April, 1948.

The deposit is exposed on and slightly above one of the river terraces along the San Dieguito river at an altitude of approximately 200 feet above sea level. It lies below the general level of the dissected marine terraces of the San Diego county coastal belt. The western margin of the Peninsular Ranges lies within a mile of the deposit on the east. These mountains, of rugged topography, range from about 500 feet to 1500 feet above sea level in the western part of San Diego county. Farther north and east, individual peaks are approximately 6000 feet high, and at the northeastern edge of the Peninsular Ranges, San Jacinto Peak has an elevation of 10,805 feet above sea level. The deposit is readily available by passable roads.

Quarrying at the deposit has been accomplished with a small bulldozer and power shovel. When the mapping was first started a cut had been made at the east end of a zone of high-grade pyrophyllite. Later a new quarry was started at the west end of the zone, on the other side of a small hill, but in direct line with the old cut (Fig. 2). The new cut was developed to points about 15 feet below the level of the old quarry when the deposit was last mapped in the spring of 1948.

PYROPHYLLITE

General properties

Although it is not of great commercial importance at present, pyrophyllite is of considerable interest because of its general relationships to talc, the micas, and the clay minerals. In discussion of industrial minerals, pyrophyllite ordinarilly is considered with talc, because of similar properties and uses of these commodities. In theoretical discussions of origin and crystal structure of clay minerals, pyrophyllite is usually mentioned because it is closely related to montmorillonite. The chemical formula given in old text-books for montmorillonite is identical with the pyrophyllite formula, and the two minerals now are generally considered to have a similar crystal structure (Grim, 1942; Hauser, 1941; Ross and Hendricks, 1945). Pauling (1930) had earlier recognized the structural similarity of pyrophyllite and talc.

In a classification of silicates according to the framework of silicon and oxygen atoms, pyrophyllite, talc, the micas, the clay minerals, and the brittle micas are all in the same group (Bragg, 1937). As no X-ray work was done in the present study, the discussion of crystal structure will be limited to the features of interest in explaining some of the properties and relationships of pyrophyllite.

Pyrophyllite is found in several colors, but white, brown and green are most common. It is soft, with a hardness of between 1 and 3. In general physical properties it closely resembles talc, and in optical properties it resembles both talc and sericite. There are two general types of occurrence. Foliated pyrophyllite is often radiated, and resembles talc in feel, luster and structure. The compact, massive variety resembles steatite. The name agalmatolite has been used in part for the massive variety, particularly in China, but agalmatolite also includes in part pinite and steatite.

Pyrophyllite yields water at high temperatures. Stuckey (1925) stated that in a dehydration test, pyrophyllite still held about 1% of water at 750°C. Nutting (1943) showed that the thermal dehydration curve for pyrophyllite is similar to that for montmorillonite in the shoulder and toe. This indicates the similar manner in which the two minerals lose water adsorbed between lattice planes, and, at higher temperatures, from the crystal lattice.

Physical properties of interest to the ceramics industries have been given for the Pioneer pyrophyllite by Richard (1935). These are listed below.

Mechanical analysis	Consists of fibrous pyrophyllite and a white colloid substance.
Working properties	At 40-mesh, fair; at 80-mesh, good.
Water of plasticity (%)	14.3
Dry shrinkage (%)	2.2
Slaking	Does not slake down in water

Odor	Argillaceous
Hardness	1-2
Drying properties	Dries fast; no warping
Specific gravity	2.9
Tensile strength	148-160 lb.

Sample bars fired at four different temperatures gave the following results:

Cone	Color	Shrinkage (%)	Absorption (%)	P. C. E.
3	White	0.1	18.5	29-33
6	White	0.1	18.4	
9	White	0.2	17.6	
12	White to cream	2.1	16.7	

Crystal structure

Many of the physical properties and the mineral relationships of pyrophyllite are readily understandable in the light of its crystal structure. The crystal lattice of pyrophyllite was first explained by Pauling (1930), and subsequent studies have confirmed his determination.

Pyrophyllite and related minerals are made up of layers. In pyrophyllite, a gibbsite layer is stacked between two layers of linked silicon-oxygen tetrahedra. These linked tetrahedra share oxygen atoms, so that in the unit cell each sheet has the composition Si_2O_5, and the two sheets are represented by Si_4O_{10}. The apices of the tetrahedra of each sheet point toward the other sheet, with the gibbsite layer between. The spacing of ions in the sheets is such that two-thirds of the hydroxyl ions on each side of the gibbsite sheet are replaced by oxygen from the silica sheets. This gives a composition of $Al_2(Si_4O_{10})(OH)_2$ or $Al_2O_3 \cdot 4SiO_2 \cdot H_2O$ for pyrophyllite.

Consideration of this crystal structure discloses several interesting features. The triple-layered sheet is electrically neutral, so that adjacent sheets are held together only by stray electrical forces. This accounts for the extreme softness and easy cleavability of pyrophyllite, and also of talc, which is similar except that the central layer is brucite, rather than gibbsite.

Slight deviations of analyses from the theoretical chemical formula of pyrophyllite can be caused by mixed layers of similar minerals, introducing small amounts of Fe, Mg, and Na, and by slight substitution of Al^{+++} for Si^{++} in the tetrahedral layers (Ross and Hendricks, 1945).

A number of workers have advanced ideas on the crystal structure of montmorillonite, but all seem to agree that the structure is essentially similar to that of pyrophyllite. Ross and Hendricks (1945, p. 41) state, "In general the micaceous minerals differ from---[pyrophyllite and talc]---in that minerals of the montmorillonite group contain an additional group of ions, the exchangeable bases, Ca, Na, etc.; the micas contain K, which is not exchangeable; and the brittle micas contain Ca, which also is non-exchangeable."

It is not necessary to here treat more fully the various possible formulas and structures proposed for montmorillonite and related minerals. It is generally agreed that in montmorillonite Mg and/or Fe is substituted for part of the Al ions in the gibbsite layer, and that possibly Al is substituted for part of the SiO_4 in the silicon-oxygen tetrahedra. Exchangeable cations may be present between the silicate layers, and water also appears between the layers.

The position of the exchangeable ions has been debated, but the details are not pertinent to the present discussion. The exchangeable ions account for the marked difference in base exchange properties between pyrophyllite and montmorillonite, pyrophyllite having no exchangeable bases. The inter-layer water in the montmorillonite may be increased greatly, accounting for the characteristic swelling of bentonite when wet.

In some minerals of the general type under discussion, such as the micas, the individual sheets are not electrically neutral, as they are in pyrophyllite, and cations such as K^+ or Na^+ or Ca^{++} are present between the sheets. These bond the sheets together, causing such minerals to be less cleavable, and harder than pyrophyllite or talc. A mineral with Ca^{++} between the layers is less easily cleaved than one with a monovalent base, because the double bond is stronger.

These salient features serve to explain some of the similarities and also some of the differences between pyrophyllite and related minerals in such properties as hardness, thermal characteristics, cleavage, and base exchange. Although Hauser (1941) speaks of "the clay mineral, pyrophyllite", it seems best at present to consider it as not belonging to any one group, but as related to the clays, micas, brittle micas, and talc.

Uses

All pyrophyllite mined in California during 1946 was used as a carrier for the active agent in insecticides, and some pyrophyllite from the Pioneer deposit was used experimentally for ceramics and cosmetics in 1948. If a larger commercial supply could be developed, pyrophyllite could be used in many industries. Stuckey (1925) offered the following list of uses of the mineral from the North Carolina deposits: roofing paper manufacture; cotton cordage; textile manufacture; paper industry; rubber manufacture; soap manufacture; pipe covering compounds; pottery and porcelain; asbestos industry; paint manufacture; toilet preparations; bleaching industries; crayons and pencils; and sheet asphalt.

The R. T. Vanderbilt company of New York, which processes much of the North Carolina pyrophyllite, gave the following list of industries using the mineral (Anon., 1943): wall and floor tile, electrical porcelain, table ware, cooking ware, sanitary ware, vitreous china, art ware, glass, enamel, cement, refractories, backwalls and radiants, heater plates, battery boxes, roofing, paint, rubber, insecticides, cosmetics, and welding rod coatings.

Experimental formation

The conditions under which pyrophyllite may form have been investigated by numerous workers. Only the most important of these investigations, with general conclusions, need be mentioned here. For the most part, the information on pyrophyllite has been acquired incidentally to studies concerning weathering and alteration of feldspars and other minerals. A number of earlier investigations, reported in foreign journals not available to the writer, have been summarized by Morey and Ingerson (1937). A more recent summary of conditions of alteration and alteration products of feldspars has been given by Folk (1947).

Morey and Ingerson (1937) listed the maximum and minimum temperatures under which various minerals have been reported as forming under experimental conditions. For pyrophyllite they reported a range of formation from 250° C to 540° C. The minimum temperature is based on work by Norton (1937) and will be discussed in more detail farther on. The maximum temperature at which pyrophyllite has been formed in the laboratory was reported by Schwarz and Trageser (references 144 and 145 in Morey and Ingerson, 1937), and Noll (ref. 141, 142, 155, in Morey and Ingerson, 1937) was quoted as having listed pyrophyllite as forming in the temperature range 400°-500° C. Morey and Ingerson listed 7 papers in which the artificial formation of pryophyllite was reported and 4 more in which it was doubtfully reported.

Schwarz and Trageser treated orthoclase or, alternately, anorthite, in pressure bombs with $\frac{1}{2}$ N HCl at temperatures above 400° C. They found that the feldspars broke up into colloidal alumina and silica and that these recombined to form the hydrous aluminum silicates, the ones formed being determined by pressure, temperature, and pH of solutions. In experiments performed on feldspars, and also on kaolin, these workers found that the amount of pyrophyllite formed increased up to a temperature of 470° C, and thence decreased, perhaps due to the volatility of silica, allowing an excess of Al_2O_3 to hydrate to boehmite. Kaolinite was formed from 200° to 400° C., pyrophyllite and boehmite from 400° to 550°, and corundum above 600° C. The kaolinite-pyrophyllite point at 400° C was suggested as a point in geologic thermometry.

This 400° point is also suggested as being diagnostic in the work of Noll (summarized by Morey and Ingerson). Noll used varying proportions of Al_2O_3 and SiO_2, in the forms of alumina and silica gels in water, in a series of experiments at temperatures ranging from 250° to 500° C and at pressures from 225 to 540 atmospheres. In the experiments that produced pyrophyllite, the Al_2O_3-SiO_2 ratio seemed critical. In experiments at 400° C and 235-300 atmospheres of pressure, pyrophyllite, kaolinite, and possibly boehmite formed with alumina-silica ratios of 1 to 2, pyrophyllite formed at a 1 to 4 ratio, and at 1 to 6 and 1 to 10, pyrophyllite and amorphous silica formed.

At 500° C and pressures up to 540 atmospheres, with an alumina-silica ratio of 1 to 2, pyrophyllite and an unknown crystalline phase were formed. At 1 to 4 ratios, pyrophyllite was formed, and pyrophyllite and amorphous silica was formed at 1 to 6 ratios. Kaolinite was formed in lower temperatures, ranging between 250° and 300° C, with alumina-silica ratios of 1 to 2.

After a number of these experiments, Noll reached the following conclusions: 1) kaolinite forms by the reaction of alumina and silica in neutral, alkali-free solutions, or in acidic alkali-containing solutions, below 400° C; 2) pyrophyllite forms from similar solutions and mixtures, but above 400° C; 3) in nature, kaolinite forms from alkali feldspars when much of the alkali is carried away, or when the active solutions are acidic; 4) pyrophyllite forms under similar conditions, but at high temperatures, which accords with its known natural occurrences, some of which are pegmatitic.

More recent experiments by American workers do not change these general conclusions. Before detailing these experiments, a further reference should be made to the minimum temperature reported by Morey and Ingerson, which was based on work done by Norton (1937). Subsequent reports by Norton (1939, 1941) suggest that this formation of pyrophyllite is in doubt.

The experiments performed by Norton involved percolating water and CO_2 at moderately high temperatures through ground feldspar. Later experiments included the use of pressures up to 500 psi. The method used provided for a constant supply of fresh carbonic acid and a removal of products of alteration. These factors were invoked as possible reasons for the occurrence of pyrophyllite at temperatures below those normally found by experimentation. The work reported in 1937 and 1939 indicated that pyrophyllite had formed from anorthite at temperatures of 250° to 350° C and pressures from 250 to 500 psi. The formula for the transformation was given as:

$$CaO.Al_2O_3.2SiO_2 + H_2O + CO_2 \rightarrow (OH)_2Al(Si_2O)_5 + CaCO_3$$

It might be mentioned that the formula given is not that commonly accepted for pyrophyllite.

In a later report, Norton (1941) stated that a re-evaluation of X-ray data upon which mineral determinations had been made shows that the product reported as pyrophyllite formed from anorthite is really either montmorillonite or beidellite. This leaves Norton with no pyrophyllite to report from his experiments. However, Gruner (1944) studied the X-ray date of Norton's 1939 report on the alteration of albite to beidellite at temperatures of 275°-300° C and decided that the alteration product was not beidellete, but was possibly pyrophyllite, if it could be identified at all.

For the present, then, the minimum temperature at which pyrophyllite is known to form under laboratory conditions can be taken as approximately 300° C, or possibly slightly less. Gruner (1939, 1944), on the basis of experiments involving the alteration of feldspars in HCl solutions, reached the general conclusion that in feldspar alteration, kaolinite, pyrophyllite, sericite, and boehmite are formed in acid solutions, and that the concentration of K ions and the Al-Si ion ratio determines which mineral will form at a given temperature. Gruner (1944) stated that he had previously agreed with Noll that pyrophyllite could not form at temperatures much below 400° C, but his experiments showed that it forms at 300° C if the concentration of Al ions is low. He found that pyrophyllite formed as an alteration product of microcline over the temperature range 300°- 525°C, although he felt that it might be only metastable below 350°C. Experiments showed that if the concentration of Al ions was high, kaolinite and boehmite formed at 300°C.

At 400°, Gruner found that pyrophyllite would form from microcline unless the concentration of K ions was too high, in which case no alteration took place. The general conclusions pertinent to the present discussion reached by Gruner have been given in the preceeding paragraph. He also stated that pyrophyllite is possibly rare as an alteration product of feldspar in nature because there is usually much alumina available, and that the seeming rarity may in part be due to the frequent mistaking of pyrophyllite for sericite.

Folk (1947) summarized most of the above-mentioned experiments. More recent work by O'Neill (1948), along the lines of the work done by Gruner, produced pyrophyllite as an alteration product of albite and labradorite, under conditions not at variance with those previously reported. This work serves to emphasize the importance of pH value and K ion concentration in determining whether pyrophyllite or some other product will form in the alteration of various feldspars.

To recapitulate, experiments show that pyrophyllite has been produced under laboratory conditions at temperatures ranging from about 300° to 540° C, from silica and alumina gel without added acid, and from kaolinite and various feldspars in acid solution.

The important factors seem to be: 1) Al-Si ratio, 2) K ion concentration, 3) pH value of solutions, and 4) temperature of solutions. If the work of Noll is accepted as correct, it is obvious that factors 1 and 4 may operate independently of 2 and 3 under certain conditions. However, taking all evidence into consideration, the following conditions favor the formation of pyrophyllite from feldspars: 1) low K and Al ion concentrations, 2) acid solutions, 3) temperatures in excess of 300°, preferably 400° C, but less than 600° C.

THE PIONEER PYROPHYLLITE DEPOSIT

Geologic setting

The Peninsular Ranges of Southern California and Baja California constitute an interesting geologic province about which there is relatively little detailed information. The dominant geologic feature is a great batholith, extending from near Riverside, California, southward into Baja California. This batholith averages about 70 miles in width, and can be traced continuously for a distance of about 350 miles, with a probable total length of approximately 1000 miles (Larsen, 1948, p. 134), although only isolated portions outcrop in the southern half of Baja California.

West of the great batholith, metavolcanic rocks form an outcrop belt, interrupted in a few places by intrusive bodies, or by overlying sediments, about 80 miles long and 10 miles wide. This belt trends approximately WNW-SSE. The distance to which it may extend north and south under younger rocks is not known. These metavolcanic rocks have been called the Santiago Peak volcanics by Larsen (1948, p. 23).

In the Santa Ana mountains, the Santiago Peak volcanics unconformably overlie the Bedford Canyon formation, which consists mostly of slates, argillites, and quartzites, and in which Triassic fossils have been found (Larsen, 1948, p. 18). The volcanic rocks are overlapped by Upper Cretaceous and younger sediments along most of their western margin. In some areas the underlying metamorphic rocks or younger intrusive rocks form the western border.

The volcanic rocks are intruded in places by rocks of the batholith, to which Larsen assigns a lower Cretaceous age (Larsen, 1948, p. 136). The batholith has been tentatively considered by some earlier workers as Jurassic in age (Miller, 1945; Dudley, 1936), but some evidence for an early Upper Cretaceous age is found in Baja California (Woodford and Harriss, 1938). The Santiago Peak volcanics are thus known to overlie Triassic rocks unconformably, and to be intruded by rocks of probable Cretaceous age. On the basis of this information, Larsen (1948, p. 24) believed the volcanic rocks to be of Jurassic age.

The Santiago Peak volcanics have been studied in detail at only a few places. Hanna (1926) called these rocks the Black Mountain volcanics in his work on the La Jolla quadrangle. B. B. Moore in an unpublished manuscript (Moore, 1930), assigned formational names to several extrusive and intrusive divisions of the series, and gave petrographic reports on several of the rock types in the Santa Ana mountains.

Larsen (1948, p. 24) stated that the Santiago Peak volcanics are chiefly andesites and quartz latites, with some rhyolites and probably basalts. They consist of alternating flows, tuffs, and breccias, with a few interbedded clastic rocks. The volcanic rocks may have been thousands of feet thick. Bodies of fine-grained intrusive rocks, including granodiorites and related rock types are considered to be associated with the volcanic rocks.

The volcanic rocks are mildly metamorphosed, presumably during close folding, and before the batholithic intrusion. They are recrystallized in places by contact metamorphism.

Larsen (1948, p. 26) described a common type of andesite as being seriate porphyritic, with calcic plagioclase the dominant phenocryst, and moderate amounts of pyriboles. In the process of metamorphism, the plagioclase has been albitized, and the original dark minerals have been replaced by chlorite and epidote. Calcite and serpentine are also fairly abundant as metamorphic minerals. In the more highly metamorphosed rocks, the groundmass has been recrystallized to a fine-grained aggregate of soda plagioclase, orthoclase, quartz, chlorite, and epidote.

The best information on the sequence of geologic events in the region under consideration in this report is that given by Hanna (1926) for the La Jolla quadrangle, which is two miles south of the pyrophyllite deposit. This is repeated in brief as follows: After the eruption of several thousand feet of volcanic material and concomitant sedimentation, intense folding occurred. Following this the peninsular batholith was intruded, intensively metamorphosing some of the volcanic rocks in the La Jolla quadrangle. Erosion then removed at least several thousands of feet of rocks, ultimately producing a mature surface. Sediments of Upper Cretaceous age then were laid down over parts of the area. Uplift and additional erosion preceeded the deposition of Eocene beds. Further erosion apparently followed the Eocene sedimentation, until the San Diego beds of Pliocene age were laid down near the present shore line.

The record since Pliocene time seems to be one of differential movement of fault blocks in the mountains to the east, with development of several surfaces of subaerial and marine planation in the whole region. Few of these are of very broad extent, but existing information suggests that some of the major surfaces might be correlated from one block to another (Larsen, 1948, p. 14).

The pyrophyllite deposit is in what Ellis and Lee (1919) term the San Diego Coastal belt. This is a narrow strip flanked by mountainous highlands on the east and by the sea on the west. Marine terraces have been developed at several altitudes along this strip, but are most extensive in the vertical range of 300 to 500 feet above sea level. These terraces have been dissected by streams. One of these, the San Dieguito River, has cut below the level of the lowest marine terrace in the vicinity of the Pioneer deposit. Successive uplifts in late Quaternary time have resulted in the development of at least three river terraces along the lower reaches of the San Dieguito River.

An irregular surface of considerable relief was cut into the Santiago Peak volcanics in the vicinity of the pyrophyllite deposit prior to deposition of Tertiary(?) clays and gravels. The sediments have nearly horizontal bedding, and overlie the erosion surface in patches, suggesting local deposition. Quaternary terrace gravels and alluvium overlie the older rocks. The present surface of the volcanic rocks is in part an exhumed one, and the rocks show the results of deep weathering. They are stained with iron oxides along fractures to depths of at least 30 feet below the surface.

Rock Types

The rocks in the immediate vicinity of the Pioneer quarry were divided into the units shown in plate 1 on the basis of degree of pyrophyllitization as determined in the field. In order of decreasing pyrophyllite content, as based on megascopic examination, and later confirmed by microscope work, the units are:

- Pyrophyllite schist
- Pyrophyllite-quartz schist
- Volcanic flow and pyroclastic rocks, moderately pyrophyllitized
- Volcanic flow and pyroclastic rocks, slightly pyrophyllitized
- Volcanic breccia, slightly pyrophyllitized

  Chiefly of original andesitic to latitic composition.

- Quartz and chalcedonic silica
- Andesite

A little andesite appears in masses too small to be mapped within these pyrophyllitized rocks, even on the large field scale used. Much andesite, however, occurs just outside the mine area proper.

The units intergrade, and distinctions as made in the field were necessarily somewhat arbitrary. Bodies of pyrophyllitized flow and pyroclastic rocks contain masses of altered rocks that were originally breccias, but the unit mapped as pyrophyllitized breccia is, in general, characterized by a nodular appearance, and contains less pyrophyllite than the other two altered volcanic units.

Andesite

The andesite in the vicinity of the quarry is purple to dark gray or green. One small area of rhyolite tuff was mapped (Pl.2), and some of the more severely altered rocks adjacent to the quarry appear to have once been agglomerates or tuffs, but no good evidence has been found to show that the bulk of the pyrophyllite was derived from anything but andesite flow rocks and breccias.

The andesite varies in texture from aphanitic to porphyritic aphanitic. Flow banding is quite pronounced locally, and several areas are underlain chiefly by flow breccia. Because of the few outcrops, extensive shearing, and deep weathering, it has not been feasible to separate different facies of the original andesite in the present mapping. The porphyritic rock contains white feldspar phenocrysts set in an extremely fine-grained groundmass. The flow breccias weather to a nodular surface, which in some places makes them resemble a pebble conglomerate. On fresher surfaces, the angular volcanic fragments are clearly scattered through the rest of the rock, and in some places they constitute the bulk of the rock.

The green andesite seems to be an altered facies of the purple andesite, and contains more chlorite. The alteration is of a propylitic type, as pyrite, calcite, chlorite, and epidote all occur as alteration products.

The andesite crops out in areas surrounding the pyrophyllite deposit, and appears to completely enclose it. Both the purple and green types of andesite are tough on fairly fresh surfaces, and ring when struck with a hammer. Parallel, closely spaced joints give some outcrops a sheeted appearance. Two exposures of the green andesite are within a few feet of the edges of the area shown in plate 1, and in each place the rock is so fresh looking that it was at first thought that the andesite was unrelated to the pyrophyllite body.

In addition to the andesite shown on plate 2, small residual patches occur in the pyrophyllitized area. One boulder, about four feet in diameter, of severely altered, dark green material, with a clayey appearance, was uncovered on the east wall of the lower quarry just after completion of the map (Fig. 3). This appears to be altered, but not highly pyrophyllitized andesite. According to the quarry operator, several such boulders were encountered in the masses of higher grade pyrophyllite.

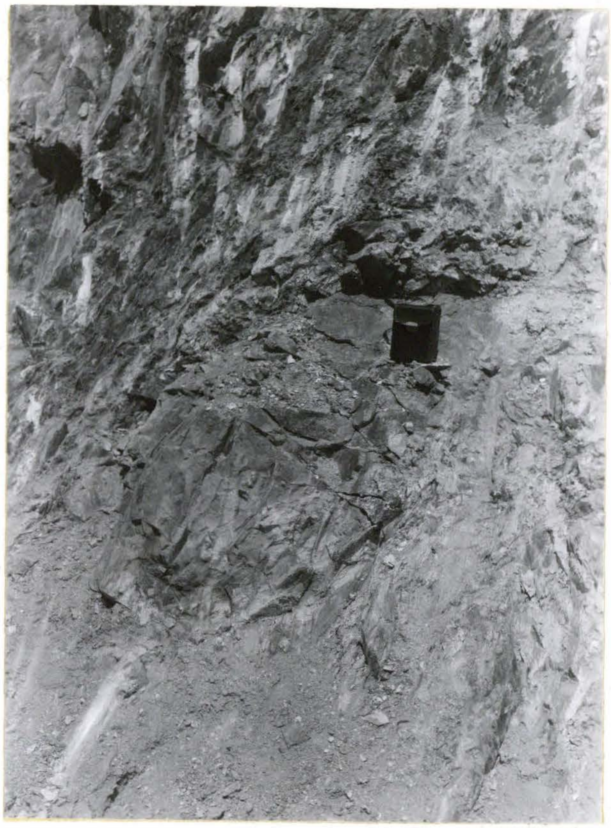

Fig. 3. Residual boulder of altered andesite in east face of new quarry.

In thin section most of the andesite is porphyritic. Sample M-5 is a breccia, with very fine-grained quartz and possibly feldspar between the angular fragments (Fig. 4). Most of the fragments are porphyritic, but a few consist wholly of microcrystalline or cryptocrystalline groundmass. The texture is pilotaxitic in some places, with tiny laths showing a flow structure around the phenocrysts. The phenocrysts are andesine, although the centers of some of the zoned crystals may contain labradorite. There is no trace of phenocrysts of pyroxene or amphibole, but chlorite is plentiful throughout the slide. The fragments are all mottled thoroughly with tiny grains of opaque minerals, which appear to be magnetite, ilmenite, and hematite. The feldspar is altered to chlorite, pyrophyllite, zeolites, a little calcite, and in shreds and patches to a low index feldspar, either albite or oligoclase. Quartz appears as microgranular aggregates in the ground mass, in veinlets cutting across the breccia fragments, and in a few relatively large grains. Many of the large grains appear fresh.

Some of these quartz grains are probably primary. One attains a diameter of .5 mm. and encloses two apatite needles. The interference figure shows a slight biaxial tendency, but this is doubtless due to strain. Some of the feldspar grains are shattered. Most sections of andesite examined show no primary quartz grains, and it is known that most of the larger quartz grains in rocks from the vicinity of the quarry are porphyroblastic.

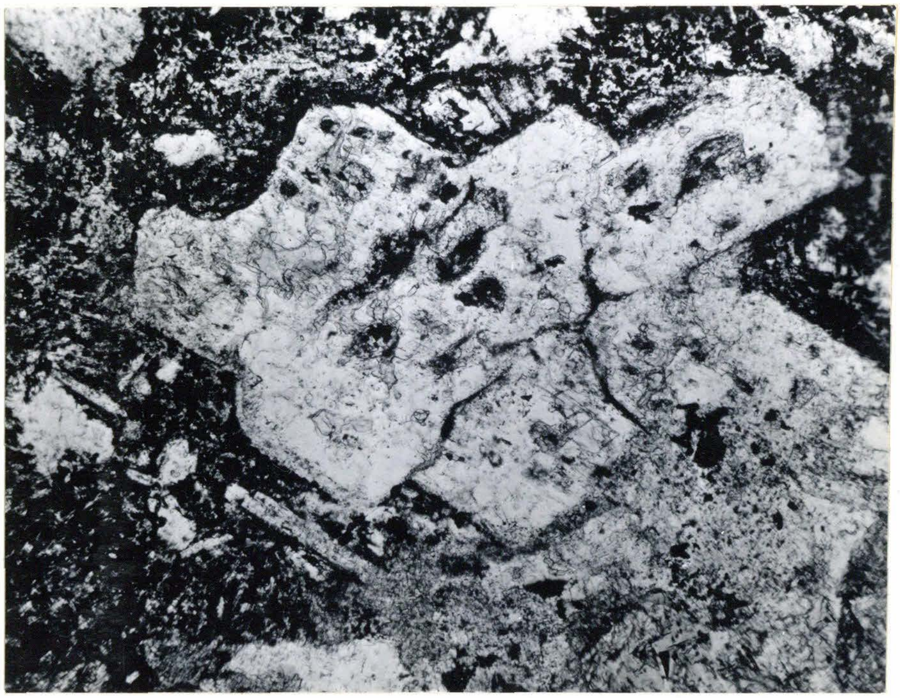

Fig. 4. Feldspar phenocryst altering to quartz and chlorite. Andesite breccia, sample M5. Crossed Nicols. x120

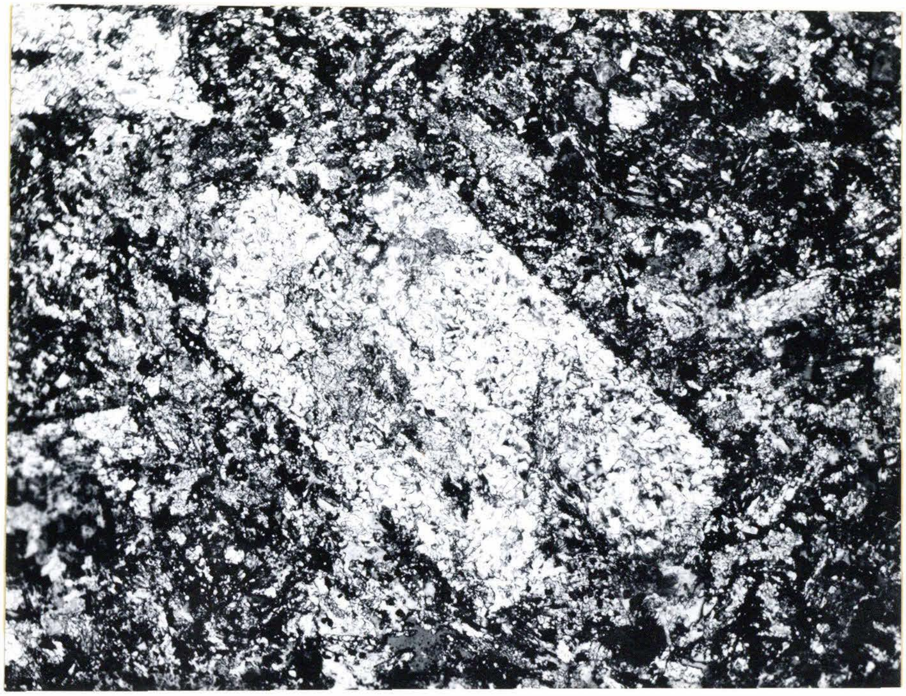

Fig. 5. Feldspar partly replaced by quartz and pyrophyllite. Green andesite, sample E1. Crossed Nicols. x120.

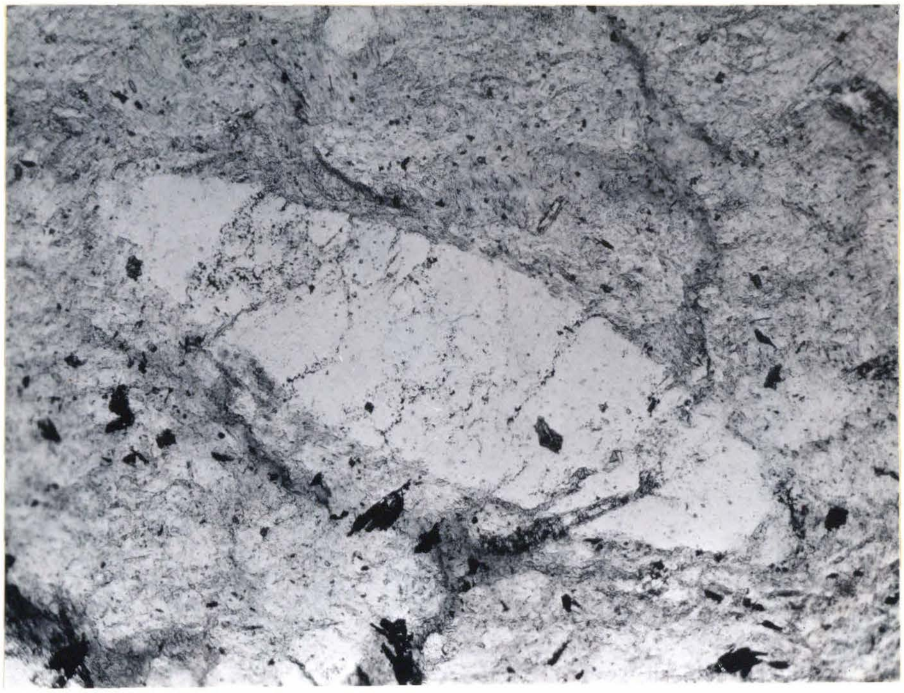

Fig. 6. Granular quartz lens in andesite residual.

Sample P14-B. Plane light. x120.

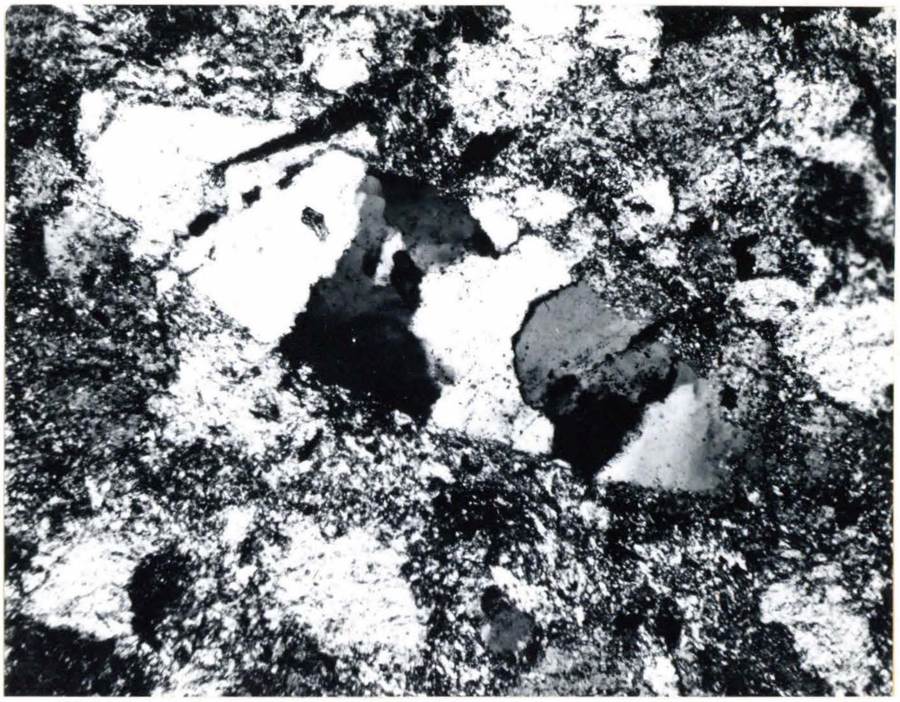

Fig. 7. Same view as fig. 6. Crossed Nicols. x120.

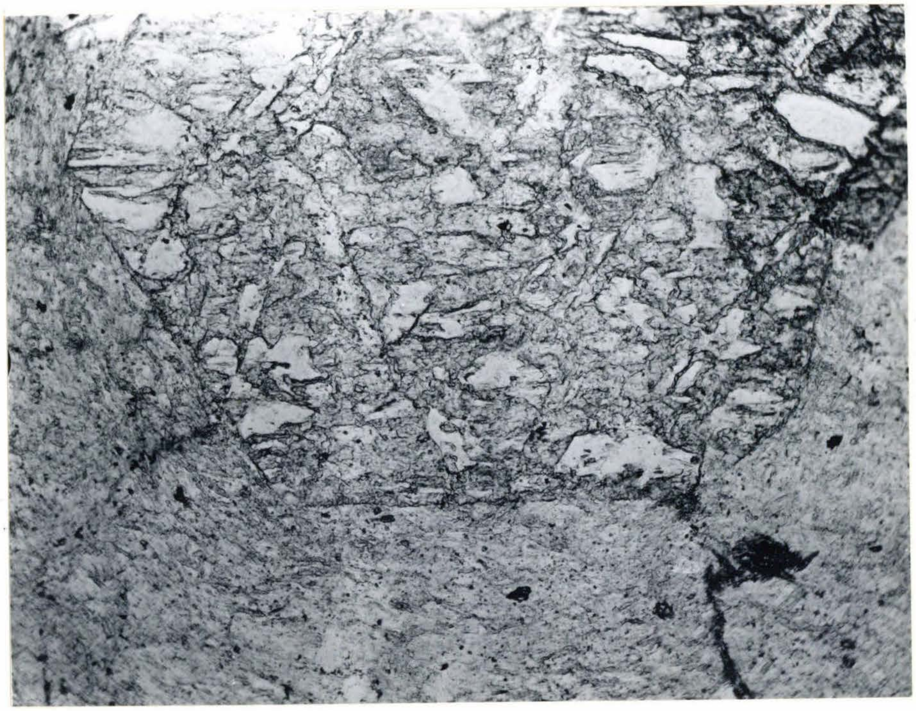

Fig. 8. Calcite replacing pyroxene in andesite residual.

Sample P14-B. Plane light. x120.

The pyrophyllite in sample M5 is replacing feldspar and chlorite. If the slide were examined with no knowledge of any proximity to the pyrophyllite deposit, this mineral would probably be called sericite, and there is no evidence in the present instance that it is not.

Most of the other andesite thin sections are similar to the one described, except that most are normal, unbrecciated flow rocks. Most of the andesite is porphyritic. The phenocrysts are altered, consisting largely of fine-grained aggregates of quartz and pyrophyllite in samples from the vicinity of the quarry (Fig. 5). Relict phenocrysts of an amphibole or possibly a pyroxene are present. Orthoclase appears as tiny grains in the groundmass in some places, and serpentine is possibly one of the alteration products in some. Fresh grains of quartz in some sections appear to be prophyroblasts rather than phenocrysts. Some are rather obviously the result of growth from a fine-grained mosaic of secondary quartz. Many of these larger grains are corroded by pyrophyllite, and are embayed and locally cut through.

One of the most interesting thin sections of andesite is from a body mapped as slightly pyrophyllitized volcanic rock. This has been designated as sample P14-B, as sample P14 is of the less altered rock. The mass of andesite was too small a body to map, and was practically all taken in the sample. The sample clearly shows its relationships to the andesite, even though it is altered. Most of the feldspar has been replaced by quartz, pyrophyllite, and calcite. Twinning striae are still recognizable in the quartz and pyrophyllite pseudomorphs. The groundmass appears to consist of fine-grained quartz, oligoclase of an index of refraction just above balsam, and calcite, with numerous opaque grains of ilmenite, magnetite(?), leucoxene, and some pyrite. Veins of an iron oxide that might be called limonite cut across all other minerals in the slide.

A peculiar feature of part of the quartz is its occurrence in cigar-shaped lenses consisting of mosaics of tiny grains (Figs. 6, 7). Some of these are connected to veinlets of quartz, and some are not. Although the relationships cannot be shown in this slide, it is believed that the lenses of quartz do not represent the same generation as that which is replacing the feldspars. However, there is not likely to be any great time difference between the two generations, as pyrophyllite is replacing both. Calcite also replaces the quartz.

Calcite is prominent in the slide, and in one grain appears to be pseudomorphous after a basal pyroxene section (Fig. 8). The relict pyroxene shows more euhedralism than any grains seen in any of the less altered andesite. In all the slides the ilmenite shows alteration to leucoxene.

Volcanic breccia, slightly pyrophyllitized

The slightly pyrophyllitized volcanic breccia contains less pyrophyllite than other rocks in the vicinity of the quarry, excepting the silica bodies. Field work shows that it corresponds in part to the rock mapped as white andesite on the aerial photograph (Pl. 2). The rock is usually white, gray, or tan, but is greenish in places and locally stained red or black along fractures.

Most of this rock is hard, and much of it appears to be silicified. It contains between 10 and 20 percent of pyrophyllite. On weathered outcrops it has a nodular appearance, as if containing many pebbles. Apparently most of it is derived from the andesite flow breccias, although textures shown in thin section do not prove this. Thin sections do show that the amount of pyrophyllite is less than in the other two types of pyrophyllitized volcanic rocks, so the validity of the rock as a map unit seems verified. Some highly silicified but little pyrophyllitized masses of normal flow rock also have been mapped with this unit.

As shown on the map (Pl. 1), the areas of outcrop of the altered volcanic breccia are not extensive. It occurs mostly in lenticular bodies that follow the general trends of the shearing. Both the nodular appearance and the relative lack of pyrophyllitization suggest that the flow breccias were altered less readily to pyrophyllite than were the normal flows. Normal volcanic flows that have been highly silicified also appear to have been less readily altered to pyrophyllite.

In thin section, the rock unit under discussion contains usually more than 50 percent of quartz. The texture is difficult to decipher because of the silicification and other alteration that has occurred. One sample shows no evidence of original porphyritic texture, but the other samples can be seen to have been at one time porphyritic.

One sample, P21, (Fig. 9) shows clearly that silicification has taken place. The phenocrysts and part of the groundmass have been extensively replaced by quartz. The groundmass is mostly a semi-opaque mass of what appears to be fine-grained pyrophyllite and opaque dust, in part hematite. Veinlets of quartz in small sutured grains appear in the groundmass, and locally irregular areas of quartz grains attain a diameter of 1 mm. The probable quartz-pyrophyllite time relations are noteworthy in another thin section, P2, where the groundmass, consisting of a fine mosaic of quartz grains, is in part replaced by stringers of the hematite-stained pyrophyllite (Fig. 10). These stringers are suggestive of serpentinization textures in the alteration of olivine. Thus, the quartz veinlets in P21 are probably residual veins. The groundmass attains a slight schistosity where there is much pyrophyllite.

Quartz replaces most of the feldspar phenocrysts in slide P21, and in these relict phenocrysts the grains are larger than in the groundmass, although the mosaic texture is still dominant.

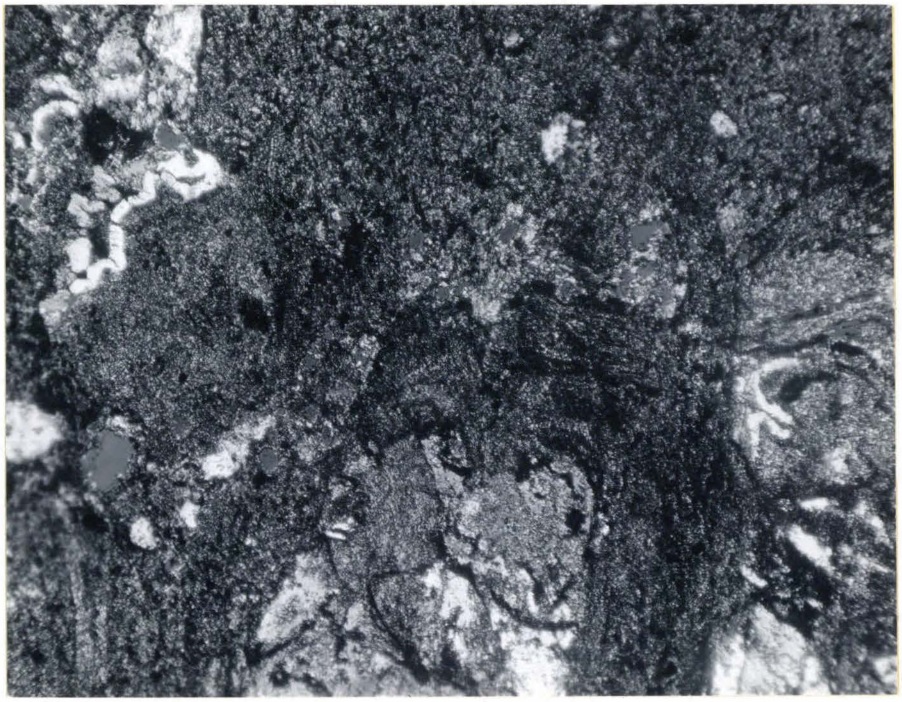

Fig. 9. Thin section of slightly pyrophyllitized breccia, showing fine-grained quartz, relict feldspar zoning, and colloform silica. Sample P21. Crossed Nicols. x120.

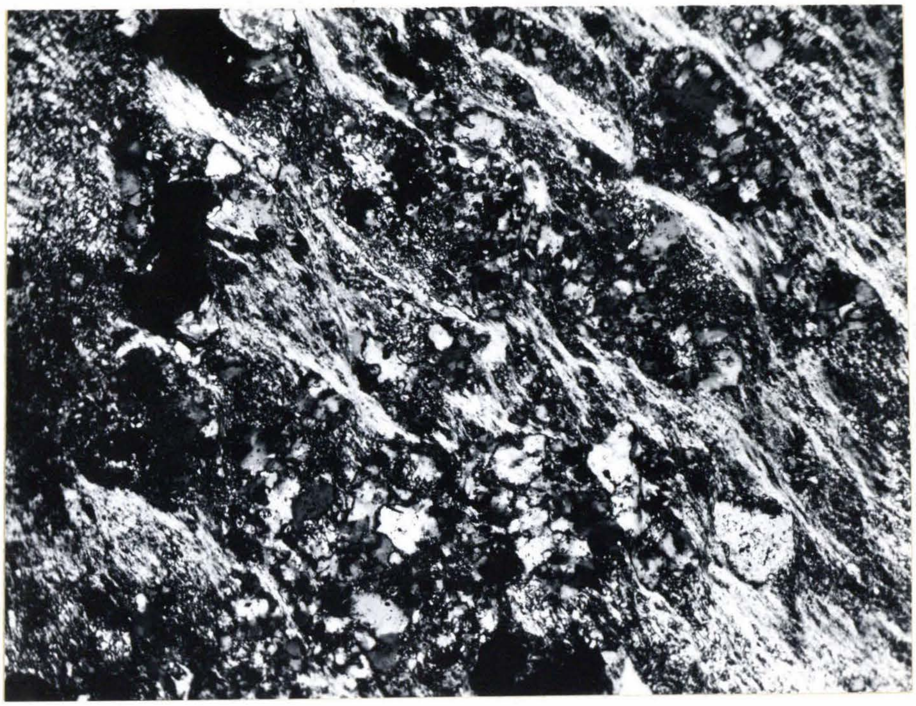

Fig. 10. Pyrophyllitized volcanic breccia showing pyrophyllite veinlets cutting quartz mosaic. Sample P2. Crossed Nicols. x120.

The quartz in both phenocryst pseudomorphs and groundmass is in part clear, and some tends toward a euhedral form. Some of the clearer portions are rimmed with inclusions that apparently are in part expelled by the growing prophyroblasts.

Clear pyrophyllite flakes replace some of the clear quartz grains. This is in addition to the scum-like pyrophyllite and hematite in veinlets replacing quartz of both porphyroblasts and groundmass. Probably the original ferromagnesian content of the groundmass has not been entirely removed, and is mechanically mixed with the pyrophyllite, whereas there is no such contamination in the clearer quartz areas.

Another feature of the silica is its occurrence in cigar-shaped masses of grains. These lenses are similar to those described on a preceeding page. Slide P21 exhibits a colloform texture of some of the quartz veinlets (Fig. 9). This suggests an open-space filling. Rogers (1928, fig. 3) shows a photomicrograph of opal and chalcedony with texture that looks very much like that seen in P21. Although the texture is seen in other slides, no good evidence was found as to its origin. Quite possibly the volcanic rocks were sheared before silicification, and some open-space filling took place along fractures. Also, relations in other slides suggest a possible replacement of amygdules or filling of cavities in places, but the original andesite seems to be free from vesicles and amygdules. Cavities could have been formed by leaching of certain minerals, however.

In addition to quartz, sample P21 contains pyrophyllite, feldspar, and small amounts of leucoxene. Some ilmenite, showing typical skeletal crystals is present, but most has been altered to leucoxene. Clear flakes of pyrophyllite are found adjacent to ilmenite and leucoxene grains in the corners of the "eyes" formed where the schistosity of groundmass flakes bends around the opaque grains. This is a texture commonly developed where porphyroblasts grow in a schistose rock. It may also form where schistosity is developed in a rock with phenocrysts that resist crushing and recrystallization under forces that develop schistosity in other minerals of the rock. Evidence in other sections suggests that in some places, particularly next to magnetite grains, chloritoid may have antedated the pyrophyllite in this particular texture, but the origin of the texture would have been much the same.

Sample M4 is from the area mapped in great detail to show the relationships between the white andesite and the purple andesite (Pl. 3). M4 is a sample of the white altered rock, and represents what is considered to be the first stage in the alteration to phrophyllite. Megascopically this rock is gray, with a greenish cast, and with a few light purple streaks. The weathered surface looks as if it contained water-worn pebbles, but fresh surfaces, and the thin section show a porphyritic andesite texture. The thin section does not indicate that the rock is a breccia, but the hand specimen suggests that it is by the manner in which the fragments weather.

Under the microscope, M4 consists chiefly of an aggregate of quartz and feldspar grains of fairly even size. The grains averaging about .08 mm. in diameter, although some grains are up to .2 mm. across. High power magnification shows that a part of this aggregate is composed of tiny grains of pyrophyllite replacing quartz and feldspar, and not showing the flaky habit characteristic of larger grains. This granular aggregation of pyrophyllite is present even in the highly pyrophyllitized rocks on beveled edges of thin sections, and suggests that the flaky habit of the mineral has developed from this more finely-grained habit.

Tiny flakes of pyrophyllite also occur in a network of iron oxide-stained veinlets in the groundmass, in flaky aggregates replacing quartz grains, and in patches which can be seen to be pseudomorphous after feldspar phenocrysts. The palimpsest porphyritic texture is only faint, and is best observed under low magnification. Both quartz and pyrophyllite have repaced the feldspar phenocrysts, and wherever the time relationships of these two minerals can be determined, the quartz is earlier. Some of the quartz is clear, and several places in the groundmass show a development of tiny euhedra.

Pyrite is present, and one euhedral grain is altered peripherally to hematite, which in turn is altered on the grain boundaries to what appear to be little bundles of chloritoid fibres. Pyrophyllite replaces the chloritoid. Pyrophyllite also appears in places to be pseudomorphous after chlorite, although no chlorite is present. Ilmenite partly altered to leucoxene is present. Hematite in veinlets cuts the ground mass in places.

Quartz and chalcedonic silica

Silica appears in lenticular to highly irregular bodies in the more thoroughly pyrophyllitized rocks. One large, irregular body, with a maximum exposed dimension of 110 feet, forms the hill southwest of the quarry, and another mass, at least 70 feet long, forms a hill east of the quarry. Most of the lenses of silica in the vicinity of the mine are elongated in the direction of the most pronounced shearing, with average maximum dimension of about 10 feet, and minimum dimension of three or four feet, (Pl. 1).

The silica weathers to blocky boulders and small, angular fragments. On fresh surfaces it is bluish gray to light brown, or locally greenish. In a few places it is stained red and black, particularly along fractures and joints. Locally it is porous, apparently because of leaching of unsilicified material during weathering.

Under the microscope the texture is similar to that of some of the groundmass of the slightly pyrophyllitized volcanic breccia, consisting mostly of a fine-grained mosaic of quartz. There is no trace of a palimpsest porphyritic texture. Some larger quartz grains have grown at the expense of the rest of the groundmass. Pyrophyllite is absent from the thin section examined.

The mineralogy is simple, the rock consisting of quartz, a little feldspar, small subhedral to euhedral grains of epidote, a few irregular grains of leucoxene, and anhedral to subhedral grains and aggregates of hematite and limonite, appearing along fractures.

The origin of the larger masses of silica is not known. They might represent silicified portions of the andesitic and latitic volcanic rocks. There is also the possibility that they are devitrified rhyolites. Silica masses in andesitic rocks near Lake Hodges, east of the quarry, show field relations similar to those associated with the pyrophyllitized rocks. The silica from near Lake Hodges appears to represent devitrified rhyolites, and inclusions of these siliceous rocks appear as lenses in the adjacent andesite flow breccias. However, it is evident that at least some of the silica has been introduced at about the time of the pyrophyllitization.

Volcanic flow and pyroclastic rocks, slightly pyrophyllitized

Most of the material mapped as slightly pyrophyllitized volcanic flow and pyroclastic rock is white to tan on fresh surfaces, but weathers to purple, brown, red, or black. It is hard, and although most of this material contains pyrophyllite, it cannot be scratched with the fingernail. This rock contains less silica than the altered breccias, and, unlike the latter does not have a gritty feel under the fingernail. Some samples show palimpsest porphyritic texture in hand specimen.

Outcrops include areas of massive rock weathering to rounded blocks, as well as areas where close jointing gives a sheeted effect. The weathered surface is typically rough. There is a slight development of a pebbly surface, but this is not so pronounced nor so common as in outcrops of the rocks that were originally breccias.

Most of the rock has a finely granular appearance, with little schistosity evident in hand specimen. Some exposures have been leached to form a moderately porous rock. Silica bodies occur within the unit as mapped, but they are not as numerous as they are in some of the more highly pyrophyllitized rock types. One sample, taken from an area mapped as slightly pyrophyllitized volcanic rock, was found to include an irregular mass of greenish andesite, altered and partly pyrophyllitized.

In thin section the slightly pyrophyllitized volcanic rock has several textural variations that apparently are reflections of the original rock types. Both porphyritic and non-porphyritic volcanic rocks are involved. In most slides the porphyritic texture is only faintly visible, and is shown chiefly by differing orientations of pyrophyllite flakes and by differing textures of the quartz. Palimpsest zoning and twinning of original feldspars is evident, although no feldspar is present in the slides examined (Fig. 11).

Quartz and pyrophyllite are present in approximately equal amounts in most of the slides examined, although any very accurate determination is difficult because of the fine grain size and an iron-oxide staining that obscures details. Quartz occurs as a very fine-grained mosaic and in grains of larger growth. The coarser grains are clear and fresh, and seem to have been formed by growth from the groundmass mosaic. Pyrophyllite replaces quartz both in the smaller and larger grains (Fig. 12). Most phenocryst phantoms have been altered mostly to pyrophyllite.

The pyrophyllite occurs as tiny flakes in most of the sample, although locally, particularly where it replaces the fresher-looking quartz, flakes and shreds large enough to show full birefringence are developed. Remnants of the vein network along which pyrophyllite formed can still be seen by the difference in size between the flakes of the veinlets and those of the groundmass.

Leucoxene and hematite are the only opaque minerals observed.

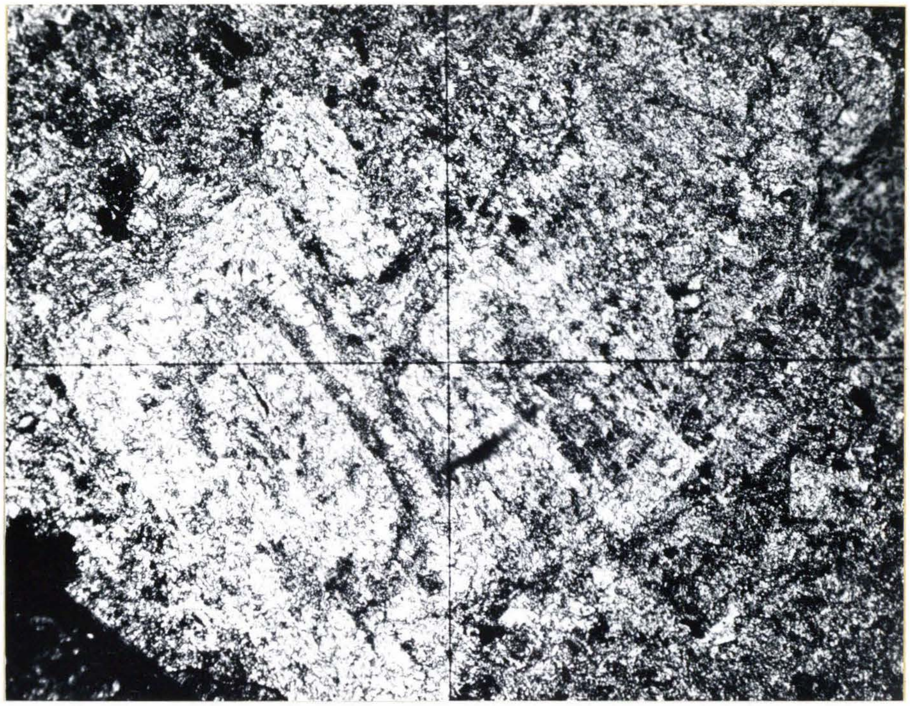

Fig. 11. Slightly pyrophyllitized volcanic rock, showing relict zoned plagioclase phenocryst. Sample P18. Crossed Nicols. x50.

Fig. 12. Slightly pyrophyllitized volcanic rock, showing embayed quartz grain. Sample P16. Crossed Nicols. x200.

The leucoxene is in more irregular grains than it is in the less altered rocks. Two generations of hematite are apparent. One is represented by tiny, pinkish opaque grains and dusty particles scattered through the groundmass, and apparently was formed by alteration from ferromagnesian minerals of the original volcanic rock, and perhaps in part from ilmenite. The second generation is in blood-red translucent to opaque veins along fractures cutting the groundmass. This generation is of supergene origin, and is seen in most slides of the entire suite, even in what appear to be relatively fresh samples.

The discussion just given concerns typical slightly pyrophyllitized volcanic flow rock. Two somewhat different rock types also were grouped with this unit in the field. One of these, represented by sample P20, is a tuffaceous-appearing tan-colored rock with a chalky appearance. The other type looks either like a reddish-brown sandstone with a few larger, well-rounded sand grains, or like a much weathered sandy tuff with a few spherulites. Megascopically this reddish-brown rock does not appear to contain much pyrophyllite, but its field occurrence shows a close relationship to the surrounding rock. It is represented by sample P23.

The thin section of sample P20 is so covered with opaque dust and tiny grains, some white in reflected light, that it is difficult to tell much about the rock. No porphyritic texture is evident.

The rock is extremely fine-grained except for a few rounded quartz grains as much as 0.1 mm. in diameter. Most of these appear to be fresh. The groundmass not obscured by the opaque material is a fine-grained aggregate of pyrophyllite and quartz.

Thin veinlets cut through the groundmass of sample P20. Most of these are composed of tiny quartz grains, but some pyrophyllite appears in the veinlets, possibly replacing the quartz.

A consideration of the megascopic and microscopic characteristics and the chemical analysis of sample P20 suggests that it is derived from a slightly more fine-grained, in part glassy, facies of the original volcanic rocks than the more typical rocks in the mapping unit, and that more silicification and less pyrophyllitization has taken place.

Sample P23 is seen in thin section to differ far more from typical rocks of the unit than P20 does. It consists mostly of a reddish-brown translucent to opaque mineral in colloidal aggregates and locally in spherical grains with a faintly discernable radiating structure in some places. Some of these spherulitic grains have a core of quartz and pyrophyllite aggregates with the red mineral forming the rim. Quartz and pyrophyllite also appear in granular aggregates through the groundmass. One grain of what is apparently microcline was seen.

Little laths of either quartz or feldspar are oriented at random through the slide. Possibly the rock was originally a latite or quartz-latite, with a fine-grained or glassy groundmass containing tiny feldspar laths. These laths may still be feldspar, or may have been replaced by quartz. No good indication of their present index of refraction was obtained.

The spherical grains and the colloidal appearance of the red material suggests the presence of iron and aluminum hydroxide gels of the type formed in lateritic weathering. Gibbsite or other "bauxite" minerals may be present. Only a small amount of the rock represented by sample P23 is present in the area mapped.

Volcanic flow and pyroclastic rocks, moderately pyrophyllitized

Most of the rock mapped as moderately pyrophyllitized volcanic rock is chalky white, light gray, or tan on fresh surfaces, weathering to brown or red outcrops, amd much stained to red or black along fractures. In hand specimen it plainly contains much pyrophyllite, but it is scratched with the fingernail only with difficulty, and in many places not at all.

A residual porphyritic texture is evident on fresh surfaces of most specimens, although there is not much color contrast between the phantom phenocrysts and the groundmass. The rock contains little grains of silica, but these are neither as numerous nor as evident as in the slightly pyrophyllitized volcanic rocks. Most fresh samples of this rock do not show any schistosity, although a few specimens show a rudely-defined alignment of grains, and weathered outcrops tend to have a platy to schistose appearance.

The rock occurs in general in the areas surrounding the pyrophyllite and pyrophyllite-quartz schists, interfingering with these and with slightly pyrophyllitized rocks away from the deposit. Lenticular bodies of this rock are found in adjacent rock types, and it contains lenses of them. In practically all places the lenses are aligned with long directions parallel to the most common shearing direction.

In outcrop, this rock unit is distinguished from lower grades by its lower silica content, higher pyrophyllite content, relative softness, and tendency toward schistosity in weathered outcrops. The outcrops are not so bold as those of the slightly pyrophyllitized rock. From more highly pyrophyllitized types, this rock is distinguished by greater silica content, greater hardness, and poorer schistosity. It also tends to weather to rougher surfaces than the higher grade rocks.

In thin section, the rock is seen to contain more pyrophyllite than it does quartz. The thin sections examined all show the palimpsest texture of a porphyry. The groundmass is a fine-grained aggregate of fresh-appearing pyrophyllite flakes and quartz grains. Most of the feldspar relicts are altered to fine-grained pyrophyllite aggregates, although some consist of quartz partly replaced by pyrophyllite. Some sections contain as much as 30 percent of feldspar, which appears in the fine-grained groundmass rather than in the phenocryst generation. This feldspar is probably mostly untwinned oligoclase, with a little orthoclase. Most of the slides examined contain less than 10 percent of feldspar.

There is a pronounced tendency for the pyrophyllite to form tiny rosettes, both in the groundmass and on the phenocryst phantoms. A schistosity is well displayed by the alignment of pyrophyllite flakes. Some feldspar relicts are observable only with rotation of the stage under crossed Nicols. The alignment of pyrophyllite flakes then delineates the outline of the replaced feldspar.

Some sections are cut by veins of hematite. Leucoxene is scattered through the slides, in anhedral to subhedral grains, some of which show some ilmenite. A comparison with other slides suggests that some ilmenite grains grew during the pyrophyllitization, as there seem to be fewer but larger grains in the higher-grade rocks.

Pyrophyllite-quartz schist

In appearance most of the pyrophyllite-quartz schist differs little from the high grade pyrophyllite schist. The higher silica content can be seen in the slightly more granular look. The pyrophyllite-quartz schist is white, greenish gray, or pink, but is stained red and black along fractures, as are all the other rock types. It is scratched by the fingernail in most places, but with some difficulty. Although it is schistose, the schistosity is not so regular nor so pronounced as in the pyrophyllite schist. Chalky white phenocryst phantoms can be seen in some specimens.

On weathering, this rock breaks down into little wedges and plates as a result of the schistosity and shearing. Some areas of it contain more silica than others, and it contains many lenses of silica ranging from microscopic dimensions to 10 feet in length .

Most of the pyrophyllite-quartz schist is associated with the high grade rock near the quarry, and it interfingers with, and contains lenses of the less-pyrophyllitized rock types. Test pits and bulldozer cuts at several places in the vicinity of the quarry expose this rock. It is not known to occur in large bodies, however.

In thin section, the rock is a fine-grained aggregate of pyrophyllite flakes with a little cryptocrystalline quartz and a few larger, fresh-looking grains of clear quartz (Fig. 13). These grains are embayed and cut by pyrophyllite streamers. Some of these clear quartz grains give good interference figures, some of which appear faintly biaxial.

Fig. 13. Pyrophyllite-quartz schist, showing quartz grain cut by fine-grained pyrophyllite. Sample P7. Crossed Nicols. x200.

A well defined schistosity has been developed in the pyrophyllite, and the original porphyritic texture was not discernable in any of the thin sections examined (Fig. 14). An island-and-sea texture of some of the quartz grains indicates the replacement of these grains by pyrophyllite, as separate islands of quartz show simultaneous extinction under crossed Nicols in many places. The quartz is replaced both centrifugally and centripitally by pyrophyllite. This has been observed also in other rock types.

Some pyrophyllite flakes in the pyrophyllite-quartz schist are large enough to show cleavage, but no interference figures could be obtained. These larger grains do not show good extinction, but have the "curly maple" texture of micas at the darkest positions. The largest quartz grains seen, which are larger than the pyrophyllite flakes, are about .1 mm. across. Most of the quartz present is in tiny grains scattered through the smaller pyrophyllite flakes. Most of these smaller quartz grains are less than .03 mm. in diameter.

The network of replacing pyrophyllite veinlets can still be seen in the thin section of sample P12 by the orientation and thickness of the flakes in the veinlets.

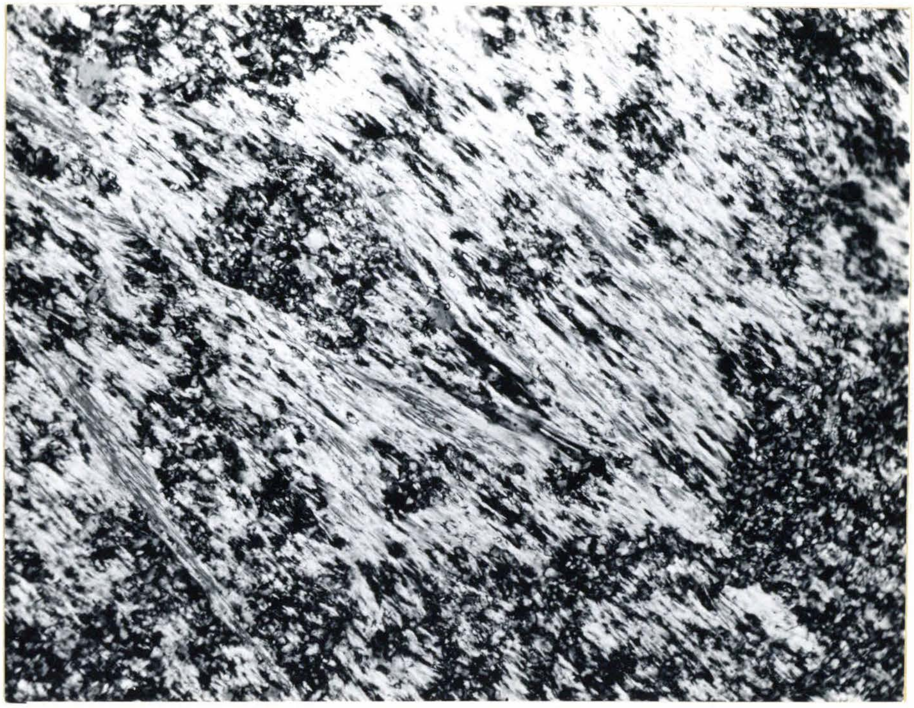

Fig. 14. Pyrophyllite-quartz schist, showing schistosity of pyrophyllite. Crossed Nicols. x120

Pyrophyllite schist

The pyrophyllite schist appears in one elongated body in which the two quarries have been developed. The rock is white or very light gray when fresh, but is stained by iron oxides along fractures. A few dark spots are scattered throughout. Schistosity is well developed, and the material breaks into long splinters, slabs, and roughly rhombohedral blocks. It breaks to fairly smooth surfaces in the direction of schistosity, and with a hackly surface at right angles to it.

The pyrophyllite is fibrous to massive, but chiefly fibrous. No rosettes were noted in the field. It has a faintly soapy feel, and most of it is readily scratched with the fingernail. In general appearance it resembles talc in most respects.

The pyrophyllite schist grades into the pyrophyllite-quartz schist in the direction normal to the most pronounced shearing, and apparently interfingers with it in the direction of this shearing, which is also the direction of schistosity. One lens of silica was mapped within the high grade body, and the quarry operators report that others are encountered from time to time.

The operators also report that they occasionally find boulders of a greenish, clayey-looking rock entirely surrounded by pyrophyllite, and bodies of rock that would apparently correspond to the less pyrophyllitized rocks of the field designation.

Under the microscope the phyrophyllite schist is similar to the pyrophyllite-quartz rock except that it contains more pyrophyllite and less quartz. Sample P10 taken near the edge of the body shows more fine-grained quartz in the groundmass than sample P11, which was taken from the center of the body.

The phenocryst palimpsests can still be detected in the thin sections examined, all of them replaced by pyrophyllite. A few coarser aggregates of quartz are present, some grains attaining a size of .08 mm. This quartz is of a fresh, clear appearance, and appears to be altering to pyrophyllite. The pyrophyllite appears in little shreds and flakes with a definite preferred orientation. No flakes large enough to determine any optical properties are present, although there is a tendency toward a development of aggregates of larger flakes than those seen in any of the other rock types.

Structure

Larsen (1948) points out that the structural trends in the region of the Peninsular Ranges of Southern California are dominantly northwest-southeast. In the vicinity of the Pioneer pyrophyllite deposit the rocks are sheared along zones that are vertical or dip steeply, and the dominant trend of the shear zones is about N45°W. Locally this trend swings away from the prevailing direction, as near the east end of the quarry, where the structural trend is about east-west, and near the southern end of the area shown on plate 1, where the trend is SW-NE.

Strongly developed shear zones also occur at right angles to the major direction, and in some places the rocks are broken up by fractures that trend in all directions. No evidence is available as to displacement of any of these shear zones. A suggestion of folding is seen in the manner in which linear elements swing around what are apparently the axes of folds in the metavolcanic rocks. In the eastern part of the area shown in plate 1 such a linear element, perhaps original bedding in the volcanics, swings partly around the axis of a west plunging syncline and passes under the terrace cover to the north.

As no stratigraphic sequence has been worked out in the original volcanic rocks, and as it probably would be impossible to follow such a sequence, if available, through the metamorphic changes that have occurred, it is not possible to give any details on exact structural relationships in the vicinity of the quarry.

The intense shearing that passes through and near the pyrophyllite body is not observable in the surrounding area. The regional structure trends in general NW-SE, although in the area shown in figure 1 the strongest direction of shearing is slightly east of north, with a secondary shearing trend in a northwest-southeast direction.

The various grades of pyrophyllitized rocks occur in elongated bodies with maximum dimensions paralleling the shearing zones passing through the vicinity of the deposit, and these bodies interfinger with each other in this direction. The bodies of silica shown in plate 1 illustrate this feature in a striking manner. The relationship of the pyrophyllite occurrence to the structure of the area is clearly indicated.

Mineralogy

The general features of the mineralogy have been mentioned in the discussion of rock units mapped. It might be well, however, to present in more detail some features of the minerals associated with the deposit.

Feldspar

The feldspar of the original metavolcanic rocks is mostly andesine, so far as can be determined from the thin sections examined. Cores of some zoned crystals may be labradorite. The feldspar of the groundmass is albite or oligoclase, untwinned, with some orthoclase. The phenocrysts are subhedral to euhedral, and many show pronounced zoning. The groundmass feldspar is largely anhedral except in some cases where subhedral laths are found, oriented in flow lines in places.

Quartz

Quartz is present in most of the slides. In the andesite it occurs in a few grains that might have been phenocrysts, but most of the larger, fresher quartz grains are secondary. The quartz occurs in several forms. In the large masses of silica, the quartz is a fine-grained mosaic of anhedral to subhedral grains with some grains showing definite crystal boundaries, although most of the boundaries are sutured. One feature common to most of these granular masses is the tendency toward a lenticular shape.

Within the finer-grained masses, larger grains have grown in places, and these tend to be clear of inclusions. In rocks other than the bodies of silica, quartz appears in fine-grained aggregates in the groundmass and in fine to coarse-grained aggregates replacing feldsparphenocrysts. The tendency for a few grains to be enlarged and clear of inclusions is indicated also in these rocks, although most of the larger grains are embayed by pyrophyllite in the rocks of higher grade.

In some of the fine-grained aggregates, the quartz is cryptocrystalline, intimately associated with other minerals, which include, in various slides, orthoclase, pyrophyllite, oligoclase, iron oxides, titanium minerals, chlorite, and serpentine. All of these are not necessarily present in any one slide. In many places the aggregation of minerals appears to represent a devitrification of a glassy groundmass at least to some extent.

The quartz mosaics are cut by quartz veins in places. Altogether then, there are at least three generations of quartz, one in the original andesite, one replacing feldspars in groundmass and phenocrysts of the volcanic rocks, in some instances in replacement veins, and a third generation of vein quartz that cuts the second generation. Because of the relationship of the pyrophyllite to these two generations of introduced quartz, it is believed that the presence of two generations of hydrothermal quartz is more apparent than real, and that silicification took place in two or more waves, not separated by much time, and not everywhere apparent.

Pyrophyllite

In hand specimen, the pyrophyllite is uniform in color, being white or creamy white, with local stains and specks of opaque minerals and quartz. The latter give an overall gray appearance to some specimens.

In thin section the pyrophyllite occurs in tiny anhedral grains and anhedral to subhedral shreds and flakes. In the least pyrophyllitized rocks the flakes are so small that they show low birefringence, and the birefringence increases with the pyrophyllitization as a result of the increase in size and concentration of the flakes. In the case of the smaller flakes and grains, there is a greater tendency toward an admixture of fine opaque grains, giving a cloudy look in plane light. In even the most highly pyrophyllitized rocks the individual flakes are not large enough to give interference figures. The preferred orientation of these flakes gives a mass birefringence effect, however, with definite positions of maximum and minimum illumination over relatively large areas.

The pyrophyllite replaces feldspar, quartz, chlorite, and groundmass minerals of the andesite, and presumably replaces all other minerals as they are absent from the high grade rocks. In some slides the pyrophyllite appears principally in a network of interlocking veinlets of flakes with low birefringence and admixed opaque dust. The size increase of the flakes and the coalescence of these veinlets can be followed through several slides as the total amount of pyrophyllite increases. From information available, there seems to be practically no pyrophyllite occurring with the bulk of the quartz and chalcedonic silica.

Iron and Titanium Oxides

Hematite appears in two generations. It is definitely a late, possibly the latest, mineral in many places, where it occurs in fractures cutting all other minerals present. Hematite is also intimately associated with pyrophyllite, magnetite, and ilmenite as a product derived from alteration of the original ferromagnesian minerals of the volcanic rocks, and also possibly from pyrite and ilmenite. Normally hematite, and the yellowish associated material which may be called limonite, would not be expected to form under the conditions that have altered the volcanic rocks and produced the pyrophyllite, so the more finely divided hematite not associated with fractures is possibly also a late product of weathering. The only difference between the two types of occurrence would be then that one has been introduced and the other derived from the original constituents of the rock.

Ilmenite is believed to be present in greater abundance than magnetite in most of the rocks. Chemical analyses indicate that more titanium oxide is present than iron oxide in rocks that have been analyzed. The alteration product leucoxene is the most prominent opaque mineral in the higher grade rocks, except for hematite in a few places. The bulk of the hematite does not appear in chemical analyses because of the rejection of most stained areas in the sampling. The ilmenite appears in anhedral to subhedral grains and sometimes shows the skeleton crystals typical of this mineral. It is extensively altered to the white, opaque product leucoxene in all slides. The leucoxene is stained with iron oxides in many places.

Magnetite occurs in the andesites and less pyrophyllitized rocks as an alteration product of the original ferromagnesian minerals, and possibly as a primary mineral with the ilmenite. It is in fine-grained anhedra and dusty particles, and some of it has been altered to hematite.

Pyrite

Pyrite occurs in a few slides and hand specimens. Some cubes of hematite or limonite in the more pyrophyllitized rocks may be pseudomorphs after pyrite. The exact time relations of the pyrite are not known, except that in one or two places it has altered peripherally to iron oxides. Pyrite occurs in the less altered andesite and associated with the silica masses. It is possibly a product of a pre-pyrophyllite propylitization of the andesite, or has been introduced with the quartz, or both. It has not been observed in any of the higher-grade rocks.

Leucoxene

Irregular to subhedral white opaque grains associated with the ilmenite are considered to be the mineral leucoxene, which is titanite in part. Most of the ilmenite has altered to this product. Most of it is white, but some is stained red by iron oxides.

Epidote

Epidote is present in a few slides as tiny anhedral to euhedral grains and aggregates. Its occurrence only in the less altered andesite and in the quartz and chalcedonic silica suggests that it is an alteration product of the andesite, and that it has altered to pyrophyllite in the other rocks.

Chlorite

A mineral not seen in any of the higher-grade rocks, but present in the andesite is chlorite. It is an alteration product on feldspar phenocrysts and in some places constitutes a large part of the andesite groundmass. It occurs in shreds and patches and in some large fan-shaped grains with sweeping extinction. It appears to be one of the earliest minerals to alter to pyrophyllite, and some of the lower grade rocks that contain no chlorite have pyrophyllite that appears to be pseudomorphous after it.

Serpentine

Serpentine, one of the metamorphic minerals of the andesite, alters early to pyrophyllite. It occurs as tiny veinlets and aggregates in the andesite groundmass, generally with fibres transverse to the veins. There is very little of the mineral in the andesite, and it is completely lacking in the pyrophyllitized rocks.

Calcite

Calcite is not common, and its origin is uncertain. In one slide, sample P14-B, it occurs with pyrite, as poikilitic porphyroblasts enclosing leucoxene and pyrophyllite. It also appears to be pseudomorphous after a pyroxene. In another thin section of andesite the calcite replaces feldspar and is replaced by pyrophyllite, to all appearances. Calcite could be formed as a result of propylitic alteration of the andesite, or from circulating ground water as a very late mineral. The evidence for its origin is not conclusive, although at least some of it appears to be earlier than the pyrophyllite.

Zeolite

An alteration product that is probably one of the zeolites occurs in very tiny grains on the feldspar in one of the thin sections of andesite.

Apatite

Apatite, in tiny, euhedral grains, is an accessory in some of the andesite. A trace of P_2O_5 is reported in the chemical analysis of even the High Grade pyrophyllite.

Chloritoid

A mineral associated with pyrite and magnetite and hematite in some thin sections of andesite is probably chloritoid. It appears in little bundles of fibres next to the opaque minerals, and is replaced by pyrophyllite.

"Bauxite"

Aluminum hydroxides of uncertain nature and origin are believed to occur in a few places. The red colloidal substance in sample P23 may be in part aluminum hydroxide of the type to which the name cliachite, among others, has been applied, and the spheres with faint radiolitic texture may represent gibbsite. Boehmite may be present in slight amount in some of the more highly pyrophyllitized rocks.

Paragenesis

It is evident from microscopic study that two processes have operated on the volcanic rocks of the region. One has been a regional metamorphism of relatively low degree, probably accompanied by an alteration of a propylitic type. The chlorite, serpentine, epidote, albite, and possibly calcite, pyrite, and some quartz were formed as a result of the first metamorphism.

The second process produced the pyrophyllite deposit, and its results were superimposed upon those of the first. The first change in this second process was a silicification. The silica possibly was introduced from the same sources as the solutions that brought in the pyrophyllite. This is suggested by the general concurrence of the boundaries of silicified and pyrophyllitized rock.

The evidence suggests that the pyrophyllitization immediately followed the silicification, and that the processes were essentially simultaneous in places. This is shown by the presence of both silica and pyrophyllite replacing feldspar in the same slide. The silicification was not complete in all places, and the unsilicified rocks were more readily replaced by pyrophyllite. The units mapped as silica may or may not have been silicified at this time.

The prior occurrence of silica in most places is seen in the textural relationships between the silica and pyrophyllite in thin section and in the field relationships. The area examined in great detail (Pl. 3) shows the alteration of purple andesite to a white rock that does not differ greatly in appearance from the pyrophyllitized volcanic breccia mapped near the quarry, and which in thin section is seen to be essentially a partly silicified andesite with some pyrophyllite replacing the silica.

The facts that the textural relationships of the andesite can be traced to the edge of the high grade body, and that the original minerals disappear in the direction of the quarry, show that pyrophyllite has replaced all other minerals of the original metavolcanics, both primary and secondary.

The heat and presence of aqueous solutions attendant upon the pyrophyllitization probably have aided some processes of a general metamorphic nature. For example, the secondary growth of some of the quartz grains and their clearance of inclusions probably went on during the formation of the pyrophyllite.

The only mineral known to be later than pyrophyllite is the supergene hematite, but part of the quartz probably is also later as are calcite and the "bauxite". The evidence for the age of the calcite has been discussed. White quartz veins cut some of the silica masses, and may extend into some of the pyrophyllitized rocks, but this is not certain.

Aluminum hydroxides that might be called "bauxite" in a broad sense could be formed in two ways. As explained more fully on an earlier page, an aluminum hydroxide such as boehmite could readily form under conditions similar to those that produce the pyrophyllite. Minerals more common to bauxite deposits, such as gibbsite, are usually the result of prolonged chemical weathering of aluminous rocks in tropical climates. The rocks in the vicinity of the Pioneer deposit probably were subjected to prolonged weathering sometime during the Tertiary. This is all speculative, but it may be well to mention that Lindgren (1933) cites a report of the Bureau of Soils that shows that an examination of several thousand soils from all parts of the United States revealed the presence of aluminum hydroxides in but one sample, and that one was from southern California.

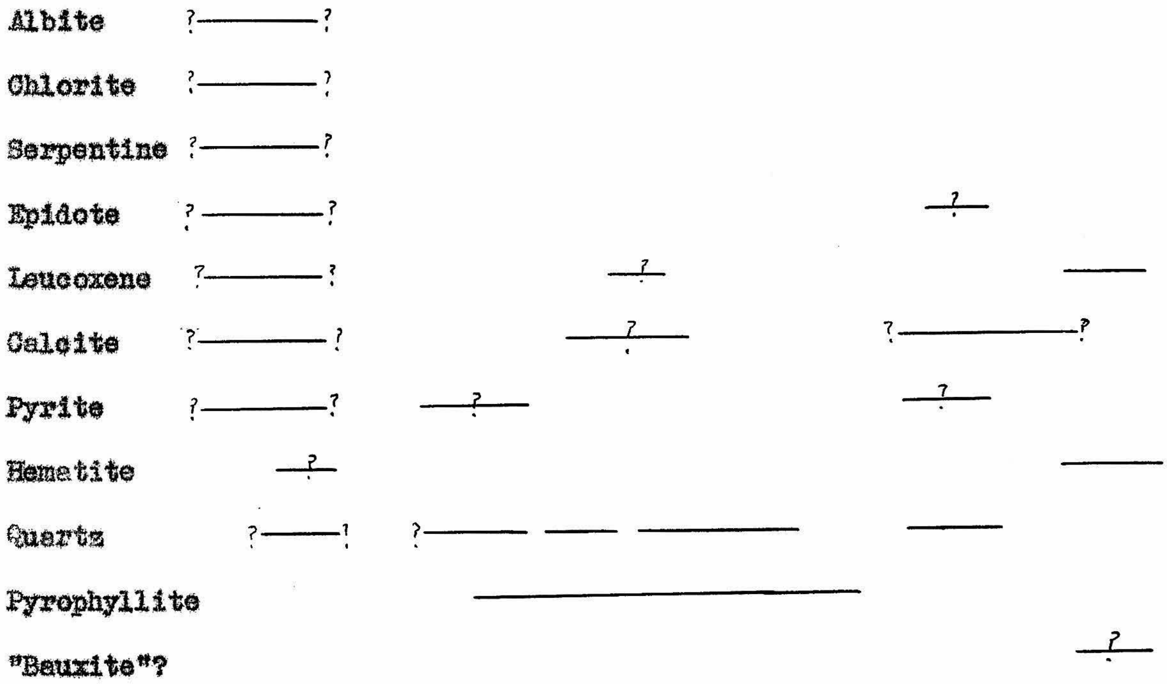

Fig. 15. Paragenesis diagram showing some inferred time-relationships of minerals in the pyrophyllitized rocks. The earliest group of minerals shown represent, at least in part, the propylitization of the andesites. The time interval, if any, between this process and the pyrophyllitization is not known.

Chemical analyses

Four chemical analyses of rocks in the vicinity of the pyrophyllite deposit are shown in the following table:

Analyses of rocks from Pioneer pyrophyllite deposit

	#20	#6	#12	#11
SiO_2	80.13	65.58	77.16	66.74
Al_2O_3	11.79	24.07	18.29	26.68
Fe_2O_3	.28	.38	.16	.44
FeO	n.d.	n.d.	n.d.	n.d.
MgO	.06	.45	.05	.06
CaO	.74	.30	.10	.05
Na_2O	n.d.	n.d.	n.d.	n.d.
K_2O	n.d.	n.d.	n.d.	n.d.
H_2O	3.10	3.43	3.13	4.65
H_2O -	1.00	.46	.21	.16
TiO_2	1.85	.68	.65	.70
P_2O_5	.24	.07	.05	.02
Total	99.19	95.42	99.80	99.50

Eilun H. Kane--analyst

Sample no. 20 is a rock mapped as slightly pyrophyllitized volcanic flow and pyroclastic rocks, and resembles an altered tuff in the field. Sample no. 6 is from near the south side of the quarry, and in hand specimen shows chalky-looking phantom phenocrysts. No. 12 is pyrophyllite-quartz schist from the north wall of the pit, and no. 11 is pyrophyllite schist from the floor of the quarry.

An attempt has been made to calculate normative minerals for these rocks, using certain assumptions based for the most part on known modal minerals. Unfortunately, because of small grain size and extensive iron oxide staining in some of the thin sections it has not been possible to make a micrometric study of the one rock that is not readily calculable into a norm. This is sample no. 6, which is discussed in more detail later on.

The analyses were not complete, in that neither the alkalies nor the ferrous iron was determined. Inspection shows that Na and K are conspicuously absent except in sample no. 6. In the normative calculations for samples 20, 12, and 11, the calcium was used as a basis for calculating titanite (to account for leucoxene), the excess TiO_2 was calculated as rutile, although it is actually present as ilmenite. The Fe_2O_3 was assigned to hematite. So little P_2O_5 is present that it is reported as a trace of apatite, without assigning any calcium to it. If calculated, the apatite would amount to a few tenths of 1 percent at most.

For remaining minerals, all Al_2O_3 was assigned to pyrophyllite, and excess silica calculated as quartz. The MgO was disregarded. Ross and Hendricks (1945) have shown that Mg may proxy for Al in the space lattice of pyrophyllite. Except in the case of sample 20, the H_2O determined agreed closely with the amount required for pyrophyllite, and was not very far off in 20. The calculated minerals agree quite closely with petrographic and field data. The normative mineral percentages, by weight, for the three rocks under discussion are given below.

	#20	#12	#11
Pyrophyllite	41.76	64.44	94.32
Quartz	51.48	34.08	3.78
Rutile	.88	.56	.64
Titanite	2.55	.39	.20
Hematite	.32	.16	.48
Apatite	tr.	tr.	tr.
Total	97.33	99.97	99.42

These rocks show a progressive decrease in free silica and increase in pyrophyllite in the direction of the High Grade pyrophyllite mass. There is also a general decrease in the titanium oxide. The variability of the hematite is explained by the excessive iron oxide staining along fractures in all parts of the area. Petrographic study shows that the apparent sequence revealed by these analyses is not to be accepted at face value in all respects. The increase in pyrophyllite shown is valid enough, but the silica relationship is not. Sample no. 20 is a silicified rock, as shown by chemical and microscopic evidence. Sample 12, and probably sample 11, have not been derived from rocks so strongly silicified. That is the reason sample no. 6 appears at first to present an anomaly. With respect to pyrophyllite there is a regular sequence from sample 20 through 6 and 12 to 11. Sample 6 has the lowest silica content of the four rocks analyzed, and in free quartz content stands somewhere between samples 11 and 12. It has not been so thoroughly silicified as samples 20 and 12, and possibly not so much as 11.

The status of sample 6 is explained by the following facts: 1) silicification preceeded pyrophyllitization in some, but not all places, 2) pyrophyllite replaced silica in some, but not all places, 3) pyrophyllitization of feldspar was an early event in most places, but some feldspar, as in sample 6, escaped both silicification and pyrophyllitization, even in otherwise highly pyrophyllitized zones. Thus, in some respects, sample 6 is more closely related to the original andesite than any of the other three rocks analyzed.

Because of the fine-grained and opaque nature of much of sample 6, only an approximate determination can be made of its constituent minerals in thin section. It contains some quartz, pyrophyllite, and feldspar, and an opaque to translucent material that is white in reflected light, with a more pearly luster than the flaky pyrophyllite shows. There are three possibilities available for the calculation of Al_2O_3in excess of that required for known modal minerals: to assign the alumina to sericite, kaolinite, or to an aluminum hydroxide such as boehmite. Since there is no evidence of the presence of sericite, and no way of estimating how much alkali to assign to it, no sericite is calculated, although its presence is a distinct possibility. A calculation of any reasonable amount of kaolinite does not leave enough silica to form the quartz that is clearly present in thin section.

The norm for sample 6 has been calculated by taking 10 percent of the alumina left over from the feldspars and calculating it as boehmite. To simplify things further, all TiO_2 has been calculated as rutile and all Fe_2O_3 as hematite, and the small amount of CaO has been assigned to anorthite. Boehmite may or may not be present, but some type of aluminum hydroxide possibly is, whether of low or high temperature origin. Boehmite could be of either type of origin.

The norm for sample 6 is given below.

Pyrophyllite	54.0
Quartz	6.8
Albite	24.6
Anorthite	1.4
Orthoclase	10.0

Boehmite	2.0
Hematite	.4
Rutile	.7
Apatite	tr.
Total #6	99.9

This calculation gives an approximate check with the estimated mode, which is about 50% pyrophyllite, 20% quartz, and 30% feldspar. The alkalies have been considered to make up the difference between the analyses total and 100%, and have been apportioned between potash and soda in the proportions found in typical andesites. The amount of alkali taken is probably too high, as other undetermined elements probably constitute some fraction of 1% in the total. A slight decrease in normative feldspars would give an increase in quartz sufficient to bring the norm more closely in line with the estimated mode.

Comparison with other deposits

Three commercially important pyrophyllite deposits of North America have been described. These are those in North Carolina, (Stuckey, 1925), in Newfoundland, (Buddington, 1916; Vhay, 1937), and on Vancouver Island (Clapp, 1914). Pyrophyllite has been reported from many other localities in various parts of the world, but they have not been so thoroughly described as the deposits mentioned. The main features of these will be outlined and some comparisons made with the Pioneer deposit.

North Carolina deposits

The best known and economically most important deposit of pyrophyllite in the United States is in the Deep River region of North Carolina. The following account of the geology of the occurrence is abstracted from the report of Stuckey (1925). A group of pyrophyllite bodies occurs in a series of Algonkian volcanic and sedimentary rocks that have been tightly folded. Numerous shear zones occur along the sides of the folds. Pyrophyllite of hypothermal origin occurs in these shear zones as elongated lenses, and is confined to these zones. The folded rocks include slates, acid tuffs and breccias, rhyolites, andesites, and diabases, but the pyrophyllite occurs only in the acid tuffs and breccias. The pyrophyllite lenses conform to the strike and dip of the enclosing rocks.

Stuckey has shown that the pyrophyllite was formed by metasomatic replacement of the acid volcanics by hot solutions introduced along the shear zones. He implies (1925, p. 448) that the shear zones along which the alteration took place were formed principally in the acid volcanics because these rocks were less competent. This would suggest that possibly lithology was more important in localizing the channelways for the solutions than in determining any preferential replacement.

Petrographic study of the Deep River pyrophyllite shows that pyrophyllitization was preceeded in most places by a marked silicification, with attendant decrease in feldspar content of the rocks. Development of pyrite and chloritoid in places accompanied or followed the silicification and preceeded the pyrophyllitization. At other points the pyrophyllite immediately followed the silica. The chloritoid seems to have replaced iron oxides. In every case silicification preceeded pyrophyllitization, and the feldspars disappeared with the advent of the quartz. The purer pyrophyllite bodies commonly include sericite and lenses of quartz and partly altered country rock.

Stuckey concluded that the Deep River deposits were similar in type of origin to those of Newfoundland, and that intermediate conditions of temperature and pressure operated during pyrophyllitization.

The general nature of the Pioneer deposit is similar to that described by Stuckey, although the California occurrence is much smaller and more localized. The Pioneer deposit seems to show less lithologic control in its development, but about the same degree of structural control. The replaced rocks of the Pioneer deposit were less silicic than those in North Carolina, and the mineralogy is somewhat simpler at the Pioneer deposit. The development of silica before pyrophyllitization is similar in both places, except that it was more extensive and more consistent in the Deep River region.

Newfoundland deposits

The Newfoundland deposits, the production from which was increased during World War II (Snelgrove and House, 1943), have been described by Buddington (1916), and Vhay (1937). The pyrophyllite occurs in Pre-Cambrian volcanic rocks in the vicinity of Conception Bay.

These rocks, which Buddington has named the Avondale volcanics, are a thick series of rhyolite and basalt flows with corresponding breccias and tuffs and some interbedded water-worn material. The volcanic rocks were subjected to regional alterations such as silicification and chloritization, which they evidence wherever they crop out. The pyrophyllite occurs almost exclusively in the rhyolite flows, with some pockets in the rhyolite breccias and conglomerates. The pyrophyllite bodies occur as single, well-defined veins, or as zones, consisting of a series of veins, pockets, and lenses.

The petrographic and chemical analyses made by Buddington bring out some interesting relationships. Some of the rocks are in part pyrophyllitized, some pinitized, and some silicified. The pyrophyllite is frequently found as an interlocking network of films that veneer lenses of the quartz-pyrophyllite rocks, or replace the matrix between quartzose nodules. Some of the bodies contain as much as 90% pyrophyllite, a little quartz and white mica, and traces of other minerals. The petrography shows that silicified rhyolite has been transformed into pyrophyllite by decrease in quartz, feldspar and impurities, and an increase in pyrophyllite.

A study of the chemical and mineralogical relationships involved in this transformation leads Buddington (1916, p. 148) to the conclusion that "it is necessary that metasomatic replacement of both the quartz and feldspars should have proceeded synchronously and at a much faster rate with respect to the quartz than with respect to the feldspars," to account for the intermediate rocks of the series. This would involve the introduction of large amounts of alumina, replacement of alkalies by hydroxyl, and solution of silica, both that in free quartz and that in other minerals.

Of particular interest is the suggestion, arising from the above considerations, that the silicified rhyolite that has been pyrophyllitized was a homogeneous glass, as the postulated mineral changes would require that in a crystalline rock there would have to be simultaneous replacement of feldspars by silica and pyrophyllite, and of quartz by pyrophyllite. It may be mentioned here that some of the thin sections from the Pioneer deposit suggest that these changes have occurred, although simultaneity is not demonstrable.

Pinite instead of pyrophyllite is found by Buddington to have been developed in some rocks. He shows that a balanced equation can be written, deriving either pinite or pyrophyllite from orthoclase, with the release of silica and potassium silicate. An equation involving sericite and pyrophyllite is given as:

$$2KH_2Al_3Si_3O_{12}+6SiO_2+H_2O \rightleftharpoons 6HAlSi_2O_6+K_2SiO_3$$

If silica were present in large enough excess and if the effectiveness of hydrolysis were strong, the reaction would favor formation of pyrophyllite (Buddington, 1916, p. 148).

The conclusion was reached that the deposits were formed by metasomatic replacements of previously silicified rhyolites by thermal waters, under conditions involving dynamic stress and moderate pressures and temperatures. The solutions entered along channels determined by fault or shear zones.

Later work by Vhay (1943) in the same general area indicates nothing new as to the method of formation of the deposits. Vhay states that the pyrophyllite flakes have a random orientation, and that the schistosity of the deposits is an inherited structure preserved by differential replacement along an already established planar structure.

A comparison of the Pioneer deposit with those of Newfoundland shows some points of similarity and some of difference. Similar structural features are the locallization of pyrophyllite bodies along shear zones in both instances, and the lenticular nature of the bodies. In both cases the pyrophyllite clearly has been formed by metasomatic processes. The description of the network of replacing pyrophyllite veins, as seen in thin section, matches some of the features seen in slides from the Pioneer deposit. The introduction of some silica before pyrophyllitization is also a similar feature.

Some differences between the occurrences also may be mentioned. For one thing, the original rocks of the California occurrence were less silicic. For another, the silicification in the Pioneer deposit seems to be much more closely related to the pyrophyllitization. True, some areas of the Pioneer deposit have been completely silicified, or nearly so. It is not believed, however, that the area of high grade pyrophyllite was ever completely silicified. Evidence for this view has already been presented.

Another point of difference is the lack of any known extensive development of white mica in the Pioneer deposit. Buddington's conclusions as to the factors controlling the alternate formation of pyrophyllite or pinite appear to be valid. In the part of the Pioneer deposit that is exposed, conditions seem to have favored the formation of pyrophyllite.

Vancouver Island deposits

Clapp (1914) has described the pyrophyllite deposits of Kyuquot Sound, on the west side of Vancouver Island, British Columbia. Alunite and pyrophyllite occur in the Vancouver volcanics of Triassic and lower Jurassic age. These volcanic rocks include andesites and dacites, with some fragmental masses. The volcanic rocks, more particularly the fragmental ones, have been metasomatically altered to quartz-sericite-chlorite rocks, quartz-sericite rocks, quartz-pyrophyllite rocks, and quartz-alunite rocks. Pyrite, which is present in all of the rocks, appears to have been introduced after the alunite and pyrophyllite, and perhaps during the sericitization and silicification. The metasomatic deposits are clearly related to shear zones.

Clapp (1914, p. 110) believes that the alunitization, pyrophyllitization, and part of the silicification and sericitization were caused by hot sulphuric acid solutions of volcanic origin, and that the changes took place during the accumulation of the fragmental volcanic rocks. This conclusion is based upon his conviction that alunite and pyrophyllite are probably formed only under moderate, near-surface conditions of temperature and pressure. The fine-grained, opal-like character of the associated quartz might suggest this.

Little change in total composition of the original volcanic rocks is postulated, and Clapp concludes that most of the new minerals resulted from the decomposition of the feldspars. Of course local chemical changes occurred, depending upon the type of alteration product. The quartz-pyrophyllite rocks show a gain in alumina, loss in potash, and either a loss or gain in silica. Except in one doubtful case, there seems to have been no replacement of quartz by pyrophyllite.

The rocks involved in the formation of the Pioneer deposit are more like those of the Vancouver Island occurrence than the other two mentioned. The presence of alunite and sericite have not been noted in the Pioneer deposit. It is not believed that the Pioneer deposit was formed under the shallow conditions suggested for the Vancouver Island occurrence. Also the California deposit shows evidence of the introduction of silica, and possibly alumina, resulting in a change in bulk composition of the rocks, at least in the rocks exposed in the area mapped.

Miscellaneous deposits

The most important commercial deposits of pyrophyllite in the world are those of North Carolina, Newfoundland, and the Transvaal, South Africa. Other localities for pyrophyllite which might be, or are of some commercial importance include California, British Columbia, China, Korea, Tasmania, and U. S.S.R. (Matthews, 1942).

Pyrophyllite also is reported from many places where its occurrence is of mineralogical interest only. A partial list includes Australia, Bolivia, France, Nevada, Arizona, South Carolina, and Georgia. That pyrophyllite is not really an uncommon mineral is indicated by the following list of counties in the state of California from which it has been reported: Alameda, Amador, Butte, Imperial, Inyo, Madera, Marin, Mariposa, Mono, Plumas, San Bernardino, San Diego, San Luis Obispo (Eakle, 1922; Pabst, 1938).

A few of these occurrences are of some interest, but little information is available for most of them. In the following places, at least, gold-quartz veins have been reported associated with pyrophyllite schists; Australia, Georgia, and Amador County, California (Powers, 1893; Logan, 1935). Pyrophyllite is associated with upper Triassic or lower Jurassic volcanic, or metavolcanic rocks in Madera County, California (Erwin, 1934). It occurs in connection with dumortierite in France and in Imperial County, California (Graves, 1928).

In Mono County, pyrophyllite is found in commercial quantities in two deposits, where it is seen to be replacing andalusite, among other minerals (Kerr, 1932; Peck, 1924). In San Diego County it is reported from near San Diego, and from near Encinitas (Rogers, 1912; Eakle, 1922).

Most of these occurrences have not been described in detail, at least with reference to the origin of the pyrophyllite. Most of the accounts show that the pyrophyllite occurs as a constituent of a schist, associated with vein quartz, as an encrustation of radiating fibres, or as a hydrothermal replacement product of aluminous minerals.

Pyrophyllite is probably a much commoner mineral than has been formerly supposed. In larger bodies it may have been mistaken for talc occasionally, and as a hydrothermal alteration product on minerals such as feldspars, it may be sometimes reported as sericite or kaolinite. Knopf (1924), for instance, states that the alteration product on a feldspar he studied in thin section might have been sericite, or might have been pyrophyllite. The latter possibility is very rarely even considered in such cases.

Origin of deposit

The pyrophyllite of the Pioneer deposit has been formed by replacement of sheared and slightly metamorphosed andesite and latitic flows and breccias, which possibly have slight admixtures of clastic and pyroclastic rocks. The metasomatic alteration was accomplished by solutions of hydrothermal origin, which came in along shear zones, adding silica and possibly alumina to the rocks, and removing most other elements from the zone of greatest mineralization.

The replacement origin of the deposit is evident from the distribution of the rocks mapped, from the study of thin sections, and from a study of chemical analyses of some of the rocks. As evidence of replacement, the following features of the deposit are listed:

1) Aggregates of pyrophyllite flakes occur as pseudomorphs after feldspar.

2) Pyrophyllite appears in network of veinlets in groundmass of slightly altered andesite, and there is a progressive increase of the pyrophyllite in the direction of the high grade body.

3) Replacement of quartz by pyrophyllite is shown by embayment of quartz grains and by pyrophyllite veins cutting quartz grains leaving island and sea texture with islands showing simultaneous extinction.

4) There is apparent replacement of chlorite, chloritoid, and other minerals as shown by possible pseudomorphs and the disappearance of these minerals in the highly pyrophyllitized zone.

5) Purple and green andesite have altered to a white nodular rock containing silica and pyrophyllite, the alteration taking place along fractures and joints, but with irregular boundaries, and with no noticeable change in volume (Pl. 3).

6) Fragments and lenses of relatively unaltered, or little altered rocks occur in unsupported bodies surrounded by more highly pyrophyllitized rocks.

7) Residual textures, such as phenocryst relicts and breccia fragments appear in rocks partly altered to pyrophyllite.

8) Rocks showing different degrees of alteration have interdigitated boundaries, as mapped in the field.

9) There is a loss of some elements and addition of others as shown by chemical analyses.

A silicification of the andesite in the vicinity of the pyrophyllite deposit also can be demonstrated. Mosaics of quartz grains, pseudomorphous after feldspars, and veinlets of quartz in the groundmass of the andesite indicate the replacement of parts of the original rock by silica. Evidence in thin section of pyrophyllite replacing quartz, and the presence of the silica lenses in highly pyrophyllitized rock show that the silicification, at least in part, preceeded the pyrophyllite. These two points, if taken without other evidence, might suggest that silicification everywhere preceeded pyrophyllitization.

However, other factors suggest that pyrophyllitization and silicification were in part synchronous, and that silicification did not precede pyrophyllitization at all points. Evidence supporting these contentions includes the following:

1) Quartz and pyrophyllite appear on feldspar phenocrysts in the same thin sections.

2) Unpyrophyllitized, but also unsilicified, or only partly silicified, rock bodies appear within the high grade areas.

3) Unreplaced feldspar appears in rocks on the margin of the quarry.

4) Palimpsest andesitic texture appears in most rocks up to the edge of the quarry, but is absent from the highly silicified rocks.

The last point suggests that if silicification had been complete at all, or even at many places, the residual texture would have been destroyed in most rocks in which it is now found. It might be mentioned that the above factors do not prove simultaneity for the quartz and pyrophyllite. Incomplete and rather spotty silicification might have been accomplished before the advent of the pyrophyllite, and it is evident that some of the pyrophyllite is later than much of the quartz. It is also known that some of the quartz is later than the rest, since veinlets of quartz cut quartz mosaics in the groundmass of the altered andesite. Further, some of the large quartz bodies may represent devitrified rhyolite flows.

Structural control of the alteration is well shown by the distribution of rocks (Pl. 1). The lenticular nature of most of the rock bodies connected with the deposit, and the alignment of these lenses parallel to the shearing trend is almost conclusive. The concentration of higher-grade pyrophyllite along zones of greatest shearing is very suggestive. The replacing solutions obviously rose along channelways controlled by the shear zones. Lithological control seems to have been relatively unimportant, as it cannot be shown that there is any particular difference between the replaced and unreplaced rocks in the general vicinity of the deposit.

The schistosity in the high-grade zone could have originated in one of two ways; 1) by selective replacement of minerals already possessing a schistosity, or 2) by application of directed stresses during or after the formation of the pyrophyllite. Both of these processes may have operated to some extent, as there are zones showing some schistosity in the less altered rocks. However, the presence of palimpsest andesitic textures extending up to the very walls of the high-grade deposit shows that the pre-pyrophyllite andesite had not been extensively altered to a schist. It is not likely that andesite would develop schistosity along a fractured zone a few feet wide and leave the texture of the surrounding rocks so little changed. It is more probable that schistosity developed in the softer pyrophyllite. In thin sections of slightly altered rocks the pyrophyllite is the only mineral that shows any preferred orientation, and the more abundant the pyrophyllite, the more pronounced is this type of orientation.

Hurlbut (1935), in a study of elongate inclusions in the Bonsall tonalite, found that these were oriented in the general direction N65°W, with a vertical dip, or locally with a slight dip to the south. He noted that this trend corresponded closely to the strike of folded and metamorphosed Triassic (and all pre-batholith) rocks of southern California, and added, "It may well be that the northeast-southwest pressure that caused the folding was not completely relieved at the time of intrusion---."

As to the time of development of schistosity in the pyrophyllite, it is suggested that it was developed at the time of replacement, and not later. That is, the replacement took place under conditions of moderate stress. If much shearing had followed the formation of pyrophyllite, the quartz and leucoxene grains within the schist would have been rolled, and possibly broken. They show no evidence of cataclastic texture at all. That the stress was not great, however, is shown by the megascopic andesitic texture seen in partly altered rocks with a slight schistosity with respect to pyrophyllite under the microscope. The high-grade body probably was formed in a sheared and brecciated zone, but it did not inherit its pronounced schistosity from the original rocks.

From the foregoing considerations, the following sequence of events can be inferred for the formation of the deposit:

1) extravasation of the andesite and related rocks,

2) folding and mild regional metamorphism, with shear zones developing parallel to fold axes,

3) hydrothermal alteration, consisting of silicification and pyrophyllitization by solutions rising along the shear zones. Silica, accompanied by some pyrite, at least slightly preceeded the pyrophyllite,

4) probable introduction of quartz in veins, perhaps accompanied by sulphides at some later time,

5) erosion, possibly lateritic weathering in Tertiary times, and introduction of iron oxides along fractures.

Source of solutions

The general nature of the deposit suggests that the solutions causing alteration were of hydrothermal origin. There seem to be two possible sources for the solutions. The Santiago Peak volcanics were accompanied and immediately followed by various intrusions of granodiorite and related rocks. The nearest known body of these intrusives presumably associated with the volcanics is about 3 miles northeast of the Pioneer deposit and west of Battle Mountain (Larsen, 1948). This is a mass consisting chiefly of tonalite, according to Larsen, and immediately to the west is a smaller body of gabbro porphyry.

The younger intrusives, associated with the southern California batholith, also crop out near the deposit. About 2 miles to the north is an exposure of Escondido Creek leucogranodiorite, almost surrounded by Santiago Peak volcanics, and 2½ miles east of the deposit is an exposure of Woodson granodiorite, cutting the volcanics and the associated intrusive rocks already mentioned.

It is not unlikely that the solutions causing the alteration to pyrophyllite were associated in some way with one of these two intrusions, or with related intrusives at depth. Which igneous activity furnished the solutions is not known. If the solutions came from the intrusives associated more directly with the volcanics, the similarity of the Pioneer deposit to that on Vancouver Island might be more pronounced than now appears.

The inferred acid nature of the solutions offers no help in seeking their source. Such solutions could have been derived from various sources, depending upon a number of conditions. Larsen (1948) has pointed out the evidence for the thorough soaking of the volcanic rocks while they were undergoing regional metamorphism. The solutions causing pyrophyllitization may or may not have had the same source as the soaking solutions.

Other aluminous minerals are reported from various parts of California, and sillimanite is known to occur in the Julian schist, of Paleozoic or early Mesozoic age, in the Ramona quadrangle to the east of the pyrophyllite deposit. Merriam (1946) stated that the alumina may or may not have been introduced. Pyrophyllite associated with andalusite in Mono County (Kerr, 1932) probably doe not indicate the addition of alumina to the rocks in which it is found. Sillimanite and andalusite are metamorphic minerals that are commonly found in rocks of original high alumina composition, and do not necessarily imply any addition of alumina.

Regardless of whether alumina was added or not, it is rather certain that the altering solutions contained silica, and were of a generally acid nature. The pyrophyllite itself contains as much silica as would be expected in the average quartz latite and more than in an average andesite. All rocks associated with the deposits, except the unreplaced andesite, contain more silica than the pyrophyllite.

From the evidence cited in preceding pages, most pyrophyllite would appear to have been formed at intermediate temperatures and pressures. Buddington (1916) and Stuckey (1925) have concluded that the deposits they described were formed under such conditions, and while the mineralized areas were buried under considerable thicknesses of rock. Clapp (1914) concluded that the Vancouver Island pyrophyllitization was essentially a near-surface phenomenon, occurring as the result of solfataric action during the accumulation of the altered volcanic rocks, but such an origin would not necessarily preclude the existence of moderately high temperatures.

The Pioneer deposit offers no direct evidence of the temperatures attained during mineralization, or the depth of burial, and only indirect evidence that moderate dynamic stress operated at this time. The deposit may well have been buried under several thousand feet of volcanic rocks and sediments at the time of formation. No stratigraphic or structural proof is available, but a great deal of erosion must have taken place in the vicinity since the formation of the deposit. It is also likely, as shown earlier, that moderate regional stress was still operative at the time of origin of the deposit.

In the case of a rock sample previously described (P14-B), a piece of little-pyrophyllitized andesite has been found surrounded by more highly mineralized rock. The quartz lenses (Figs. 6, 7) are aligned in the same general direction, are obviously introduced, and are not residual lenses left after the slight pyrophyllitization had taken place. Harker (1939, pp. 313-314) describes a somewhat similar occurrence of quartz in a metamorphic rock, and says of the quartz, which has been introduced, "instead of making veins, as it would do at a low temperature, it has taken the form of parallel elongated ovals and tongues with blunt or rounded extremities." The quartz replacing groundmass and feldspars in andesite at some distance from the quarry occurs in the form of veinlets. This would suggest a decrease of temperature away from the quarry area, which doubtless was near a channel for the hot solutions, and also an increase in temperatures with time, from the beginning of silicification to the complete development of the pyrophyllite deposit.

The same line of reasoning may be applied to the megascopic quartz lenses mapped around the quarry. Evidence already presented shows that these bodies cannot be considered as residual masses left after pyrophyllitization of a previously completely silicified rock mass. They may, however, represent residual rhyolitic inclusions in andesitic flow rocks.

As to the chemical nature of the replacing solutions, certain tentative conclusions may be drawn, on the basis of chemical analyses and the experimental data cited. Silica has been added to the rocks in the vicinity of the deposit, but the relationship of the silicifying to the pyrophyllitizing solutions has not been established. The silica was certainly at least in part earlier than the pyrophyllite. The question of the addition of alumina to the rocks is also in doubt. A comparison of the percentage of alumina in pure pyrophyllite with that in the average andesite would suggest that some alumina has been added. The chemical analyses show a general increase in aluminain the direction of the more highly mineralized rocks.

At certain given places, such as in the high-grade body itself, alumina has been added to the original rocks. However, alumina might have been removed from at least a part of the silica bodies near the deposit. Experimental work has shown that if the alumina concentration becomes too high at any given time, boehmite rather than pyrophyllite may form. It is that the alumina of the original volcanic rocks of the area has been redistributed, but not supplemented appreciably.

If the addition of alumina should be required, it seems not too difficult to derive it from hydrothermal solutions. A suggestion has been made of a possible addition of alumina to rocks in the Ramona quadrangle to the east (Merriam, 1946) by solutions possibly related in a broad way to those causing the alteration at the Pioneer deposit. Schwartz (1938) has stated, however, that the amount of alumina in hydrothermally altered rocks generally tends to be unchanged.

The replacing solutions obviously removed most of the alkalies, in most places during the early stages of alteration. The early removal of alkalies probably was the case in most of the pyrophyllitized zones, as experimental data show that high concentrations of K ions tend to suppress the formation of pyrophyllite, except possibly in the presence of solutions of sufficient acidity. No information is available as to the probable pH values of replacing solutions. It can only be said that the conditions outlined in the various experiments described earlier must have obtained.

The equations involved in the formation of pyrophyllite from various sources have been published in some of the papers cited above. These reports show that pyrophyllite has been produced artificially from albite, anorthite, microcline, labradorite, kaolinite, and from a proper mixture of alumina and silica gel in water. The formulas for any of these reactions are simple to derive, but the chemical relationships are undoubtedly somewhat more complex under natural conditions, and the disposition of excess ions becomes a problem. In the present study, no information is available as to what happened to the alkalies in the altered rocks. They were carried off in solution, certainly, along with certain other elements, but their ultimate disposition is unknown. The general chemical changes involved in the formation of the pyrophyllite deposit are relatively simple, but not enough information is available to work out any stoichiometric relations.

Conclusions

Conclusions as to various features associated with the origin of the Pioneer pyrophyllite deposit have been stated in preceding sections. The salient points are summarized below.

The deposit was formed by replacement of folded meta-andesite flows and breccias. Replacement was accomplished by hydrothermal solutions circulating principally along shear zones parallel to fold axes. These solutions were of intermediate temperatures, and moderate stress was operative during the mineralization. Silica was introduced, and possibly alumina as well. Alkalies and other elements, except some traces of those in accessory minerals, were removed from the more mineralized rocks. Silicification preceded pyrophyllitization in places, was probably contemporary with it in others, but was very slight in parts of the deposit.

The important factors governing the formation of pyrophyllite were temperature and composition of the replacing solutions, which contained silicaand probably had low Al and K ion concentrations in most places.

Deep weathering in the vicinity of the deposit, after it was exposed by erosion, resulted in the introduction of secondary hematite and limonite. Possibly lateritic weathering during Tertiary time produced aluminum hydroxides.

The pyrophyllite deposit should extend downward along the shear zone to appreciable depths. The lower-grade zones of quartz-pyrophyllite rocks may become richer in terms of pyrophyllite at greater depth, although residual masses of silica and less-altered rock should be expected. The secondary iron oxides should decrease with depth, so that the general grade of the deposit might well be improved. Other areas of partly pyrophyllitized rock in the general area surrounding the quarry may show an increase in quality with depth if quarrying operations are attempted.

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