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LARAMIDE TECTONICS FROM PARADISE TO HELLS GATE, SOUTHEASTERN ARIZONA

by

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Abstract

The thrust faults in Arizona south and east of Tucson are interpreted as part of a single coherent fault system extend-along the North American Cordilleran belt. The allochthon in southeastern Arizona includes parts of two major thrust lobes, the southeastern one extending east to the Rio Grande and south into Mexico, and the northwestern one extending northwest toward Superior, Arizona, and perhaps west to Phoenix. Where the thrust lobes adjoin in southeastern Arizona, the northwestern lobe is distinguished from the southeastern one by containing substantial amounts of Precambrian crystalline rock, by having a dynamically metamorphosed lower plate, and by containing some underthrust masses.

The allochthon of each tectonic lobe is made up of two or more major thrust plates, which are further broken into many smaller ones. Tectonic transport of the plates was consistently east-northeast and the total distance of transport is estimated to be many tens of miles, and a geologic situation exists which, if it can be substantiated through additional work, may indicate that the allochthon moved about 170 km (100 mi). Thrust faulting took place in the early, or Piman, phase of the Laramide Orogeny, and probably was most active in the interval between 75 and 80 m.y. (million years) ago in the western part of the region and possibly was slightly later in the eastern part.

The continuity of the major thrust faults is abundantly disrupted by younger faults and segments of the thrust faults are concealed by younger rocks. The younger faults include possible tear faults and related minor thrust faults of the late, or Helvetian, phase of the Laramide Orogeny, some mid-Tertiary and late Tertiary gravity glide faults and low-angle normal faults, and abundant Tertiary and Quaternary high-angle normal faults. The major thrust faults are locally concealed by stocks of Laramide age (post-75 m.y.), mid-Tertiary volcanics, and younger gravels in the basins.

Introduction

Objective

This article is a review of recent developments in the synthesis of the tectonics of Arizona south and east of Tucson (Fig. 1). Key areas of study extend from the town of Paradise in the Chiricahua Mountains in

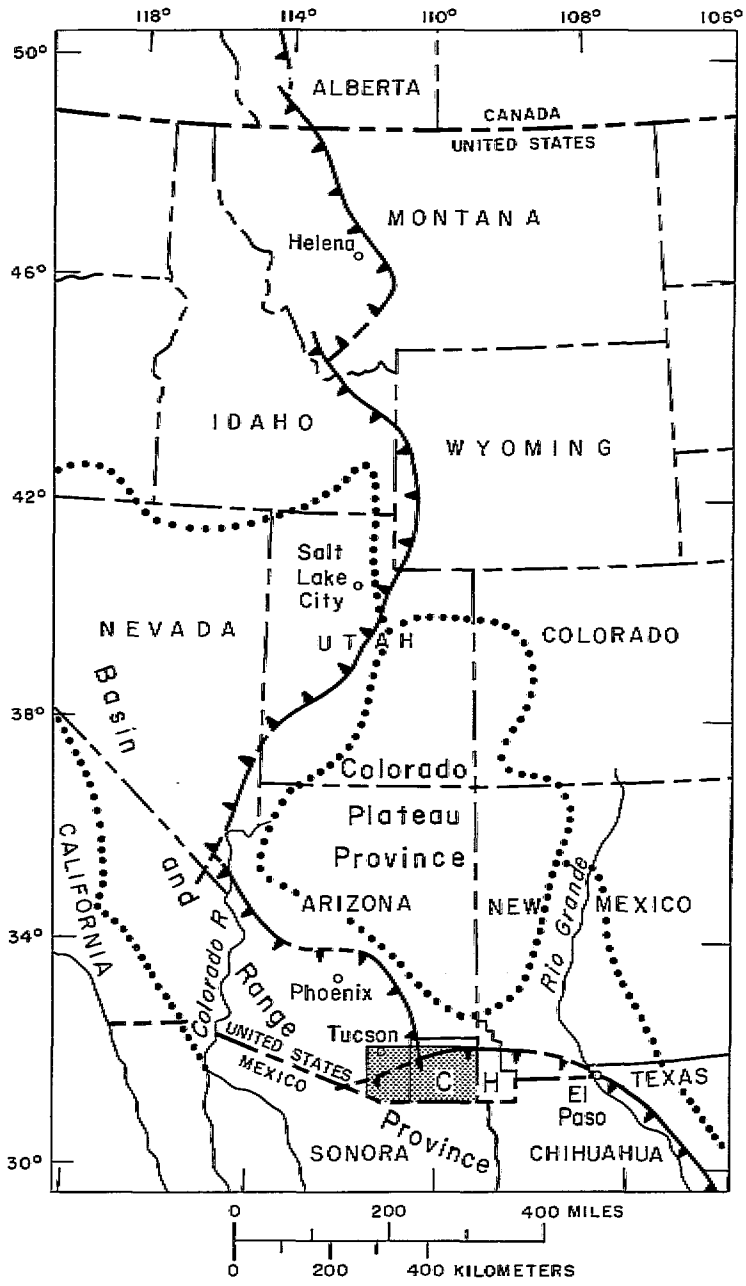

Figure 1. Index map showing postulated relations between major thrust faults in part of southeastern Arizona and thrust fault system of the Cordilleran belt. Areas of Cochise County, C; and Hidalgo County, H. Pattern shows area of Figure 3.

the east to the vicinity of the canyon narrows named Hells Gate, on the east flank of the Rincon Mountains in the west. Inasmuch as this article accompanies many others on diverse parts of Arizona and articles on facets of tectonics other than ones based on geologic mapping, it must necessarily be brief. Southeastern Arizona is structurally complex and so this brief review is restricted to Laramide thrust faults; the evidence on which the following interpretation is based will be skeletonized. This review is supported by the mapping efforts of many previous workers in the area.

Thrust faults have long been recognized in southeastern Arizona, but opinions have varied as to whether they are local or regional in extent. This uncertainty undoubtedly persisted because broad expanses of young deposits separate the areas in which are found the older rocks and the thrust faults. Furthermore, most of the older geologic investigations in the region were of short duration, were spread out over several generations, and were focused on small areas or on the topics of stratigraphy or economic geology. With the conclusion of a series of quadrangle studies by the U.S. Geological Survey, a regional tectonic synthesis was undertaken to determine the nature and continuity of the Laramide thrust faults, using existing data where possible and mapping or remapping selected key areas. Where reinterpretations of field relations are proposed, they are based on new geologic mapping at least as detailed as the original work; the new mapping cannot be included in this brief review but will be included in a more comprehensive report now in preparation. Such reinterpretations are offered with the understanding that this constitutes a normal growth of our grasp of the complex geology of the region.

Geological Framework

Southeastern Arizona lies in the Basin and Range geologic province about 100 km (60 mi) south of the Colorado Plateau. This part of Arizona is underlain by an extensive sequence of rocks ranging in age from early Precambrian to Holocene. Many of them are bedded or layered rocks of sedimentary, volcanic, or metamorphic origin, and these rocks were intruded at different times by stocks of granitoid rocks and by smaller bodies of porphyry (Fig. 2). These rocks were deformed during two orogenies and were also mildly deformed during the intervening and later times. The oldest sedimentary and volcanic rocks of the region, some of which are 1715 m.y. (million years) old, were metamorphosed to form the Pinal Schist during the older orogeny, the Mazatzal Revolution, at the close of early Precambrian(X) time. Large synorogenic and post-orogenic stocks were emplaced in the schist 1650-1450 m.y. ago. Upper Precambrian(Y) rocks of the Apache Group are a post-orogenic marine sequence lying unconformably upon the crystalline basement rocks and preserved under a disconformable contact beneath Paleozoic rocks in the northern part of the region. Diabase was injected into the Apache Group and younger rocks (Troy Quartzite) about 1200 m.y. ago. During Paleozoic time, a sequence of clastic and carbonate rocks about 2,000 m thick was deposited discontinuously in a shallow sea between the orogenic periods; only the largest disconformity in this sequence is shown on figure 2. Another unconformity marks the retreat of the sea from the region during Permian time, and thereafter continental conditions prevailed, with one exception of short duration. During Triassic to mid-Cretaceous time, before the Laramide Orogeny, a sequence of volcanic and clastic rocks with a composite thickness of many thousands of meters was deposited mainly under subaerial conditions. During the Triassic and Jurassic Periods, some stocks were emplaced and some block faulting occurred. Tectonically quieter times prevailed during the Early Cretaceous, and

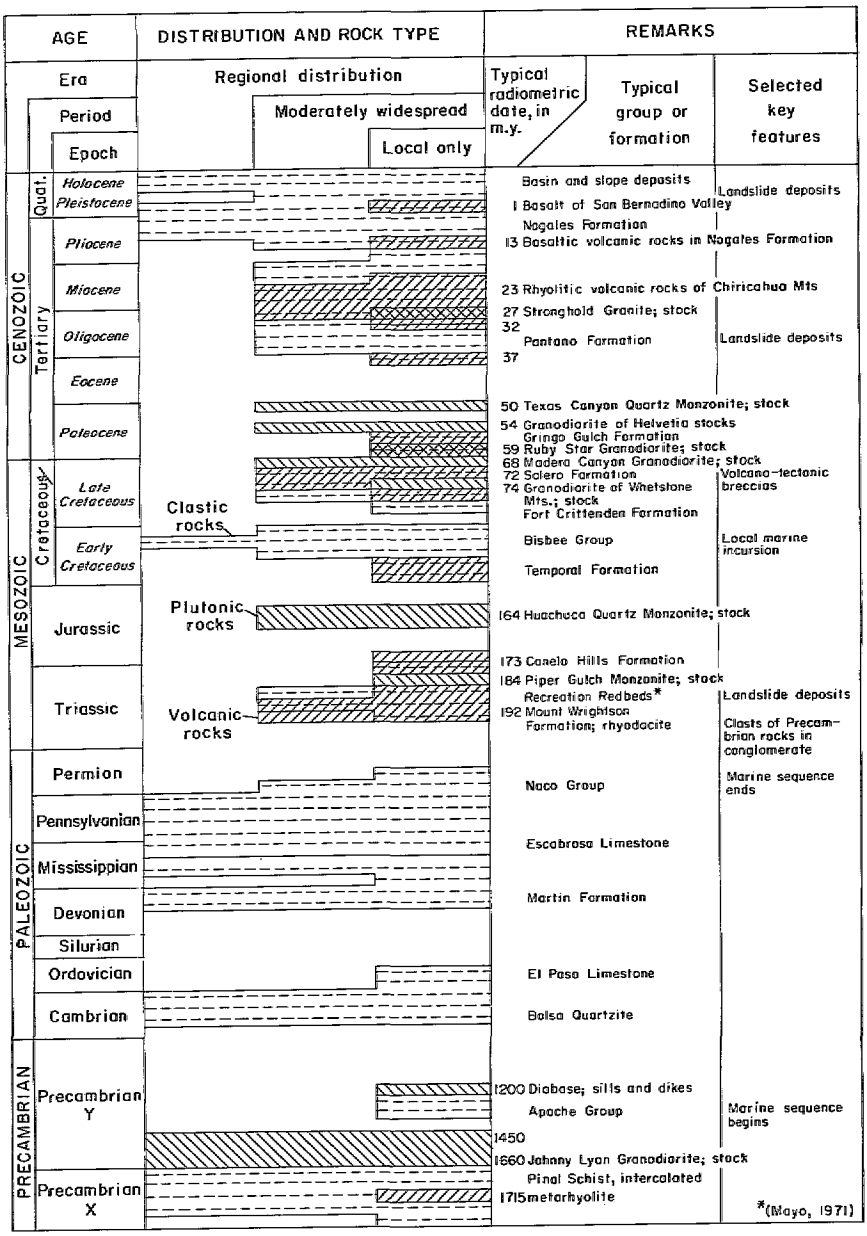

Figure 2. Generalized diagram showing areal and temporal distribution of sedimentary, volcanic, and plutonic rocks in part of southeastern Arizona. Age range of typical group or formation not shown, and the associated radiometric date is not necessarily obtained from the unit named.

for a short time marine sediments were deposited from an arm of the sea which extended into the area from the southeast.

Laramide orogenic activity began during the mid-Cretaceous about 90 m.y. ago, and extended through the Paleocene, to about 53 m.y. ago (Drewes, 1973a). Tectonic and magmatic activity increased throughout the region but this activity varied in intensity and in kind from place to place. Major compressive deformation produced some folds and some thrust faults on which tectonic plates moved east-northeastward across an autochthon which consisted mainly of the Precambrian crystalline basement rocks. The plates moved at least 32 km (20 mi) and probably as much as 160 km (100 mi). This thrust faulting occurred at the peak of the Piman phase of the orogeny about 75 m.y. ago in the western part of the region and perhaps a bit later in the eastern part. In the western part of the region massive injections of stocks occurred during two intervals, the one about 73 m.y. ago and the other 68 m.y. ago, at the close of the widespread Piman phase. A tectonically quiet period marked the early Paleocene in some areas, but elsewhere more stocks were emplaced during still another magmatic episode. The fairly local Helvetian phase of the orogeny was marked possibly by strike-slip movement along a large tear fault and by minor amounts of relative northwestward movement on thrust faults and small amounts of left-lateral movement on small tear faults. Two additional magmatic events were recorded in the western part of the region during the Helvetian phase (Drewes, 1974b) and perhaps only one in the eastern part.

Post-orogenic time began with strong erosion of the orogenically uplifted areas. By Oligocene time, clastic rocks were accumulating in topographic basins, volcanism and normal faulting were widespread, and plutons were emplaced in a few areas. Tectonic denudation accompanied rapid erosion in several areas that were strongly and rapidly uplifted during mid-Tertiary and late Tertiary times, such as the Rincon gneiss dome. This tectonic denudation produced structural features that may form a gradational sequence from megabreccia sheets of landslide origin, to glide plates, to low-angle normal faults. The most recent volcanism occurred during Pleistocene time (1.0 m.y., Marvin, 1973, written commun.) and the youngest faulting during late Pleistocene. Coarse detritus is still being deposited in broad marginal areas of basins and finer detritus is found generally in the central areas of basins.

Thrust Faults

Three aspects of the thrust faults of southeastern Arizona are considered in the following order: (1) continuity, (2) description—geometry, age, and direction and amount of tectonic transport, and (3) relations to tectonic features in adjacent regions.

Continuity of Thrust Faults

Evidence derived from a compilation of the existing geologic maps and from some new geologic maps of selected areas indicates that the main thrust faults of Laramide age probably formed a continuous structure across much of the region. Direct evidence of fault continuity is unavailable, due primarily to the extensive alluvial cover in the valleys, and also to the local cover of Tertiary volcanic rocks and concealment due to Tertiary normal faulting. Indirect evidence based on the degree of similarity, or lack of similarity, of exposed faults is used, with the premise that the greater the uniformity of the style of deformation and the more extensive the area in which uniformity is demonstrable,

the greater is the likelihood that the thrust faults form part of a regional system.

In the course of compilation, several existing geologic studies showed structural features possibly anomalous to the rest of the region. The reported local variations of kinds of structures, ages of movement, directions of movement, and style of deformation were of particular concern. In other places radiometric ages were obtained from key rock units and other rocks were correlated with sequences that recently have been well dated. Only a few local reinterpretations and new ages are mentioned below; a more complete and detailed account is being prepared to accompany a geologic map compiled at a scale of 1:125,000.

1. The reported isoclinally folded thrust faults in the northern Dragoon Mountains (Gilluly, 1956) and in the northern Chiricahua Mountains (Sabins, 1957) are reinterpreted to be imbricate thrust-fault slices.

2. The southwest overturned large fold reported by Epis (1956, and compiled by Cooper, 1959) overlying a thrust fault in the southern Swisshelm Mountains was found by P. T. Hayes and me to be a homocline cut by many high-angle faults. To the south this feature is cut by several sets of steeply dipping faults, one of which may have a large component of strike-slip movement. To the west the homoclinally dipping rocks overlie a thrust fault along which at least some movement is of mid-Tertiary or younger age.

3. The thick sequence of Bisbee Formation (where divisible, Bisbee Group) that Gilluly (1956) mapped as overturned northwest of Courtland is believed to be right side up, and the upper part of the sequence, toward the southwest, is probably an Upper Cretaceous unit and not part of the Bisbee. In the same area, the blocks of Paleozoic rock that had been mapped as fault slivers between the Bisbee to the north and the Gleeson Quartz Monzonite to the south are seen to have a matrix of tuff and welded tuff like the quartz latite member of the volcanic rocks at South Pass about 10 km west of Courtland, as well as the Sugarloaf Quartz Latite, much of the Uncle Sam Porphyry west of Tombstone which is now seen to be mainly a welded tuff, and the upper part of the Salero Formation and the Cat Mountain Rhyolite (of Mayo, 1971). Each of these formations contains exotic chips or blocks, is mainly a rhyodacite welded tuff, and is radiometrically dated as 72-73 m.y.

4. The thrust fault of mid-Tertiary age reported by Raup (Hayes and Raup, 1968) along the Babocomari River, immediately south of the Mustang Hills, is reassessed as a left(?)-lateral strike-slip fault probably of late Laramide age.

5. In the northernmost Mule Mountains, the east-trending fault zone between Paleozoic rocks to the north and the Bisbee Formation to the south, mapped by Gilluly (1956) and revisited by Jones (1963), is clearly a near-vertical structure. It probably extends east of the limestone wedge through the hills of the Bisbee Group and ultimately beneath the alluvium of a broad valley. The wedge of limestone and the flexures in the Bisbee Group near the projected segment of the fault suggest that the fault is a strike-slip fault rather than a normal fault zone in which a trap door-like horst was formed.

In each of the cases cited above, and in other cases not described here, the apparently anomalous age, direction of movement, and style of deformation have proved to be explainable by an alternative interpretation, one that fits the pattern of the thrust faults and associated features in the other mountain ranges of the region.

Description of Thrust Faults

Fault Geometry

The interpretation that the main Laramide thrust faults are probably of regional extent requires that the distribution and geometry of the fault plates be clarified. The postulated thrust plates must make sense both geometrically and paleogeographically. The reconstruction of the thrust faults and plates must explain the presence of some little-faulted mountain ranges, such as the Whetstone Mountains, among intensely faulted ranges. The reconstruction must also accommodate the constraints placed by the large, vertically oriented, pre-thrust fault structural features, such as some normal faults and stocks. Through recently completed studies by many geologists, the trace of the main faults—the regional plate geometry—can be identified and some of the pre-Laramide vertical structural features critical to the regional paleogeography may be deduced.

The regional compilation at a scale of 1:125,000, highly condensed in figure 3, shows that an autochthonous terrane underlies the northeastern part of the region and smaller areas in the central and western parts, and that allochthonous rocks underlie the larger part of the region. The allochthonous sheet comprises two lobes in which the tectonic style differs. In each of these lobes, the allochthon is divisible into two or more major thrust plates. West of the San Pedro River the outliers and half-outliers of the autochthon consist entirely of the crystalline rocks of the basement, but the main area of autochthon to the east of the river and along the northern margin of the area of figure 3 is made up of all the pre-Laramide formations (fig. 2).

The northwestern lobe of the allochthon crops out in the Sierrita and Rincon Mountains, and possibly also in the northern tip of the Santa Rita Mountains where it cannot be adequately shown on figure 3; the southeastern lobe extends across the many other mountain ranges of southeastern Arizona. The thrust plates of the northwestern lobe are distinguished on the ground by a substantial involvement of Precambrian rocks, by widespread dynamic metamorphism, and by underthrusting in at least the eastern part of the lobe. The thrust plates to the southeast contain Precambrian rock only locally, dynamic metamorphism is very local, and all of the plates appear to be overthrust.

The break between the two tectonic provinces is an indistinct zone along which there was much deformation in post-Laramide time. Initially the break may have been a tear fault, although other relations could explain the break, too. Much of the structural break is concealed by alluvium, some of it is obscured by Tertiary normal faulting or glide faulting, and some of it may have been changed by local, late Laramide thrust and tear faulting. Tentatively, this structural break is viewed as the border between two major lobes of a thrust fault system.

The allochthon of the southeastern tectonic lobe consists of two major thrust plates, of which the upper is here called the Cochise plate (overlying the Cochise thrust fault) and the lower the Hidalgo plate (overlying the Hidalgo thrust fault). The Cochise plate is known only in the central part of the region, mainly in Cochise County, although it probably extends across the southwestern part and into adjacent Sonora. The Hidalgo plate, on the other hand, extends across much of Hidalgo County, New Mexico, reaches the El Paso area, and undoubtedly also is widespread in Chihuahua and Sonora. The separation of this allochthon into the two major plates is based on a substantial repetition of stratigraphic units, and in places on the occurrence of a small amount of Precambrian rocks imbricated between Paleozoic and Mesozoic rocks along an intri-

EXPLANATION

SURFICIAL DEPOSITS--Mainly younger gravel deposited in valleys

BEDROCK--Undifferentiated sedimentary, igneous, and metamorphic rocks; mainly exposed in the mountains but includes some young volcanic rocks in a few valleys, and some pediments

ALLOCHTHON--Shown differentiated only in southeast tectonic lobe. Projected beneath post-orogenic rocks, including surficial deposits, and across areas intruded by post-orogenic rocks

Cochise thrust plate

Hidalgo thrust plate

AUTOCHTHON--Projected beneath post-orogenic rocks and across areas intruded by post-orogenic rocks

SELECTED STOCKS--Quartz monzonite, granite, monzonite, and monzonite porphyry of Jurassic and Triassic age

GRANODIORITE AND QUARTZ MONZONITE--Stocks and plugs of Late Cretaceous age, dated at 70-75 m.y.

SAMPLE SITE--Radiometrically dated stock, plug, or related volcanic rock, dated at 70-75 m.y., and trend line

CONTACT

FAULTS--Dotted where concealed or intruded. Composite symbol used where diverse movements of different ages are inferred, in each case the thrust faulting is the older event

Normal fault--Bar and ball on downthrown side. Arrow shows relative direction of movement of hanging wall of low-angle normal faults

Thrust fault--Open sawteeth on allochthonous plate (or upper plate where fault separates two allochthons)

Glide fault--Open sawteeth on upper plate. Arrow shows arection of movement

Tear fault--Arrows show relative, or actual direction of movement

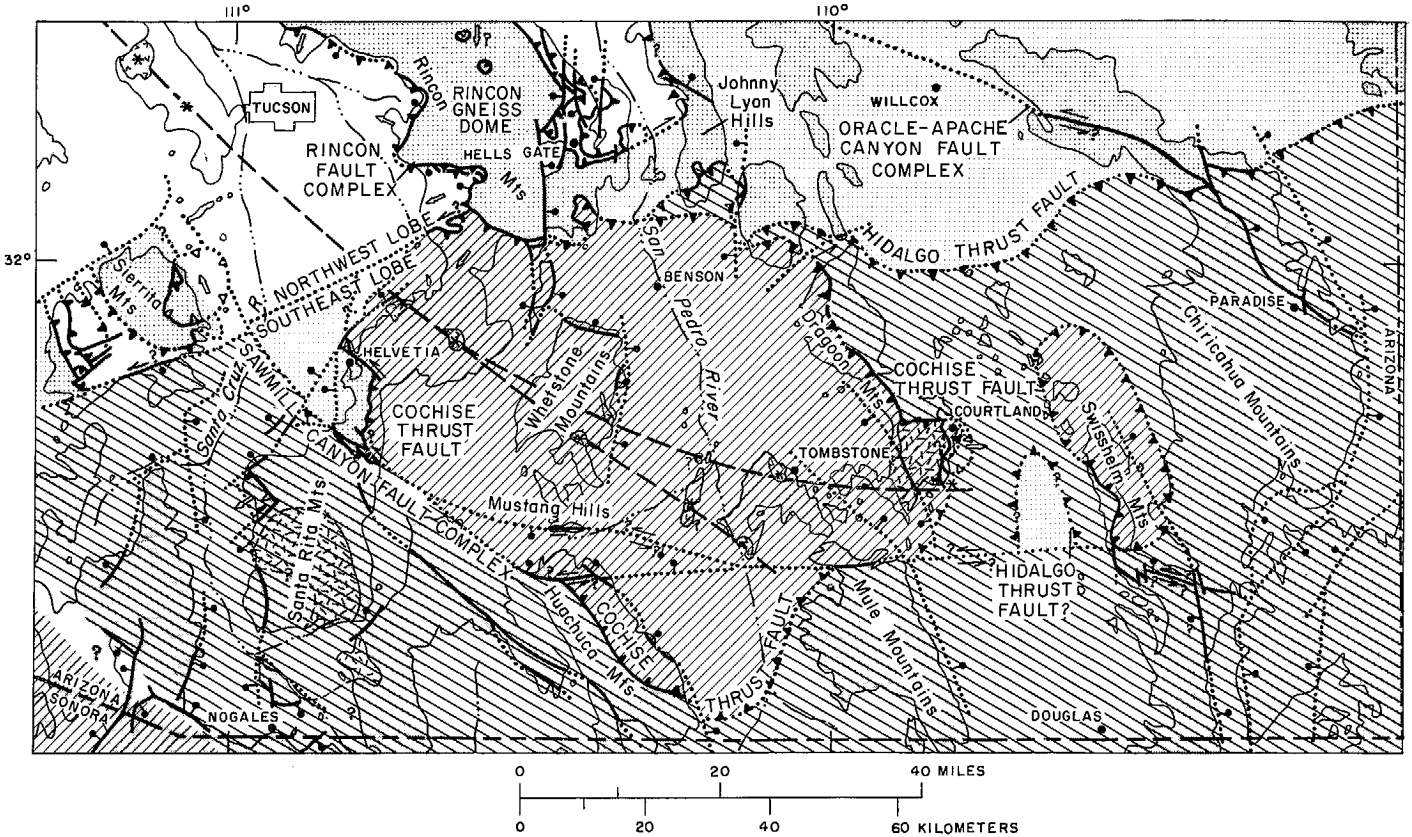

Figure 3. Map showing distribution of major thrust faults and other selected geologic features in part of southeastern Arizona.

cately thrust-faulted zone that extends from the southeastern part of the Rincon Mountains at least as far southeast as the southern Dragoon Mountains, and possibly as far as the Swisshelm Mountains. Structurally above or below this zone of major imbrication, of which the lowest fault surface is called the Cochise thrust fault, the thrust faults are generally smaller and less complex bedding plane faults, along which younger rocks have slipped over older ones. Along the Cochise thrust fault older rocks are commonly placed upon younger ones. Near the postulated break between the two thrust lobes, the Hidalgo plate has been tectonically thinned and, in places, it is faulted out entirely so that the Cochise plate rests directly upon the autochthon. Other features of these major plates—klippen, fensters, and subplates—cannot be described in a brief summary and, as can be seen from the liberally scattered queries on figure 3, some of these projections are more speculative than the major features described above.

In a region of subhorizontally oriented thrust faults, vertically oriented structural features older than the thrust faults provide certain paleogeographic constraints. In the southeastern tectonic lobe there are at least 6 stocks of Jurassic or Triassic age. The rocks adjacent to the Sawmill Canyon fault zone are shown to have moved large distances vertically in Triassic to Early Cretaceous time (Drewes, 1973a). Most of these stocks and the fault zone do not provide constraints, for they occur in areas thought to be part of the Hidalgo thrust plate and their postulated downward extensions in the autochthon are concealed or at least are unknown to the southwest where geologic data are sketchy at best. However, the Gleeson Quartz Monzonite and Copper Belle Monzonite Porphyry of the southern part of the Dragoon Mountains are thought to lie in the Cochise thrust plate. Their downward extension ought to appear first in the Hidalgo thrust plate and ultimately of course in the autochthon, too. This thought will be developed further after presenting the evidence on the direction and amount of tectonic transport.

The tectonic makeup of the northwestern lobe of the allochthon is less well understood than that of the southeastern lobe because the study area is too small to do more than sample this different terrain and because the area that lies near Tucson was strongly modified by low-angle fault movement and metamorphism in mid-Tertiary time. Like the southeastern lobe, the northwestern one has two major thrust plates of Paleozoic and Mesozoic rocks. In the Rincon Mountains, these plates are separated by a third plate, of radiometrically dated Precambrian granodiorite (Drewes, 1972 and 1974a, and Rincon Valley area, unpub. data). Both upper and lower plates are further broken by minor bedding-plane thrust faults along which younger rocks typically have been moved over older rocks. The rocks of the lower plate commonly are dynamically metamorphosed; the rocks are mostly recrystallized, some have a slaty cleavage, and others are deformed by abundant small flow-type penetrative drag folds. The middle plate, of granodiorite, is unmetamorphosed, and is shattered rather than cut by small faults. The upper plate is also unmetamorphosed, but it is internally much faulted and is locally warped into folds that are open or only moderately tight and that in places have axial planes subparallel to nearby thrust faults.

On the west flank of the Sierrita Mountains there are also two major plates of Paleozoic rock, with an intervening plate composed chiefly of Mesozoic rock (Drewes and Cooper, 1973). A massive plate of granitoid rock, at least a part of which is of Precambrian age, overlies the plates of Paleozoic and Mesozoic rocks. In contrast, the rocks on the east flank of the mountains consist of autochthonous Precambrian rocks, of Paleozoic and Mesozoic rocks which are tectonically deformed in the style of the upper plate, and of rocks which post-date the thrust fault. With the concept that many of the rocks overlying the Precambrian base-

ment of the east flank slid north-northwestward on the San Xavier thrust fault (Cooper, 1960), or glide fault, of mid-Tertiary age, these rocks may have been moved from the area of the southeastern lobe onto rocks of the northwestern lobe.

Some rocks in the northern tip of the Santa Rita Mountains, near Helvetia townsite, may also be part of the northwestern tectonic lobe, for only in this part of the mountains is there a considerable repetition of Precambrian and of Paleozoic rocks (Drewes, 1971a, 1973a). The minor thrust faulting and tear faulting attributed to the Helvetian phase of the Laramide Orogeny (late Paleocene) has shifted several small thrust plates northwestward or the underlying mass southeastward and possibly across the proposed break between the tectonic lobes. This late deformation, described in detail in a structural analysis of the Santa Rita Mountains (Drewes, 1973a) is probably related to tear-fault movement on the Sawmill Canyon fault complex and on smaller subparallel faults north of it.

Direction and Amount of Tectonic Transport

The major Laramide thrust plates were tectonically transported east-northeast. An east-northeast or west-southwest orientation of compressive stress is shown by the alinement of tear faults in that direction and by the general north-northwest orientation of the axes of drag folds, and transport to the east-northeast is indicated by the many folds that are vergent in that direction. An opposite direction of vergence is found in the small drag folds on the east flank of the Rincon Mountains and in some larger folds south of the mountains. East of the Rincon Mountains, field evidence suggests that the lower major thrust plate was underthrust beneath the other plates and extended east of the San Pedro River. The lower plate is locally thrust along a gently eastward-dipping fault beneath generally autochthonous granodiorite of the Johnny Lyon Hills that is unconformably overlain by the upper Precambrian(Y) Apache Group and the Paleozoic sequence of the Johnny Lyon Hills (Drewes, 1974a, sections B-B' and D-D'). A hypothesis that some of the leading edge of the allochthon of the northwest lobe was underthrust is more attractive than the alternative that overthrust plates were moving from opposite directions at about the same time. The thrust plates are thus seen to have moved east-northeastward across both tectonic lobes, and in a part of the northwestern lobe the lower major plate was underthrust.

The breaking up of the allochthon into the two tectonic lobes may have been caused by the local(?) underthrusting. As a result of the greater friction produced by the local(?) underthrusting of the leading edge of the northern part of the allochthon, the resistance to further movement must have been greater on the northwest side than on the southeast. The consequent strain within the allochthon may have caused the allochthon to separate into the plates of the northwestern and southeastern tectonic lobes, which may then have continued their movement independently.

The total amount of transport of the allochthon was probably large. Evidence in the Rincon Mountains (Drewes, 1973b) indicates that the minimum distance of transport between upper and lower major thrust plates of the northwestern province probably was 16 km (10 mi) and possibly was 32 km (20 mi). The evidence consists of a duplication in separate tectonic plates of several Paleozoic formations in the direction of tectonic transport. Over the shorter distance, the gaps in the physical continuity of the plates, caused mainly by later normal faulting, sedimentation, or intrusion, are mostly 1 km (0.6 mi) and nowhere more than 3 km (2 mi); over the longer distance the gaps in the continuity of the plates are about twice that size, due allowance having been made for

mid-Tertiary to late Tertiary low-angle normal faulting and gravity gliding on the west flank of the Rincon Mountains.

A distance of 100 km (60 mi) of movement may be proposed between the Cochise and Hidalgo thrust plates in the central part of the southeastern lobe, subject to obtaining more geologic support. The constraints placed upon a concept of regional thrust faulting by pre-Laramide stocks have already been mentioned. The Gleeson Quartz Monzonite, which is radiometrically dated (Marvin and others, 1973) as Jurassic (a single date at 178 m.y.), has been mapped by Gilluly (1956), accepted by McRae (1966), and confirmed by this study as overthrust upon Paleozoic and Cretaceous rocks. East of the quartz monzonite stock, and possibly in a separate structural block, is the Copper Belle Monzonite Porphyry, a strongly altered, very coarse-grained rock taken by Gilluly to be of about the same age as the quartz monzonite. The Cochise thrust fault lies east of the quartz monzonite, and a branch of it may actually lie east of the monzonite porphyry. Gravity gliding, perhaps related to volcano-tectonic activity, has vastly complicated the relations in the Courtland-Gleeson area, all of which I would place within the Cochise plate. The quartz monzonite stock and possibly the Copper Belle Monzonite Porphyry east of the stock are rootless at this location and, judging by the evidence of the Rincon Mountains, the downward extension of these masses must lie 32 km or more to the west-southwest.

Continuation of the quartz monzonite and monzonite porphyry in a lower structural level may occur in the Squaw Gulch Granite and Piper Gulch Monzonite of the southern Santa Rita Mountains and the extension of the granite in the quartz monzonite of the northern Patagonia Mountains, about 100 km (60 mi) to the west-southwest. The Squaw Gulch Granite is in large part a modal quartz monzonite (Drewes, 1971b and 1975, unpub. data) and, together with the extension in the Patagonia Mountains (Simons, 1973) and, discounting the cover of younger rocks, it underlies an area considerably larger than that of the Gleeson Quartz Monzonite. The Piper Gulch Monzonite is a very coarse grained rock that strongly resembles the Copper Belle Monzonite Porphyry but is otherwise almost unique in the region; this rock lies east of the Squaw Gulch Granite.

Eight available radiometric ages, based both on the K-Ar method on slightly chloritized biotite and on the Pb-alpha method on zircon, show that the granitoid rocks to the southwest are 145-184 m.y. old (Drewes, 1971b and Simons, 1973) or Jurassic and Late Triassic. A single age obtained from biotite of the Gleeson stock to the northeast is 178 m.y. (Marvin and others, 1973). These ages are comparable, but additional dating is needed to strengthen a correlation based solely on radiometric data.

Petrographic and chemical studies of the Gleeson Quartz Monzonite and the Copper Belle Monzonite Porphyry as detailed as those of the granitoid rocks to the southwest are also needed to evaluate their correlation. Should these additional studies support the proposed correlation, then the actual direction and amount of movement between the major thrust plates are fixed, and the Cochise plate moved 100 km east-northeast over the Hidalgo plate. Although the amount of movement between the Hidalgo plate and the autochthon remains unknown, it may be estimated in the same order of magnitude, thus placing the combined distance at about 160 km (100 mi).

The amount of tectonic transport of the major thrust plates in southeastern Arizona suggested by the meager available evidence is of about the same order of magnitude as that proposed for the Laramide thrust faults in northern Utah. Crittenden (1961) suggests a movement there of 40 miles or more, and Eardley (1951, p. 330) gives a distance

of 75 miles or more. Stewart and Poole (1974) tentatively suggest an even larger distance, perhaps 100 miles or more. The general similarity in proposed magnitude of thrust faulting in the two regions is of particular interest because different kinds of evidence are used; in Utah the evidence is based mainly on palinspastic reconstructions, whereas that used in Arizona involves the duplication of a sequence of rocks and the possible separation of parts of a stock.

Age of Thrust Faults

The thrust faults in many of the mountain ranges of southeastern Arizona have been recognized to be of Laramide age. In the Santa Rita Mountains the thrust faulting is more precisely dated as having occurred 75-80 m.y. ago (Drewes, 1973a), and in the eastern part of the region, some data from southwestern New Mexico (Gorbitt and Woodward, 1970) suggests that the age may be somewhat younger, perhaps latest Cretaceous or early Paleocene.

Evidence bearing on the age of thrust faulting in the western part of the region is more abundant than in the eastern part. Rocks at least as young as the Fort Grittenden Formation, dated by its locally prolific fauna as Santonian or later Cretaceous (Miller, 1964 and Drewes, 1971c), and in places also the overlying dacitic rocks of the Salero Formation and its correlative rocks are deformed. Gill and Gobban (1966) date the Santonian at about 82-84 m.y. The overlying rhyodacitic rocks of the Salero Formation and their correlative units, which are dated in many places as 72-73 m.y. old (summarized by Drewes, 1971c), are post-orogenic. Moreover, five small granodiorite stocks, radiometrically dated as 70-75 m.y. and mostly as 73 or 74 m.y., lie along a belt (see dashed line on figure 3) that is not apparently broken across the tear fault(?) border between the two tectonic provinces; apparently these are among the oldest post-thrust fault rocks. While compressive deformation probably occurred throughout much of the Piman phase of the Laramide Orogeny, the peak of thrust faulting probably occurred during the interval of 75-80 m.y. ago.

In the eastern part of the region, the rocks thought to be correlative with the dacitic rocks of the Salero Formation seem to be somewhat younger in appearance, and in Hidalgo County, New Mexico, a locally folded andesitic unit, the Hidalgo Volcanics, is radiometrically dated (Hayes and Kottlowski, 1973, oral commun.) as latest Cretaceous or early Paleocene. In New Mexico, the Hidalgo Volcanics do not appear to be overlain by rhyodacite volcanics, as in Arizona, so the upper age limit of the orogeny cannot be closely dated there. Other rocks of probable Late Cretaceous age also have not been precisely dated. Consequently, neither the youngest possible age of deformation nor a significant range of age of the time of deformation can yet be given.

The widespread occurrence of chips and blocks of exotic rock types as xenoliths in the volcanic rocks of late Late Cretaceous age of the region may indicate a genetic as well as temporal association of the volcanic rocks with the thrust faulting. Exotic blocks are reported in the andesitic rocks and the Cat Mountain Rhyolite of the Tucson Mountains (Mayo, 1971), in the Salero Formation of the Santa Rita Mountains, in the Uncle Sam Porphyry west of Tombstone (Gilluly, 1956, and Drewes, 1971c), and in the Sugarloaf Quartz Latite and the volcanics of South Pass, of the Courtland area (Gilluly, 1956, and this report in the section on continuity of thrust faults). Slightly different origins were ascribed to the mixed rocks of these areas, but all of them involved

volcano-tectonic processes. Conceivably, the compressive stress prevailing during the time of thrust faulting helped to retain a magmatic pressure building up below the thrust plates. With the cessation of the compressive stresses, the release of the magmatic pressure may have been more explosive than usual for such events, producing first an assortment of vent breccias and tectonically unroofed sills, and later a more passive emplacement of stocks and other volcanic rocks.

Tectonic Relations to Adjacent Regions

The tectonic features of the Laramide Orogeny in southeastern Arizona are not unique, for they resemble in many ways the features associated with the Cordilleran thrust belt of the eastern Great Basin. Indeed, these tectonic features may extend from British Columbia, with but minor interruptions, far into Mexico (fig. 1). Where sufficiently well delineated, the frontal edge of the thrust belt is found to be made of a series of large lobes, behind which the major plates moved somewhat independently of each other. Internally the rocks of each of the thrust lobes are broken into major plates between which older rocks are commonly moved over younger ones, and the major plates are further broken along smaller bedding plane faults that typically slide younger rocks over older ones. Throughout the Cordilleran thrust belt, movement of the thrust plates has been east to northeast, and the amount of movement is postulated to be on the order of tens of kilometers and probably more than 100 km. A Late Cretaceous to early Tertiary age has also been proposed for the faults along this thrust belt and an eastward younging of the overthrusting has been recognized in several places. Thus, the thrust faults of the Piman phase of the Laramide Orogeny in southeastern Arizona are seen simply as a link in an extensive overthrust system.

The thrust plates of the southeastern tectonic lobe extend east from southeastern Arizona to the Rio Grande (Corbitt and Woodward, 1971) and there swing gradually southward into Chihuahua (fig. 1). The leading edge of the northwestern lobe extends northwestward along the east side of the San Pedro River; the thrust plates are largely covered but I judge that they trend gradually westward from near Superior to the vicinity of Phoenix. Thrust faults have not yet been recognized in the Phoenix area, perhaps because only autochthonous and post-orogenic rocks occur there, the last remnants of overthrust rocks having been destroyed by erosion or concealed by younger deposits. On the other hand, further study of the Precambrian terrane and of the few small remnants of Cretaceous and lower Tertiary rocks near Phoenix may lead still to evidence of thrust faults. Thrust-faulted rocks of Paleozoic and Mesozoic age occur further northwest between Wickenburg and the Bill Williams River in western Arizona.

Postscript

Since the time this manuscript was submitted to the Arizona Geological Society for publication, a new geologic study made of part of the central Dragoon Mountains by Stanley B. Keith and Larry F. Barrett (see their companion paper in this Digest) indicates that some structural features reported in my paper may be amenable to alternative interpretation. Time is too short to permit a joint review of certain critical field interpretations if, indeed, it is needed at all, for their map is both detailed and the key features were carefully rechecked by them. But a few comments on the second-order interpretations or "office interpretations"

are offered that may indicate the direction in which a solution to the questions they raise may lie.

In brief, Keith and Barrett report that a segment of Gilluly's (1956) Dragoon thrust fault (my regional Cochise thrust fault) is better interpreted as an unconformity between Glance Conglomerate and Paleozoic formations, and their Black Diamond fault is a normal or reverse fault between the Bisbee Formation of Early Cretaceous age and various rocks of Precambrian to Cretaceous ages, rather than another thrust fault. Where the reported difference is essentially a field interpretation, such as the nature of a contact or the age assignment of a rock, I have no basis for an opinion, for I followed Gilluly's work, but clearly such reinterpretations deserve serious attention. However, where second-order interpretations, such as occur in structure sections, are made from new field work, I might offer some suggestions because the major structural features must make sense with respect to neighboring areas in which I have some minor experience, as well as make sense internally within the restudied area. From our independent work, both Gilluly and I find structural interpretations involving major thrust faults—some of them upended—attractive working hypotheses in areas northwest and southeast of the central Dragoons, and consequently projecting such structures through the area in question is at least reasonable. Now, the major northeastward overturned fold shown by Keith and Barrett, and also substantially shown by Gilluly, is nowhere seen to involve the Precambrian crystalline rocks; rather it appears to be a disharmonic structure and so must be separated from the crystalline rocks by a fault. So far I believe everyone is in accord. From their local study Keith and Barrett prefer to view the amount of movement along this fault as relatively minor, and from more regional studies both Gilluly and I view the amount as more substantial. This question is difficult to resolve in any case and is probably unsolvable in most small localities studied independently. For example, my own study of the Santa Rita Mountains (Drewes, 1971a, 1971b, and 1973a) provided no answer to questions on amount of tectonic transport on thrust faults, nor did a preliminary compilation of recent maps between the San Pedro and Santa Cruz Rivers. Only with a still more regional study did evidence of large magnitude of movement appear, and even that evidence requires further support to provide the basis of anything more than a working hypothesis. Surely, then, impressions obtained from local areas must be viewed with caution. Now, if the fold buckled against the buttress of an uplifted block along the Diamond Peak fault, as Keith and Barrett suggest, one might wonder why the fold is overturned rather than upright, as a chevron fold perhaps; or perhaps erratically crumpled rocks might be expected. Having a large fold overturned suggests a more fluid situation in which thrust movement was unhampered, but of course that does not prove it.

Next, the proposed uplift of a buttress in pre-thrust fault time of a mass sufficiently substantial to withstand unbroken the forces of a thrust plate that has even the modest amount of movement of a mile or so, as proposed by Keith and Barrett, should leave a record in the adjacent sedimentary rocks, but it does not. For example, such a sedimentary record of conglomerate wedges occurs adjacent to a pre-Laramide uplift along the Sawmill Canyon fault zone in the Santa Rita Mountains (Drewes, 1973a). But again, the absence of such support does not refute the interpretation of some early uplift in the area, it only points out the areas in which further study might be fruitful. Furthermore, is it reasonable to suppose that a block uplifted along the Black Diamond fault in pre-Bisbee time would have been available as an immovable buttress 30 m.y. or more later, in Laramide time, or is it more likely that erosion would have produced a subdued topographic ramp over which a thrust fault might have been deflected? For the present Keith and Barrett have at least pointed out that some serious questions may exist in our understanding

of a structurally complex area, a situation which I hope fosters further field efforts there.

Finally, a K-Ar determination of a biotite concentrate obtained from a specimen of the main body of the Gleeson Quartz Monzonite shows the rock to be 181 ± 5.4 m.y. old (R. F. Marvin, oral commun., 1975), which supports the original Jurassic age determination.

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ORE METAL TRANSPORT (COPPER)

LARAMIDE HOTSPOT, COPPER DEPOSITS AND PLATE MOTION IN ARIZONA, SONORA AND NEW MEXICO

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LARAMIDE HOTSPOT, COPPER DEPOSITS AND PLATE MOTION IN ARIZONA, SONORA AND NEW MEXICO

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The age and geographic distribution of Laramide porphyry copper deposits of southwestern North America is accounted for by rigid plate tectonics as this part of the North American plate moved N35 to 40°W over a fixed mantle hot spot at a rate of 3.6 cm./yr.

Relative and absolute plate motions of the southwestern portion of the North American plate during late Cretaceous and early Tertiary times have been presented by several workers[1-4]. Those studies were based upon temporal and spatial extrapolations and interpolations using topographic and magnetic data of the Pacific and Atlantic seafloors. The determination of absolute plate motions also employ tentative reconstructions of Pangea at the beginning of the Triassic as well as the concept of fixed hot spots[2]. Phillips and Forsyth[4] have added the constraint of paleomagnetism to Pangean reconstructions to derive plate motions differing from those of Dietz and Holden[2]. Those studies present only generalized motions for the Laramide interval, 70 to 50 m.y. ago. So far, very little evidence for plate motions has been developed from within the North American continent.

In this paper, the age and distribution of porphyry copper deposits in southwestern United States and northwestern Mexico are interpreted as the products of a fixed mantle plume or hotspot[2,5-8], and used to derive a rotational motion of the North American plate between 72 and 52 million years ago.

THE PORPHYRY COPPER DEPOSITS

Porphyry copper deposits of southwestern North America are geochemically distinctive petrological entities containing anomalously large amounts of copper, sulphur, molybdenum, gold, silver and rhenium. The deposits are genetically related to intrusive phases of intermediate to silicic volcanic complexes that intrude penecontemporaneous volcanic or older rocks of various aspect. Being members of the great class of calc-alkaline, intrusive and volcanic series, these mineralized stocks owe their origin to the same processes that have generated andesitic and siliceous magmas throughout the history of the Earth. Several workers[9-11] have pointed out the worldwide association of this class of mineral deposits to Cenozoic subduction zones, and particularly to those associated with the circum-Pacific andesite provinces. Modern detailed studies on the mode of occurrence of the hypogene sulphide phases and silicate alteration products in these deposits suggest that the primary mineralization is polycyclic and temporally related to igneous intrusion[12]. Carefully designed studies have also employed K-Ar dating to show that the time of igneous intrusion is very close, analytically, to the time of metallization[13-16]. The similar composition of barren and productive intrusive bodies with regard to lithophilic elements suggests that some unique factor has played a role in the genesis of those intrusions that carry commercially significant metallic sulphide constituents. The copper content of these deposits is employed here as a geochemical tracer that is indicative of a special petrogenetic process. In this case, the copper is thought to be a manifestation of a single fixed mantle hot spot. It is not implied that the sulphur, copper and other metals are necessarily directly derived from the deep mantle. They could possibly have been derived entirely or in part from the lower crust or upper mantle.

THE DISTRIBUTION OF THE DEPOSITS

The geographical location of the deposits is shown in Figure 1; the numbered localities are listed in Table 1. The most obvious feature of the figure is the great number of deposits located in southeastern Arizona and the surrounding regions. It is these deposits, exclusive of those in Nevada, Utah and northern New Mexico, that I wish to discuss in this report. The distribution of deposits also reveals two general trends, one striking from Mineral Park near Kingman, Arizona (locality 1, Fig. 1) S35°E for about 700 km. to La Caridad near Nacozari, Sonora (locality 14, Fig. 1) and the other from New Cornelia at Ajo, Arizona (locality 15, Fig. 1) N82° E for about 500 km. to Chino near Silver City, New Mexico (locality 27, Fig. 1). The significance of the latter trend is not entirely clear, but may be related to east-west zones or to en echelon northeast-southwest zones as defined by Mayo[17].

The alignment of deposits from Mineral Park, Arizona to La Caridad, Sonora coincides with the southwest Arizona zone III of Mayo[17]. Zone III is indicated by the arrows in Figure 1. Length to width ratios of the outcrops of seven Laramide intrusive bodies have been related to their alignment along this zone[18,19]. The average length to width ratio is 2.4, and the average trend of the long dimension of their outcrops is N32°W. These data suggest that this trend is real and that the intrusive bodies and copper deposits along the zone are fundamentally related to one another. This trend is transverse to the more northerly trends of the mountain ranges in this part of the Basin and Range Province and the tectonic trend of the Basin and Range Orogeny. It is also transverse to the more westerly trends of Mesozoic structures[20]. Zone III is parallel to the Utah-New Mexico zone VI of Mayo[17] which has been characterized by its lead isotope ratios[21]. The southwest Arizona trend is coincident with a segment of Spurr's "Great Silver Channel[22]."

THE AGE OF DEPOSITS

Table 1 lists the names and ages of producing porphyry copper deposits in southwestern North America as well as several undeveloped deposits of commercial and sub-commercial grade and tonnage. Only ages obtained by the K-Ar method on micas have been included. Hornblende ages are omitted because of observed complexities due to excess argon[23]. Where more than one analysis is available, the average is employed and one half of the total range of ages or 1 m.y., whichever is larger, is used as the estimate of error given in the table. Otherwise, the estimate of error is that given in the primary reference which is reported at the 68 percent confidence level for most analyses. The porphyry copper deposit at Bisbee, Arizona is not included because of its greater age, 153-177 m.y.[24]. Massive sulphide vein and replacement deposits such as the United Verde, Magma and Old Dominion are also excluded. The ages of porphyry deposits range from 52 to 72 million years, which spans the time of the "classical" Laramide Orogeny[19,25], and is identical with the span of ages for all volcanic and intrusive rocks of similar age in the region under consideration.

Figures 2a through 2e show the distribution of deposits grouped into 4 m.y. age intervals. A trend of decreasing age to the southeast is indicated. This trend, about S40°E, agrees closely with the S35°E trend of the southwestern Arizona zone XII of Mayo[17]. Figure 3 is a plot of the ages of all dated deposits against distance southeast of Mineral Park. Pima-Mission, locality 7; San Manuel-Kalamazoo, locality 19; and Inspiration-Castle Dome, locality 23 are considered as single deposits because they are: a single deposit, faulted parts of a single deposit, or two deposits dated by a single intrusion, respectively. The distances have been projected to a line bearing S40°E and passing through Mineral Park. A double error regression[26] has been applied to the data, assuming a 5 km. error in distance

and an error in the ages as is given in Table 1. The slope of regression is 35.7 ± 6.5 km./m.y. (3.57 ± 0.65 cm./yr.). The heavy solid line of Figure 2 is the mean slope passing through the mean location and age. The dashed lines indicate the one sigma error of the slope. The correlation coefficient for these twenty-five data points is 0.789, indicating that the regression has a probability of significance greater than 99%, and that 62% of the total variance of ages is accounted for by the regression[27].

LARAMIDE HOT SPOT

The changing location of porphyry copper emplacement has a rate that is typical of plate motions as derived from sea floor data and the age of magnetic reversals. This strongly suggests some relationship between rigid plate motions and porphyry copper emplacement. The locations and ages of the deposits hardly seem to be systematically related to the subduction zone of this age that has been postulated off of the Pacific coast of Baja California and southern California[1]. If such were the case, one might expect the age of deposits to vary at an angle to the trend of the subduction zone but not parallel to it.

The data can be interpreted as a migrating magma source that was moving southeasterly within the lithosphere or asthenosphere or, alternatively, as a magma source within the asthenosphere or mesosphere that was stationary as the North American plate moved northwesterly in response to the forces of sea floor spreading. The latter concept is adopted in this paper as the simplest hypothesis and because the hot spot concept has been well established[2,5,7,8], and successfully employed to explain aseismic submarine ridges and oceanic island chains. The local apparent plate motion is 3.57 ± 0.65 cm./yr. N35°-40°W during the time interval of 72 to 52 m.y. ago. The maximum dimension of the hot spot in the direction of plate motion, as derived from Figure 3, is 450 km. This value agrees with maximum width of the

zone of porphyry copper emplacement, 450 km., measured normal to the direction of motion. This diameter is similar to the 300 km. diameter of the Hawaiian hot spot[8]. Morgan[7] has estimated that hot spots would have a diameter of 150 km. These estimates are in good agreement, in view of the fact that deeply rooted plumes would tend to spread outward at the base of or in the lower part of the lithosphere.

This hot spot may have existed only for the duration of the Laramide Orogeny. If so, it seems logical that it would have begun as a small hot spot increasing in size until the time of maximum Laramide activity, ca. 65 m.y. ago, near Tucson, Arizona, and diminished in size as the Laramide volcanic activity waned. Thus, it could be that the full extent of the trace of this hot spot is already known. It is also possible, however, that this hot spot existed for a more extensive period of time and that more evidence is to be found along the projections of this trend. It is of interest to note that Guaynopita, Chihuahua near the Sonora border, lies 160 km. S30°E of Nacozari (Carta Geologica de la Republica Mexicana, 1968). At this locality, copper mineralization is known to be related to a quartz monzonite that intrudes probable Cretaceous limestone and is overlain by middle Tertiary rhyolite[28] (D.S. Bolin, oral communication, 1973). If this deposit is related to the proposed hot spot, its age should be 48 ± 6 m.y. With this extension, the trace of the hot spot is increased to about 850 km.

Coney[29,30] has presented evidence that major reorganization of plate motions occurred at about 80 and 40 m.y. ago. In view of his arguments, it seems unlikely that the Arizona trend can be extended further than about 400 km. to the northwest or southeast without some change in direction.

LARAMIDE PLATE MOTION

The direction of plate motion derived here at first seems contrary to motions derived by Dietz and Holden[2] and by Phillips and Forsyth[4]. The data presented here are thought to represent details of motion that are not resolved by the more generalized approach of those reports. The data also appear at odds with the analyses of motion of the North American plate by Coney[29,30] and by McGregor and Krause[31] for approximately this same time period. The latter two articles present data for the Kelvin-New England and Corners seamounts together with the Azores hot spot in the North Atlantic to derive a change of motion for the North American plate at about 74 m.y. ago. McGregor and Krause[31] report plate motions of N25°W from 180 to 74 m.y. ago and S65°W subsequent to 74 m.y. ago for that part of the North Atlantic. The second trend reported by them is the only other hot spot trace presently known to this writer from the North American plate for the time interval under consideration here. A pole of rotation for the North American plate for this time interval can be derived from the intersection of perpendiculars to these two trends on a sphere. The intersection lies at about 50°N latitude and 64°W longitude in the region of Anticosti Island. The location of this pole of rotation can only be considered as an approximation because only two projections are currently available to determine its position. The angle subtended by the hot spot trace in the Arizona region is about 7 degrees indicating a rotation of 0.35 degrees per m.y. for an interval of at least 20 m.y. The entire argument is predicated upon the assumption that both regions have been parts of a single undeformed North American plate since 72 m.y. ago. This assumption may prove to be incorrect, but large scale rotation within the North American plate since Laramide time seems unlikely.

Figure 2. The distribution of porphyry copper deposits as a function of age grouped into 4 m.y. age intervals:

a. Circled deposits 68.0 to 71.9 m.y.

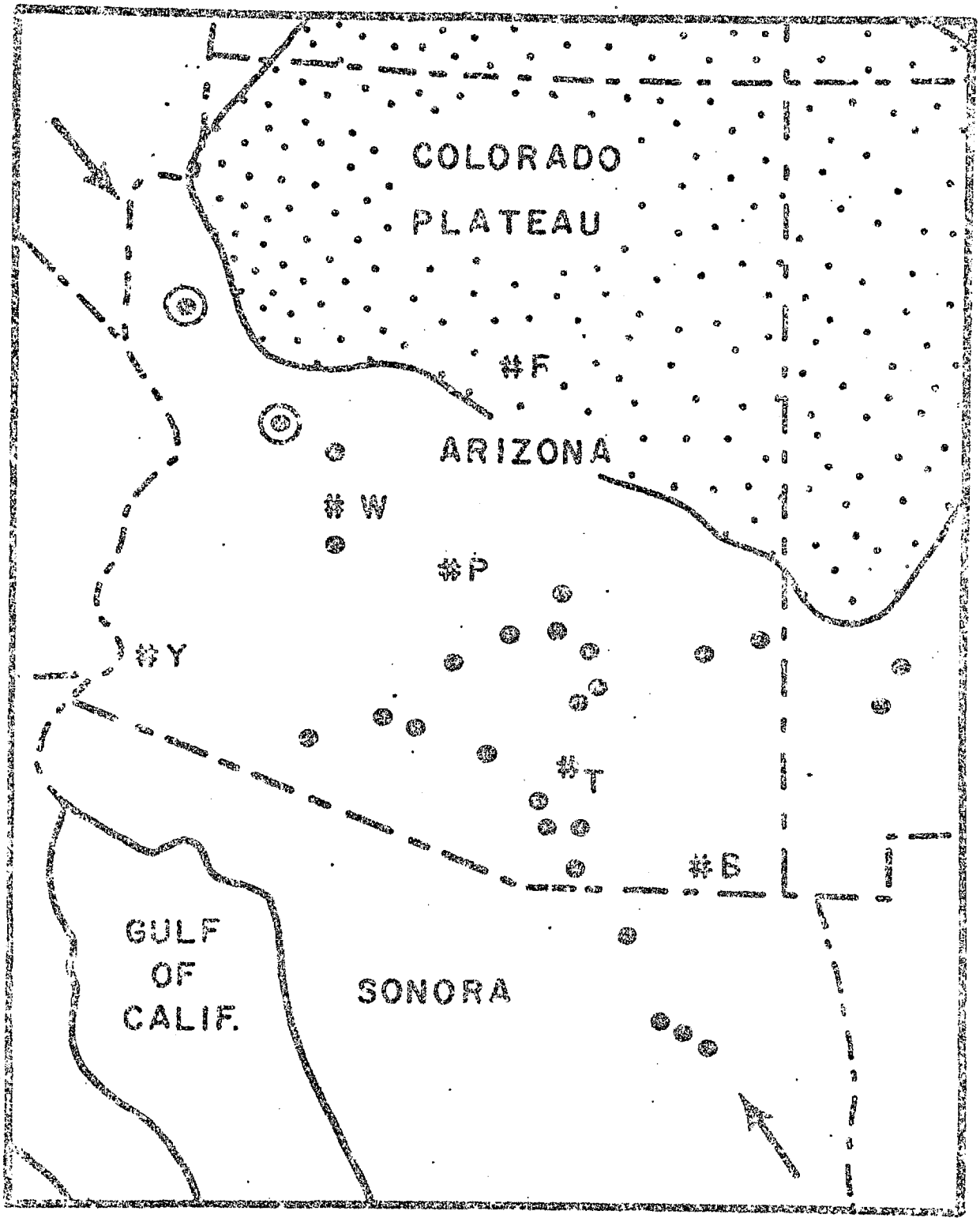
b. Circled deposits 64.0 to 67.9 m.y.

c. Circled deposits 60.0 to 63.9 m.y.

d. Circled deposits 56.0 to 59.9 m.y.

e. Circled deposits 52.0 to 55.9 m.y.

Other symbols as in Figure 1.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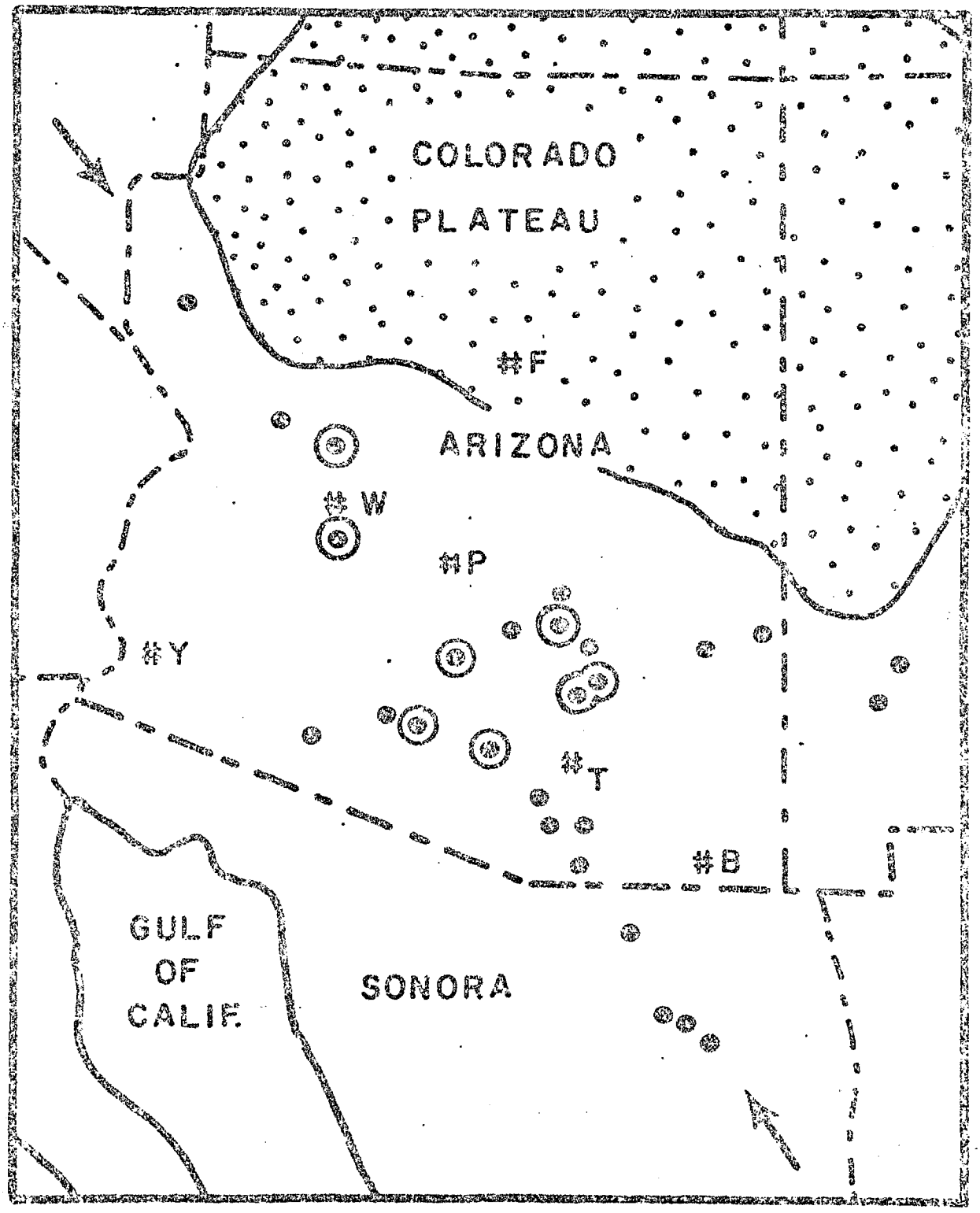
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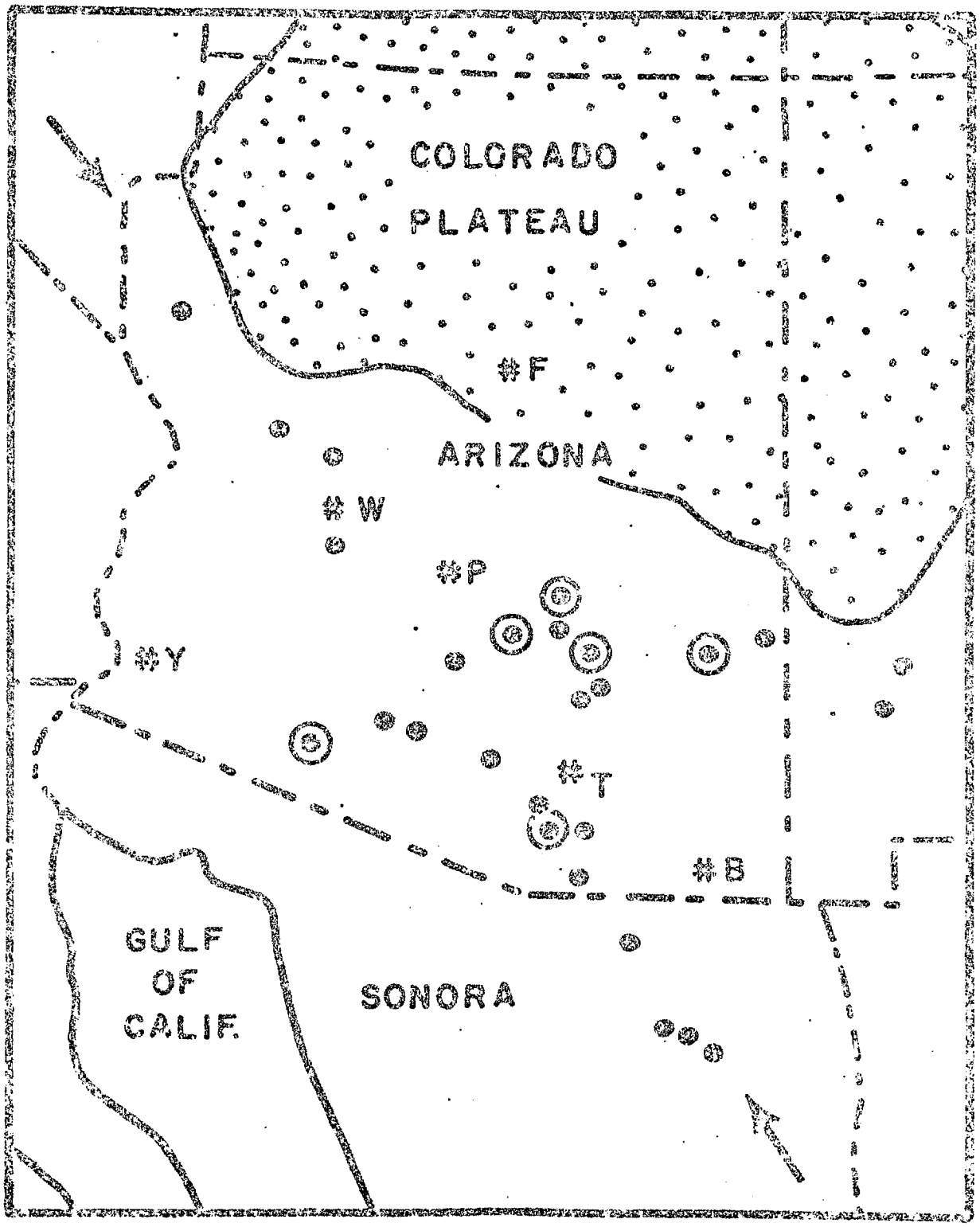
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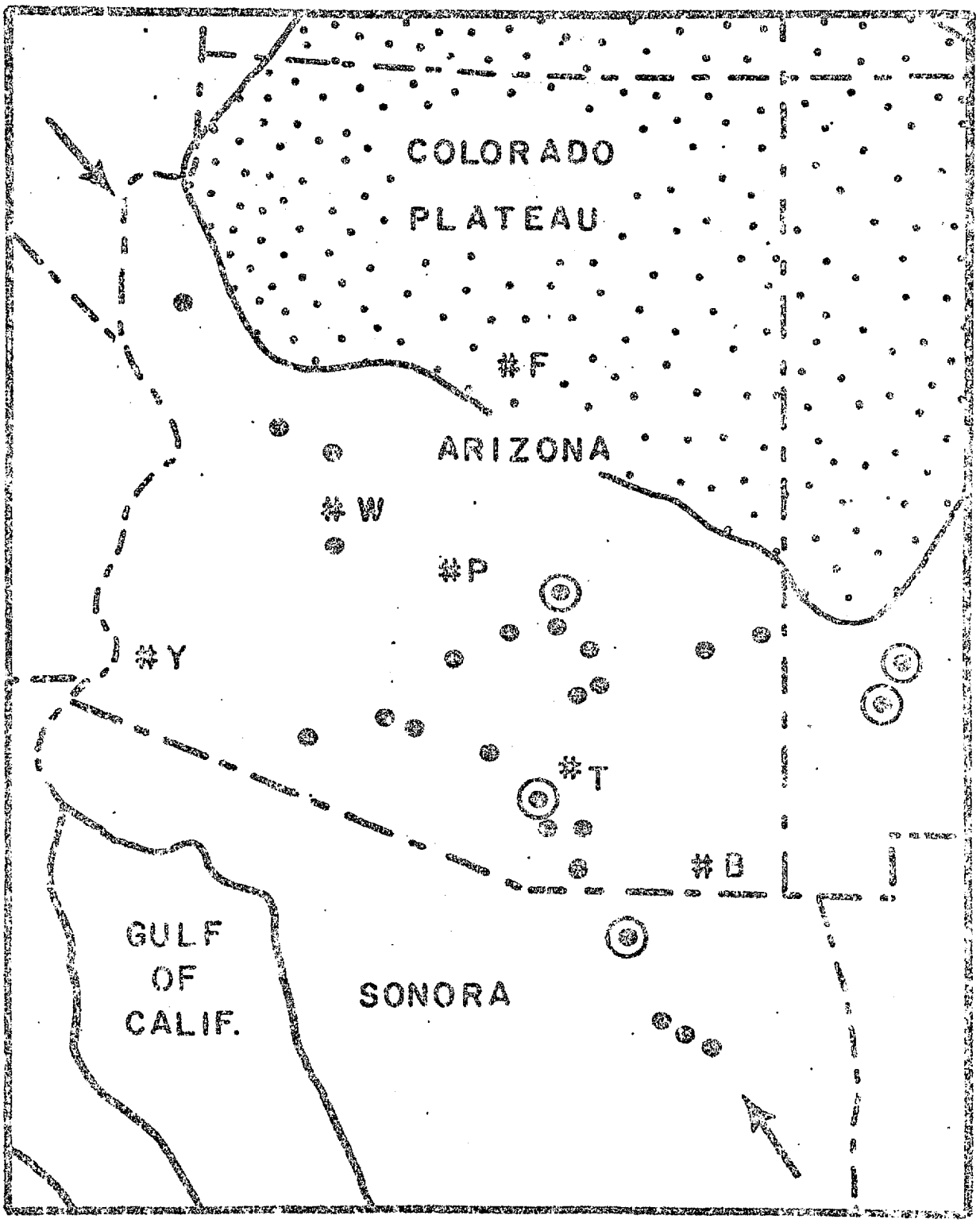
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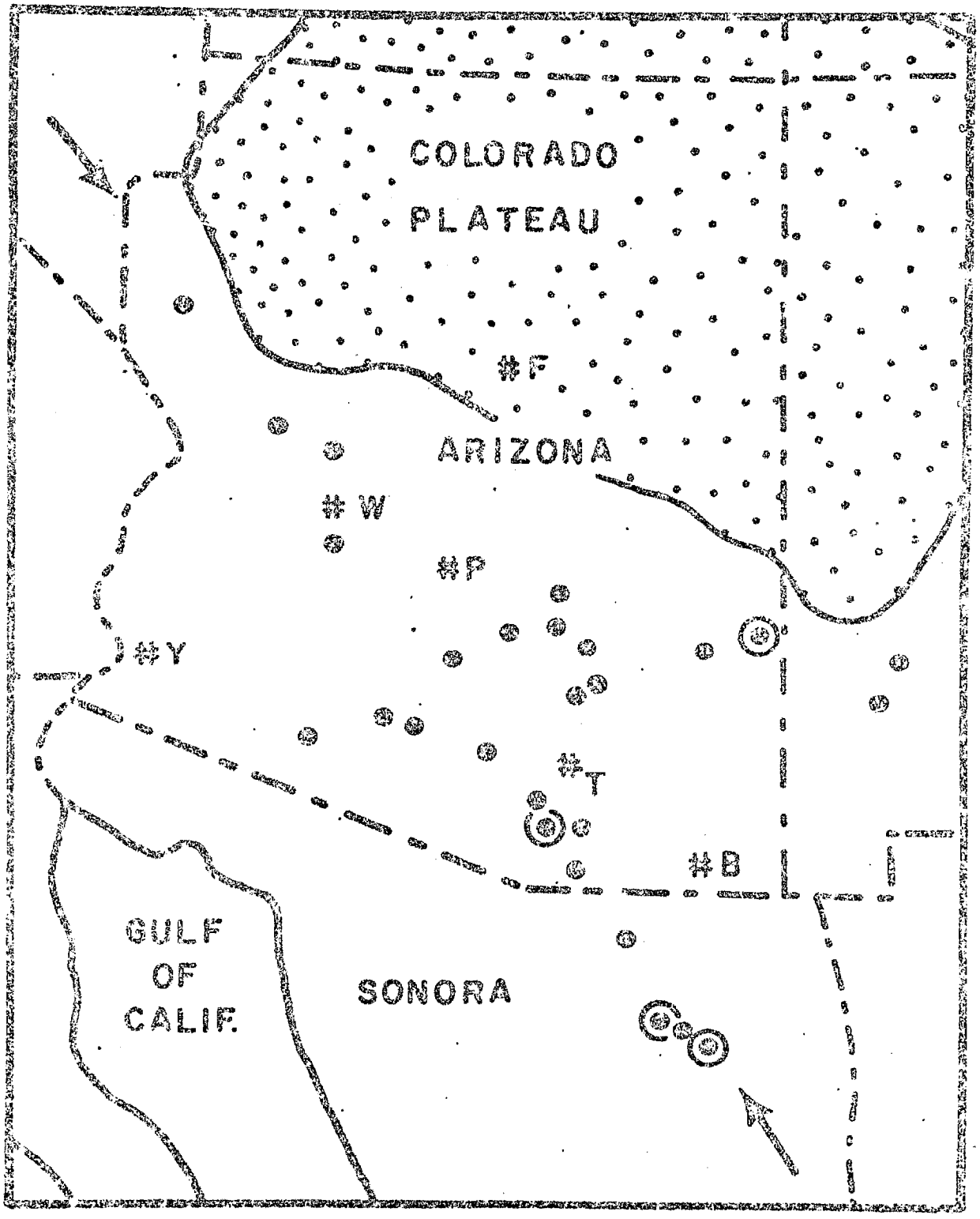
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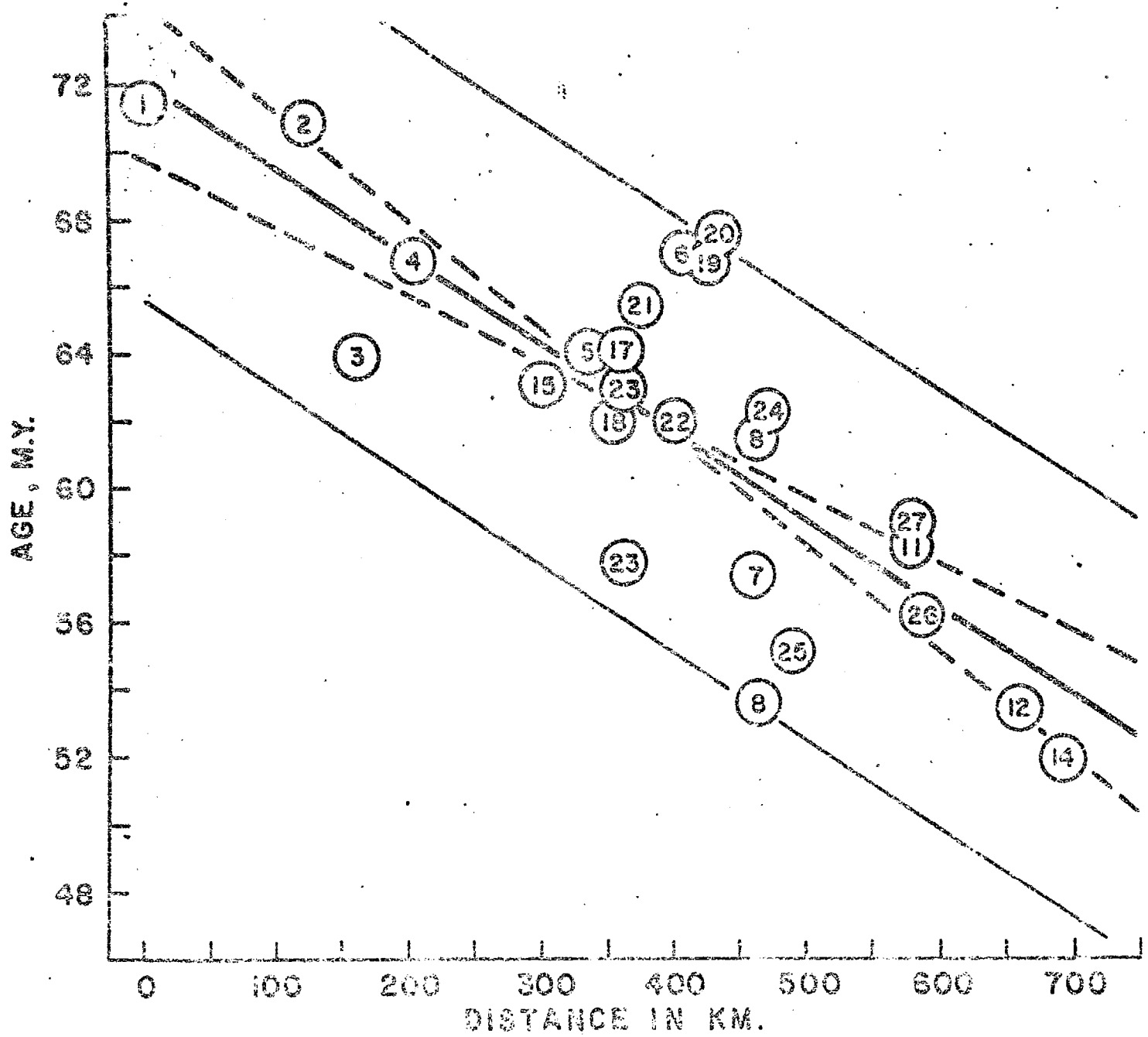
Figure 3. The age of deposits as a function of distance southeast of Mineral Park, Arizona. Distance of deposits is projected to a line bearing S40°E from locality 1. The slope of the heavy solid line is 3.57 ± 0.65 cm./yr. The dashed lines are the one sigma limits of the slope. The light solid lines are the extreme range of ages parallel to the mean line. These two lines indicate the maximum dimension of the proposed hot spot along the line, ca. 450 km.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POST LARAMIDE HISTORY OF THE DEPOSITS

Northward migration of the North American continent during the Cenozoic is compatible with, but not required by palaeoclimatological evidence for tropical and subtropical climates during the late Cretaceous and early Tertiary[19,32], and for climatic cooling from early to late Tertiary[33,34]. A warm and wet climate may also be manifest by the occurrence of early Tertiary blankets of supergene copper enrichment preserved beneath middle Tertiary volcanic and sedimentary rocks[13] for many of the deposits of the region. Titley[35] has observed that some of the porphyry copper deposits of the southwest Pacific have well developed leached capping and blankets of secondarily enriched copper[36,37]. As these deposits are but a few million years of age, and the rate of uplift and erosion are extremely high, it must be concluded that the secondary enrichment there is a product of Plio-Pleistocene time and indeed, may be in progress today in tropical climates. The lack of evidence for late Tertiary enrichment of copper in Arizona may, in part, be due to a concomitant decrease of temperature and rainfall as a result of northwestward plate migration, as well as the development of orographic rain shadows due to mountain building to the west. The northward migration of North America during the early Tertiary is compatible with palaeomagnetic data[38]. A more tropical climate for North America during the Eocene is also supported by the presence of the bauxite deposits of Arkansas (oral suggestion from Eric Cheney, 1973).

Northwestern migration of the North American plate over a fixed mantle hot spot is a predictive concept that presents a coherent and simple model that explains a unique association of the time and space relationships of this metallogenetic and petrogenetic province. It is an extension of some of the concepts and ideas of Lowell[39]. Both hypogene and supergene processes seem to be related to the plate motion and are at least approximately compatible with plate motions as deduced from evidence of the ocean basins, palaeomagnetic latitude determinations

and the data of palaeoclimatology. The concepts developed here suggest that other orthomagmatic-volcanogenic metallogenetic and petrographic provinces in continental environments should be re-evaluated in order to assess the possible role of mantle plumes or hot spots in their development.

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TABLE 1 K-Ar Dates of Porphyry Copper Deposits*
Arizona, Sonora and New Mexico

Locality on Fig. 1	Name	Distance from Mineral Park	Age*	Primary reference
1	Mineral Park	0	71.5 ± 2.6	25
2	Bagdad	120	70.9 ± 2.3	25
3	Copper Basin	160	*64.	40
4	Vulture Mtns.	200	66.8 ± 1.7	**,48
5	Sacaton	340	64.5 ± 1.4	**
6	Silverbell	410	67.1 ± 2.0	25,18
7	Pima	460	57.4 ± 1.4	25,41
	Mission	460	57.4 ± 1.4	25,41
8	Sierrita	465	-	-
	Esperanza	465	*61.6 ± 1.0	25
	Twin Buttes	465	53.5 ± 1.9	25
9	Helvetia	470	-	-
	Rosemont	470	-	-
10	Red Mountain	520	-	-
11	Cananea	585	58.5 ± 2.1	25
12	Aurora	645	*53.4 ± 1.0	49
13	Pilares	660	-	-
14	La Caridad	690	52.1 ± 2.0	***
15	New Cornelia	305	*63.0 ± 1.0	25,42
16	Vekol	335	-	-
17	Lakeshore	360	64.1 ± 2.0	25,43
18	Poston Butte	355	62.0 ± 1.0	**

Table 1, Continued

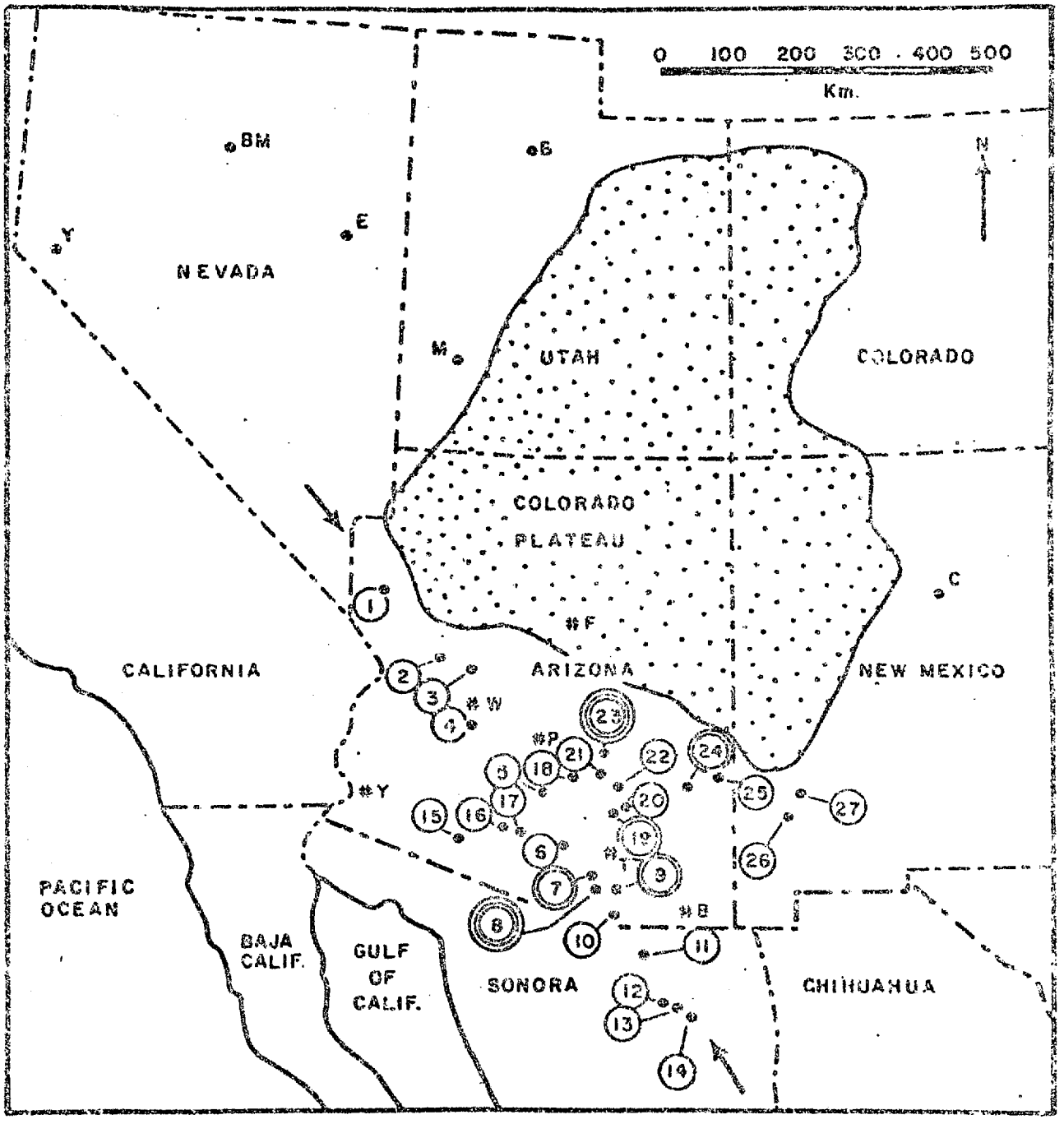
Locality on Fig. 1	Name	Distance from Mineral Park	Age*	Primary reference
19	San Manuel	425	67.0 ± 2.0	24
	Kalamazoo	425	67.0 ± 2.0	24
20	Copper Creek	430	67.5 ± 1.5	41,44
21	Ray	375	65.4 ± 1.0	23
22	Christmas	405	62.	24
23	Copper Cities	365	63.	24
	Inspiration	365	*57.8 ± 1.0	41,42,45
	Castle Dome	365	*57.8 ± 1.0	41,42,45
24	Safford (KCC)	470	62.4 ± 2.3	25,47
	Safford (PD)	470	-	-
25	Morenci	490	55.2 ± 1.5	42
26	Tyrone	590	56.2 ± 1.7	42
27	Chino	580	*59.0 ± 3.5	42,46

*Error as given in primary reference or where noted by asterisk is the total range of values applied to the mean where two or more analyses are available from the primary references. Bisbee, Arizona is not included.

**P.E. Damon, Personal Communication.

***D.E. Livingston, in preparation.

Figure 1. Porphyry copper deposits of southwestern North America. This figure includes both commercial and sub-commercial deposits. Numbered solid dots are deposits listed in Table 1. The number of circles indicate the number of deposits at each locality. The lettered solid dots are other porphyry copper deposits which are not discussed in this paper: Y, Yerrington; B.M., Battle Mountain; E, Ely; B, Bingham; M, Milford; C, Carrillos. ∅ symbols indicate towns and cities in Arizona: Y, Yuma; W, Wickenburg; F, Flagstaff; P, Phoenix; T, Tucson; B, Bisbee. Heavy arrows indicate zone III.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