Arizona Geological Society Digest Volume XVI, 1986

LARAMIDE OROGENY IN ARIZONA AND ADJACENT REGIONS:

A STRATO-TECTONIC SYNTHESIS

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ABSTRACT

Laramide orogeny consisted of three major sequential assemblages that are, from oldest to youngest: 1) east-directed folds, basement-rooted uplifts, and thrusts; 2) hydrous metaluminous arc magmatism and related dikes; 3) hydrous peraluminous plutonism accompanied by southwest-directed thrust faults. These orogenic assemblages become younger eastward and are consistent with flattening of the Farallon plate as a cause of Laramide orogeny with progressive decretion of the overriding North American plate.

The early initial Laramide phase is the earliest phase of Laramide orogeny and consists of the Laramie Assemblage in the Colorado Plateau and the Hillsboro Assemblage in the Basin and Range Province. The Laramie Assemblage of the Colorado Plateau and Rocky Mountain provinces consists of fine-grained sediments from marine and coastal nonmarine (coal-bearing) facies of the regressive, Late Cretaceous, epicontinental sea. Strandline facies contain volcanic components and exhibit facies related to straight, N60W-trending shorelines. Locally, quartz-alkalic metaluminous magmatism and related copper-gold mineralization was emplaced into the southwest portion of the Colorado Mineral Belt. The Hillsboro Assemblage of the Basin and Range Province consists of coarse continental clastics and minor volcanic components that were deposited in west-northwest-trending basins adjacent to west-northwest-trending block uplifts. The magmatic component of the Hillsboro Assemblage consists of quartz-bearing, alkalic, metaluminous volcanics and epizonal stocks of Late Cretaceous age (88-72 Ma) that are associated with copper-gold mineral deposits.

The late initial Laramide phase is the second phase of Laramide orogeny and is subdivided into the Denver Assemblage in the Colorado Plateau and southern Rocky Mountains and the Tombstone Assemblage in the Basin and Range Province. The Denver Assemblage consists of coarse arkoses and conglomerates deposited in asymmetrical synclinal downwarps that generally were formed east of east-facing basement uplifts during Maestrichtian to Paleocene time. The Denver Assemblage also consists of alkali-calcic metaluminous magmatism in the central portions of the Colorado Mineral Belt during the same time interval. The Tombstone Assemblage (Late Cretaceous or 75-65 Ma) consists of alkali-calcic metaluminous igneous rocks, with minor volcaniclastic sedimentary rocks, lead-zinc-silver mineralization, and northeast-directed folding and thrust faulting.

The medial Laramide phase is the earliest Cenozoic part of the Laramide and is the third phase of the Laramide orogeny in Arizona; it is generally of Paleocene age (65-55 Ma). In the Basin and Range Province, medial Laramide orogeny is recorded in the Morenci Assemblage of calc-alkalic metaluminous, epizonal plutons and associated porphyry copper mineralization. Sedimentation is generally absent. The principal structures of the Morenci Assemblage are the regional dike swarms that strike east-west to east-northeast; the dike swarms occur between west-northwest-striking structural elements of the pre-existing Texas Zone which experienced left-slip movement during the medial Laramide phase. On the Colorado Plateau and Rocky Mountains, a conspicuous Paleocene unconformity is developed in the stratigraphy of many basins. At the same time, calc-alkalic to metaluminous magmatism was emplaced in the southwestern Colorado mineral belt and may be a strato-tectonic equivalent of the Morenci Assemblage in Arizona.

The culminant Laramide phase is the fourth or latest part of the Laramide orogeny in Arizona and is Eocene in age (55 to 45 Ma). The Echo Park Assemblage consists of coarse-grained fan and fluvial sediments deposited in north-northwest-trending, synclinal downwarps developed en echelon in a belt in central New Mexico in the eastern part of the Laramide orogen. The Green River Assemblage consists of continental, fluvial and lacustrine sediments deposited in basins that were generally developed on the west or south sides of reverse-faulted uplifts. The Rim Assemblage consists of gravels and fluvial sediments deposited in northward flowing streams that drained a highland that was probably uplifted by underthrust plates in southwestern Arizona. The Wilderness Assemblage consists of subalkaline, peraluminous granites (two-mica granites or muscovite- and garnet-bearing biotite granites) and related gold or tungsten-lead-silver mineralization. Structurally, the Wilderness Assemblage is characterized by southwest-directed thrust faulting, mylonitization, and nappe folding. The relative movement of the upper plate toward the southwest relative to the lower plate can be more accurately described as northeast-directed underthrusting of the Basin and Range Province toward and beneath the Colorado Plateau. The Orocopia Assemblage had the deepest emplacement depths of the culminant Laramide assemblages and consists of blueschist-grade metagraywackes associated with large-scale thrusts such as the Chocolate Mountain thrust.

INTRODUCTION

Several recent developments provide dramatic new constraints for structural and dynamic interpretations of the various Laramide events. One of the most significant developments is the discovery of the Cordilleran two-mica granites and related deformation which occurred during the late Laramide orogeny (Miller and Bradfish, 1980; Keith and Reynolds, 1980, 1981; Keith and others, 1980; Keith, 1982). Other important new data consists of the several thousand line miles of deep seismic sections that were shot in 1979 to 1981 during the southern Arizona overthrust oil play as control for the location of drill holes. These seismic data showed conclusively that southern Arizona is pervasively underlain by numerous low-angle seismic reflectors down to depths of 15 km (Keith, 1980; Reif and Robinson, 1981). Drilling results north of Tucson provided persuasive evidence that the top of one array of strong reflectors was a major low-angle fault (Reif and Robinson, 1981).

Recently, detailed structural investigations have provided fabric information that constrains sliplines and kinematics along many of the various faults that had Laramide movement (Davis, 1975a; 1978a; Haxel and others, 1984). Pioneer studies used vein and dike data from middle Laramide plutons to determine stress patterns operating during intrusion of Laramide igneous suites and associated copper deposits (Rehrig and Heidrick, 1972, 1976; Heidrick and Titley, 1982). Detailed sedimentological investigations (Bilodeau, 1979, 1982) of early Laramide sedimentary rocks have furnished paleocurrent and sedimentological data that constrains the paleogeography of early Laramide uplifts.

Results of recent regional mapping in southeastern Arizona (Drewes, 1981b; Keith, 1983b) and in western Arizona and adjacent southeastern California (Haxel and Dillon, 1978; Reynolds and others, 1980; Frost and Martin, 1982; Richard, 1982; Haxel and others, 1984) have documented the pervasive regional extent of low-angle thrust faults of several episodes that range in age from late Jurassic to early Tertiary. At least some of this thrusting is probably related to the Sevier orogeny which predated the Laramide orogeny, but much is of Laramide age (Drewes, 1981b; Keith, 1982a; Haxel and others, 1984).

The low-angle normal faults of middle Miocene age that have been mapped and studied throughout the region (Davis, 1980; Shackelford, 1980; Frost and Martin, 1982) have increasingly been recognized as occurring along Laramide thrust faults (Thorman, 1977b; Haxel and Grubensky, 1984; Keith and Wilt, 1985). Since 1980, several hundred chemical analyses and several hundred new radiometric dates (Shafiqullah and others, 1980; numerous articles in Frost and Martin, 1982) provide a powerful new data base for regional stratigraphic correlation of igneous units. As a result of these new breakthroughs and the proliferation of quantitative data, a resynthesis of existing data with the new data is necessary.

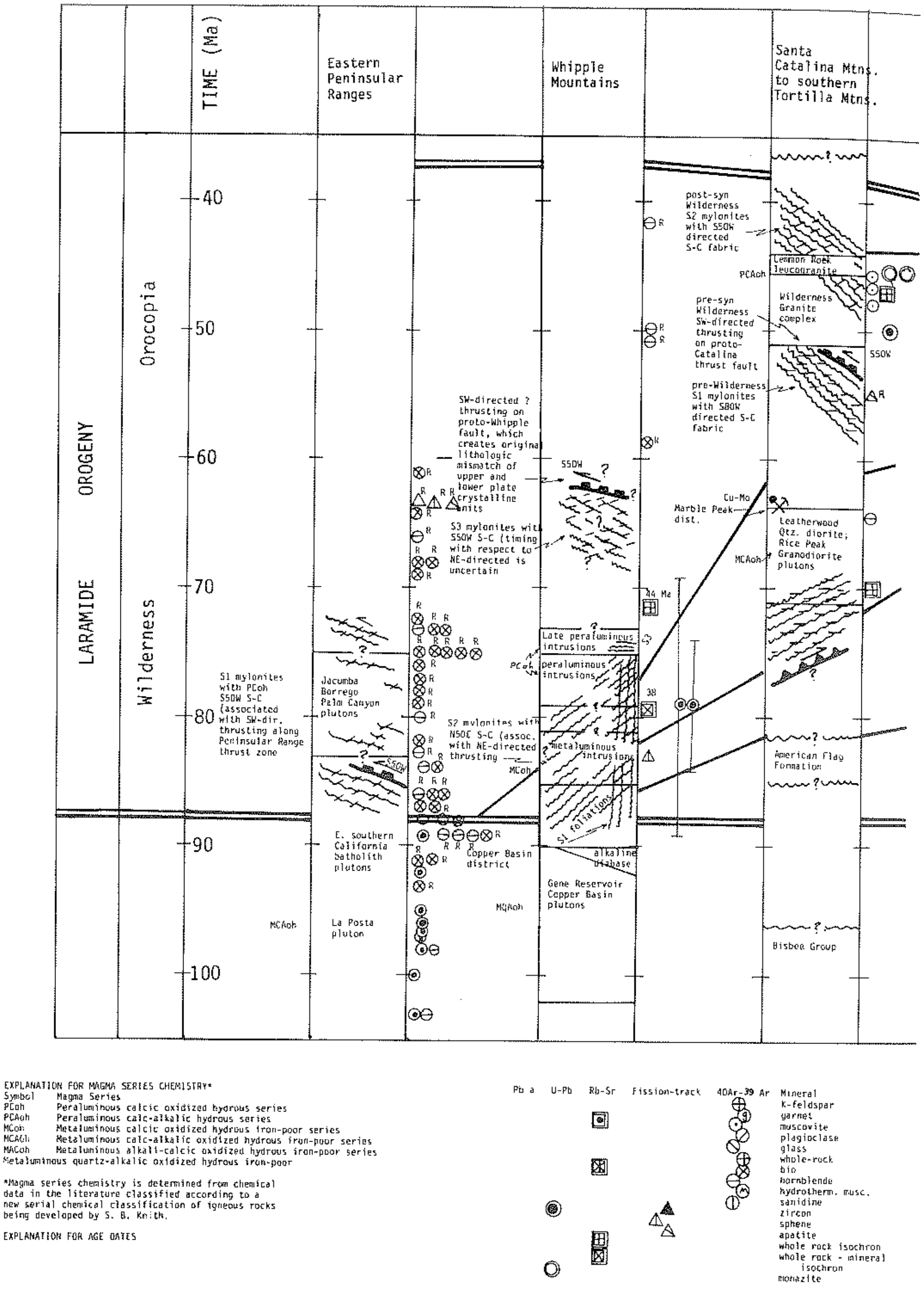
Approach and Methodology

The synthesis of Laramide orogenesis presented in this paper is based on a detailed strato-tectonic approach. A correlation chart was compiled consisting of many columns, each from a relatively limited geographic area such as a mountain range. Data shown included stratigraphy and structural data from detailed quadrangle mapping, sedimentological and fabric data from detailed topical studies, geochronological data, igneous rock chemical compositions, and metal contents of associated mineral deposits. Map relationships were used to establish relative age relationships and geochronological data was used to calibrate stratigraphy to the absolute time scale and resolve stratigraphic problems where relative age constraints were lacking. To improve stratigraphic resolution, the igneous stratigraphy (which comprised at least 70% of the data) was categorized according to a chemical classification of igneous rocks based on magma series chemistry currently being developed by Keith (this volume). The metal contents of mineral deposits that were spatially and temporally associated with various portions of the igneous stratigraphy were also systematically tabulated.

Approximately 100 local areas were selected from the region analyzed by Coney and Reynolds (1977) and Keith (1978); this included data from southern California, Arizona and New Mexico. The data was assembled into strato-tectonic columns that were similar to those used by Coney (1972) to correlate 'on land' Cretaceous-Cenozoic orogenesis for western North America with sea floor spreading data. In addition to the stratigraphic and structural data, the strato-tectonic sections contained additional data such as magma series chemistry, mineral deposit data, and radiometric data. After assembly of each strato-tectonic column, a preliminary time-distance correlation chart was developed following the methodology of Coney and Reynolds (1977). That is, the sections were located on a map of the region and projected to a medial line oriented approximately perpendicular to the plate tectonic boundary between the North American and inferred oceanic plates that were subducted through Cretaceous-Cenozoic time. The preliminary correlation chart is 14 feet long and cannot be included with this paper, although we have composited some of the columns into seven summary columns for this paper (Figure 1).

Analysis of the preliminary correlation chart revealed that the data could be grouped into diachronous, strato-tectonic assemblages that contained unique arrays of lithological, structural, economic, geochronological, and chemical characteristics. These assemblages are shown on the summary correlation chart and are also presented in a series of assemblage maps and tables throughout the text. The assemblages are named for particular type areas, in the same manner as certain formations and members of formations are named for type localities. Assemblages are similar to the rock-stratigraphic term 'Sequence' used by Sloss (1963), but are broader in concept than the Sequences, because they incorporate structures, metamorphism, and mineral deposits as well as rock-stratigraphy.

It was also apparent from the correlation chart that the various assemblages could be interpreted as phases or components of Laramide orogeny. The use of



EXPLANATION FOR MAGMA SERIES CHEMISTRY*

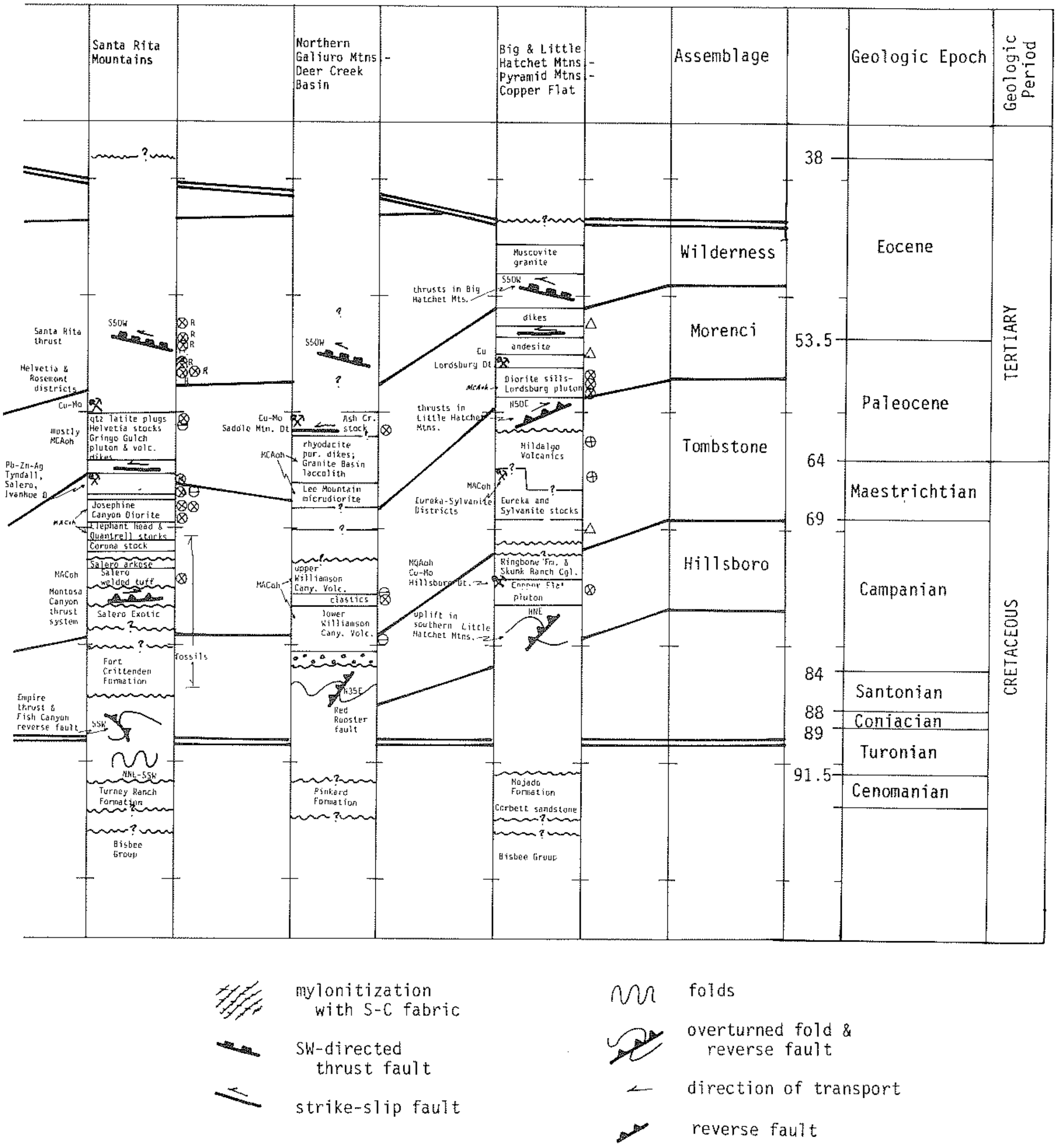
Symbol	Magma Series
PCoh	Peraluminous calcic oxidized hydrous series
PCAoh	Peraluminous calc-alkalic hydrous series
MCoh	Metaluminous calcic oxidized hydrous iron-poor series
MCAGh	Metaluminous calc-alkalic oxidized hydrous iron-poor series
MACoh	Metaluminous alkali-calcic oxidized hydrous iron-poor series

Metaluminous quartz-alkalic oxidized hydrous iron-poor

*Magma series chemistry is determined from chemical data in the literature classified according to a new serial chemical classification of igneous rocks being developed by S. B. Keith.

EXPLANATION FOR AGE DATES

Figure 1. Summary strato-tectonic correlation diagram for Laramide orogeny



in Arizona and vicinity.

the assemblage concept provided a powerful logical tool to reevaluate the broader aspects or 'facies' of Laramide orogenesis, and ultimately its plate tectonic setting.

BOUNDARIES OF LARAMIDE OROGENY

Lower Limit

Distinctions between Sevier and Laramide orogenies are commonly expressed in the literature in terms of stylistic or temporal differences. Stylistic differences are typically presented as thrust faults of thin-skinned decollement style in the Sevier orogeny versus basement-cored or basement-rooted uplifts in the Laramide orogeny. Temporal differences are typically expressed as the time from 140 to 80 Ma for Sevier deformation in the Nevada and Utah areas (Armstrong, 1968) versus the time from 72 to 43 Ma for the Laramide orogeny in the classic area of Colorado and Wyoming.

Any definitions of Sevier or Laramide orogenies that are based on categorical age and/or structural style are invalid. Some major changes in the plate tectonic process dramatically shifted the Cordilleran front eastward from its position in western Wyoming, central Utah, and the Colorado River region at about 89 Ma and established a new orogenic front some 600 km to the east at a position extending from Denver, Colorado to El Paso, Texas by about 65 Ma. This eastward migration of the Cordilleran orogenic front in the Late Cretaceous is attributable to flattening of the subducting slab in Late Cretaceous time (Keith, 1978; 1982b). Therefore, the Sevier orogeny is a product of static and stable, constant-dip subduction, whereas Laramide orogeny is a product of migratory and unstable, variable-dip, flattening subduction.

Any definition of Laramide orogeny in a given region must ultimately reflect the plate tectonic processes that drive it. Consequently, we looked for specific changes in the geology of Arizona, southern California, and New Mexico that reflected the switchover from static subduction (Sevier orogeny) to flattening subduction (Laramide orogeny). In Arizona and adjacent regions, the transition between Sevier and Laramide orogenies is manifested by marked changes in the spatial and temporal patterns of Late Cretaceous magmatism and by marked changes in the orientation of regional structural features such as folds and shorelines at about 88 Ma.

Throughout the western United States, the switchover from Sevier to Laramide orogeny is manifested by distinct changes in tectonic pattern. In general, the transition from Sevier to Laramide orogeny took place from 89 to 84 Ma in the entire western U.S. The change was initially expressed tectonically in the western United States on the east side of the coastal batholith between 89 and 84 Ma (Figure 2). After 85 Ma, the onset of Laramide

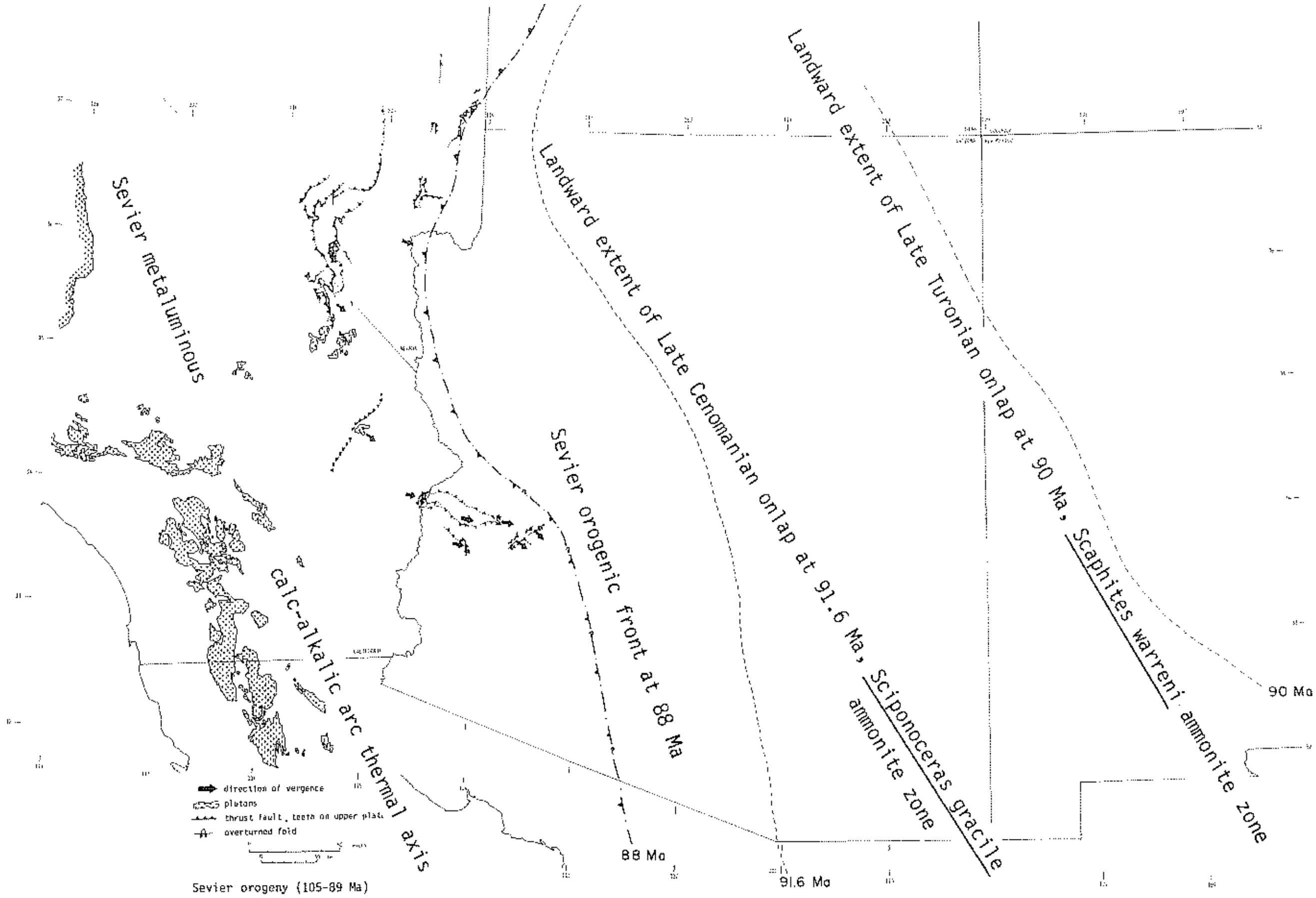


Figure 2. Map of Sevier orogeny (105-85 Ma) in Arizona and vicinity.

orogeny moved rapidly eastward throughout the western United States. In Arizona and adjacent regions, the switchover from Sevier to Laramide is marked by changes in patterns of sedimentation on the Colorado Plateau, magmatism in southern California and southern Arizona, sedimentation and deformation in southern Arizona, and detrital composition of nearshore marine sandstones on the Colorado Plateau.

Sedimentation on the Colorado Plateau

On the southern Colorado Plateau, there is a continuous stratigraphic record throughout the transition from Sevier to Laramide sedimentation, and the onset of Laramide orogeny may be dated precisely. On Black Mesa in northeastern Arizona and in the San Juan Basin of northwestern New Mexico, the beginning of the flattening process is marked by an abrupt reorientation and straightening of Late Cretaceous shorelines from the more undulatory northwesterly orientations of Sevier age (Figure 2) to straight, west-northwesterly (N60W) orientations of Laramide age (Figure 3). The shoreline reorientation and straightening occurred immediately after a major regression throughout the southern Colorado Plateau region. This regression is recorded in the Niobrara stratigraphic interval in Turonian to late Coniacian time (89 to 88 Ma). This reorientation in northern Arizona exactly corresponds to the Early Santonian shoreline within the *Scaphites depressus* ammonite zone of *Obradovich and Cobban's* (1975) radiometrically calibrated, ammonite time scale for the Late Cretaceous in North America. On the time scale, the *Scaphites depressus* ammonite zone is assigned an *absolute age of about* 88 Ma. This Early Santonian shoreline is represented by the Dalton Sandstone Member of the Crevasse Canyon Formation in the San Juan Basin and by the marine portion of the Upper Sandstone Member of the Toreva Formation in Black Mesa following the stratigraphic correlations of Peterson and Kirk (1977) and Molenaar (1983). The Dalton-upper Toreva shoreline is the oldest N60W-trending shoreline and therefore these formations represent the base of the Laramide according to the previously mentioned criteria of shoreline reorientation.

When the Laramide orogeny began to affect the southern Colorado Plateau around 88 Ma, the classic area in the Colorado and Wyoming Rockies was still experiencing marine sedimentation of the Mancos sea and would not experience Laramide orogenesis until after 72 Ma. To show the time-transgressive nature of the initiation of Laramide orogeny, the base should be fixed to a specific lithofacies that reflects its onset. In the Colorado Plateau the strandline beach sandstones that separate marine facies from continental facies provide a continuous unit. This rock-stratigraphic unit can be used to track the northeastward progression of Laramide orogeny from the southern Colorado Plateau into the classic area in the Rocky Mountains of Colorado and Wyoming. Thus, we consider those rocks that represent continental facies younger than 88 Ma and that occur west and south of the marine shorelines to be Laramide rocks. We, therefore, define Laramide rocks on the Colorado Plateau as *continental to marginal marine rocks at or above the Dalton-upper Toreva time-regressive datum (88 Ma) on the southern Colorado Plateau.*

Magmatism in Southern California and Arizona

Another maximum age constraint for the Laramide orogeny in southern California, Arizona, and New Mexico is provided by early Laramide magmatism that has been radiometrically dated. Keith (1978, 1982b) and Westra and Keith (1981; 1982) have shown that the Late Cretaceous arc magmatism may be divided into distinct geochemical zones which become more alkaline to the east, away from the trench. These geochemical belts did not begin to shift eastward until *after* 87 Ma.

This eastward shift in magmatism is shown by U-Pb data for the southern California batholith (Figure 2), which indicates that metaluminous calc-alkalic plutonism persisted in the Peninsular Range batholith until about 89 Ma (Silver and others, 1979). After 89 Ma, the Peninsular Range magmatic arc becomes extinct. However, after this, metaluminous magmatism began in Arizona and Sonora, far east of the Peninsular Range batholith. We interpret the extinction of metaluminous magmatism in the Peninsular Range batholith at 89 Ma and the eastward shift of metaluminous magmatism to be an expression of the change from static subduction in the Sevier orogeny to flattening subduction in the Laramide orogeny. Flattening subduction forced metaluminous magmatism eastward into Arizona and Sonora after 89 Ma.

In Arizona, magmatism of the initial Laramide is represented by metaluminous alkalic plutons, such as the Mudersbach pluton dated at about 87 Ma in the Plomosa Mountains (Richard Chuchla, pers. comm., 1983; Reynolds and others, 1985). By 75 Ma similar alkaline magmatism had migrated into New Mexico and is assigned to the Hillsboro Assemblage described below. Therefore, *alkaline magmatism younger than 89 Ma and associated sedimentary rocks of the Hillsboro Assemblage represent the earliest Laramide rocks in the Basin and Range Province of Arizona and New Mexico.*

As pointed out by Keith and Reynolds (1981), hydrous peraluminous magmatism is formed by anatexis of crustal materials during tectonic fusion of the underriding oceanic plate with the overriding plate. Therefore, in areas where metaluminous magmatism is intruded by peraluminous series magmatism, a shift from moderately dipping subduction to flat subduction may reasonably be inferred. Hence, in near-trench exposures in southern California, the first appearance of peraluminous series magmatism is a strong indicator of flat subduction of the Laramide orogeny.

In southern California, calc-alkalic metaluminous magmatism of the Sevier orogeny dated from 105 to 85 Ma is directly intruded by calc-alkalic peraluminous series magmatism in several areas, such as at Jacumba, the Old Woman Mountains, and the San Bernardino Mountains. The oldest, reliably dated, unequivocally calcic, peraluminous series plutons in southern California are the peraluminous, synkinematic sills in the Whipple Mountains, which have yielded dates of 89 ± 3 Ma by the U-Pb zircon method (Wright and others, 1986). In the Old Woman Mountains of San Bernardino County, the Sweetwater Wash pluton (which is calc-alkalic peraluminous series) has yielded a 4 point, whole rock, Rb-Sr isochron of 79 ± 7 Ma, (Miller and others, 1982). The Sweetwater Wash pluton, however, intrudes a metaluminous granodioritic pluton that yields an U-Pb zircon age of 72 Ma (Miller and others, 1984). K-Ar cooling ages for the Sweetwater Wash pluton are 70.5 Ma (Armstrong and Suppe, 1973). Thus, the most reliable estimate for the emplacement age for the Sweetwater Wash pluton is 71 to 72 Ma.

Numerous other peraluminous plutons in southern California (Coxcomb batholith, Iron Mountains pluton, Piute Mountains pluton, and Homer Mountains pluton) have also yielded K-Ar cooling ages between 75 and 72 Ma. By analogy with the Sweetwater Wash pluton, the cooling ages are probably close to the emplacement ages. In summary, evidence from peraluminous plutons in the southern California region indicate that flat subduction began to effect the central Mohave region by about 89 Ma and was widespread in the region by 75 to 72 Ma.

It is significant that no evidence exists in southern California for the presence of initial or medial Laramide strato-tectonic assemblages. The first assemblage to appear in the area west of the Colorado River is the culminant Laramide strato-tectonic assemblage that is manifested by the peraluminous plutons.

Tectonics in the Basin and Range Province

In the Basin and Range Province of Arizona and southern California, the beginning of Laramide orogeny is less precise because of the lack of continuous stratigraphic control. On a regional basis, Laramide orogeny definitely postdates the widespread Aptian-Albian components of the Bisbee Group. On a more limited basis, Laramide orogeny postdates early Cenomanian marine facies of the Upper Bisbee Group, particularly in the Mojado Formation of southwestern New Mexico and upper Turney Ranch Formation in the Santa Rita Mountains of southeastern Arizona (about 96 Ma on the Obradovich and Cobban (1975) time scale). These beds are affected by a deformation that is truncated by 75 Ma volcanism of the Salero Group. This deformation is the Late Cretaceous tectonic disturbance of Hayes (1970) or the early Piman phase of Laramide orogeny of Drewes (1981b).

The Fort Crittenden Formation is also, at least in part, a sedimentological expression of deformation that occurred after the Turney Ranch and Mojado formations (post 96 Ma). Fossils collected from the Fort Crittenden Formation where it crops out in the Santa Rita Mountains are Santonian to Maestrichtian in age (85 to 65 Ma). However, because the Fort Crittenden Formation correlatives in the Santa Rita Mountains underlie the Salero Formation (dated at 75 Ma), the Fort Crittenden Formation is more reasonably assigned an age of 85 to 75 Ma.

Regional synthesis of deformation affecting the Turney Ranch and Mojado formations in Arizona suggests that the uplifts were aligned approximately parallel to the N60W shorelines on the Colorado Plateau, indicating that the post-87 Ma shorelines and the structural phenomena in southern Arizona are of similar ages and may be tectonically coordinated. The age assignment of the deformation is further strengthened by the Santonian-early Campanian age of the Fort Crittenden Formation, which is probably synorogenic. As such, the Late Cretaceous deformation is considered early Laramide in age rather than late Sevier. In this way, the west-northwest-trending uplifts in southeast Arizona and southwest New Mexico may be interpreted as the initial Laramide breakup of the Bisbee Group trough of Sevier age.

Volcanic Detritus on the Colorado Plateau

The onset of major metaluminous magmatism of Early Campanian age in southern Arizona and southwestern New Mexico is recorded in sedimentary rocks of Santonian and early Campanian age on the Colorado Plateau, particularly in the Point Lookout Sandstone of the San Juan Basin (Cumella, 1981, 1983). Cumella reports that volcanic detritus is stratigraphically present as low as the Dalton Sandstone member of the Point Lookout Sandstone of Santonian age (88 - 86 Ma). No volcanic detritus is present in the underlying Gallup Sandstone (90 - 88.5 Ma). Detritus in the Gallup Sandstone was probably derived from clastic sedimentary successions such as the Bisbee Group in southern Arizona and southwestern New Mexico.

The lack of volcanic detritus in pre-88 Ma sandstones on the southern Colorado Plateau is consistent with volcanism being restricted to the area of the Peninsular Range batholith region far to the west. When the arc began to shift eastward about 87 Ma, volcanic components from the metaluminous arc began to be deposited in regressive sandstone facies on the southern Colorado Plateau. Thus, the sedimentology of sandstones on the southern Colorado Plateau suggests that flattening initially occurred between 87 and 88 Ma. These dates coincide with the dates of shoreline reorientation and arc migration discussed previously.

Summary

We propose the following definition for the lower limit of Laramide orogeny in southern California, Arizona, and New Mexico: 1) an eastward shift after 89-87 Ma of metaluminous magmatism in general, and of quartz-alkalic metaluminous magmatism in particular, in southern California and Arizona; 2) the presence of metaluminous volcanic detritus in regressive sandstone facies younger than 88 Ma on the southern Colorado Plateau; 3) reorientation and straightening to a N60W trend of shorelines after 88 Ma on the southern Colorado Plateau, 4) syntectonic, clastic sedimentation after 88 Ma and development of wedge-style, N60W-trending uplifts within the former site of the foreland trough where Bisbee Group sediments had been deposited, and 5) appearance of peraluminous magmatism in southern California at about 89-87 Ma.

Upper Limit

The termination of Laramide orogeny on the Colorado Plateau is represented by a widespread unconformity known as the 'Eocene erosion surface' (Epis and Chapin, 1975; Gresans, 1981). In the San Juan Basin in northwestern New Mexico, rocks of the San Jose Formation below the Eocene erosion surface are Wasatchian [early Eocene or as young as 50 Ma] (Baltz, 1967; Lucas and Ingersoll, 1981). Along the Mogollon Rim segment of the Colorado Plateau in Arizona, 'Rim gravels' contain clasts yielding early Eocene dates and could be middle Eocene in age. The 'Rim gravels' are truncated by the late Eocene-early Oligocene unconformity as they are locally overlain by late Oligocene-Miocene volcanics (K-Ar date of 28 Ma by Peirce and others, 1979).

Thus, strata on the Colorado Plateau in Arizona represent the Laramide interval if they are middle Eocene or older (older than 43 Ma). Such rocks would contain no late Eocene or younger volcanic clasts, whereas rocks from the early Galiuro orogeny (Keith and Wilt, 1985) contain a few volcanic flows and/or volcanic clasts of latest Eocene or early Oligocene age. A regional unconformity of late Eocene to early Oligocene age described by Peirce and others (1979) on the Colorado Plateau separates the Laramide and Galiuro orogenies. This unconformity in southern Arizona, however, commonly represents a much longer period of time because sedimentary and volcanic strata of the later parts of the Laramide and of the early parts of the Galiuro are generally not preserved.

In southeastern Arizona the termination of Laramide orogeny can generally be dated at about 44 Ma, which is the youngest age of the Wilderness intrusive complex in the Santa Catalina Mountains (Keith and others, 1980). The upper limit of Laramide orogeny in the Basin and Range Province of Arizona may be defined as the termination of the peraluminous magmatic event and its associated mylonitic deformation.

In a more conventional way, the upper limit of Laramide orogeny in the Basin and Range Province of Arizona has been defined less precisely by the unconformity that truncates numerous areas of porphyry copper mineralization, which are related to calc-alkalic, metaluminous magmatism of Paleocene to early Eocene age (Damon and Mauger, 1966). This unconformity is overlain by early Oligocene sedimentary and volcanic rocks as old as 37 Ma. However, because the Eocene-aged peraluminous plutonism of the Wilderness Assemblage probably occurred at fairly deep crustal levels, these plutons were not sufficiently uplifted and unroofed to be exposed to erosional processes until mid-Miocene time (about 18 Ma). Thus, there is no physical way through the classic use of unconformities to precisely date termination of the Laramide orogeny (the peraluminous granitoids of the Wilderness Assemblage) and the beginning of the Galiuro orogeny (the pre-ignimbrite sediments of the Mineta Assemblage) (Keith and Wilt, 1985).

LARAMIDE STRATO-TECTONIC SUBDIVISIONS

In any given area the Laramide orogeny can generally be subdivided into four broad phases that sequentially overprint previous phases in a systematic manner. The Laramide orogeny is divided into four major phases: the early initial, late initial, medial, and culminant Laramide orogenic phases (Table 1). Each phase may contain one or more strato-tectonic assemblages as lateral or vertical tectonic facies. On a regional basis the orogenic phases are time transgressive, so that all phases of the Laramide orogeny become generally younger in a west to east direction (Figure 1).

Table 1. Summary of Laramide assemblages in Arizona

PHASE	ASSEMBLAGE	SEDIMENTATION	MAGMATISM	STRUCTURES	MINERAL RESOURCES	AGE (Ma)
Culminant LARAMIDE	Echo Park	arkosic alluvial fans	generally absent	NW-trending, sharp, asymm. downfolds, en echelon	uranium	56-43
	Green River	alluv. plains, mudflats & lacustrine facies	none	large, NW- to N-S trending asymmetrical thrust uplifts	oil shale, potash uranium, oil, gas	56-43
	Rim	fluvial gravels	none	shallow NE-dip paleoslope (Eocene erosion surface)	none	56-43
	Wilderness	none	peraluminous calcic and calc-alkalic 2-mica granitoids	shallow-dipping mylonite zones low-angle SW-dir. thrusts large amount of transport	Au disseminations and veins W veins, minor Ag-Pb-Zn	80-43 AZ 50-43 NM
	Orocopia	none	none greenschist metamorph. of metagraywackes	large regional thrusts Chocolate-Vincent thrusts vy. large amt. shortening	qtz pods, minor Au	60-43 AZ
Medial LARAMIDE	Morenci	none	calc-alkalic, epizonal plutonism & volcanism hydrous, metaluminous	NE to ENE striking dikes distributed left shear through Texas Zone	porphyry Cu-Mo; Cu-Zn skarns; Cu-Ag vns; fringing Zn-Pb-Ag	75-50 AZ 59-50 NM
Late Initial LARAMIDE	Denver	cse. clastics in asym. basins E of E-facing basement uplifts	local nepheline alkalic magmatism	N-trending, E-facing monoclinal uplifts		74-72 UT 68-64 AZ 70-65 CO
	Tombstone	continental clastics large exotic blocks interbed volcaniclastics	alkali-calcic, hydrous plutonism & pyroclast. volcanism, metaluminous	NW-striking, NE-dir. folds & thrusts with 1-10 km shortening	Pb-Zn-Ag veins & replacement deposits	80-70 AZ 70-64 NM
Early Inital LARAMIDE	Laramie	regress. marine-nonmar. ss, sh, ls, bentonite	none very few volcanic clasts	N60W trending shorelines broad N60W folds	coal abundant oil, uranium	88-72 AZ 88-65 NM
	Hillsboro	cse. continental clastics congl. & alluv. fans	alkalic hydrous volcanic & small stocks metaluminous	E-W wedge uplifts & basins WNW-ESE striking, high-angle reverse faults on uplifts	epigenetic Cu-AU porphyries	88-65

Early Initial Laramide Orogeny

LARAMIE ASSEMBLAGE

Name

The Laramie Assemblage is defined in Arizona as those formations above the *Scaphites depressus* ammonite zone, which is the earliest time zone that marks a dramatic reorientation and straightening of shorelines on the southern Colorado Plateau. The Laramie Formation in the Denver Basin of Colorado is considered to be the type locality of the Laramie Assemblage. Between 1875 and 1890 Laramie Formation or Laramie Group was widely used for the coal-bearing, lagunal-paludal strata that conformably overlay the fossiliferous marine Cretaceous throughout the Rocky Mountain West. Because subsequent paleontological work showed that the Laramie strata varied widely in age from Late Cretaceous to Early Eocene, the U.S. Geological Survey in 1910 restricted the term Laramie to a particular time-stratigraphic interval in the Denver Basin. The Laramie stratigraphic problem was summarized in detail by Knowlton (1922). Because the term Laramie is still well-known and constitutes a useful rock-stratigraphic term to describe formations that represent the tectonic environment of the early initial Laramide orogeny, we suggest that the term Laramie be resurrected as Laramie Assemblage to designate the formations, structures, and mineral resources of the early initial Laramide orogeny in the Colorado Plateau and Rocky Mountains. General characteristics of the Laramie Assemblage are summarized in Table 2.

Table 2. Characteristics of Laramie Assemblage of the early initial Laramide orogeny

SEDIMENTS	MAGMATISM	STRUCTURES	RESOURCES
regressive marine-nonmarine	none	N60W-trending shorelines	coal
coal-bearing fluvial clastics		broad, open N60W-trending anticlines & synclines synkinematic with deposition	oil
regressive marine ss w/ volcanic detritus			uranium
fossiliferous marine shale, limestone & bentonite			
N60W striking facies related to N60W striking shorelines			
oscillatory regresssion to NE			

Rocks of the Laramie Assemblage

In detail, the Laramie Assemblage consists of four major rock types, which are, from landward to seaward: 1) braidplain deposits of siliceous, pebbly, trough-crossbedded sandstones and subordinate siltstones; 2) coal-bearing, coastal plain sediments of low-angle crossbedded sandstone and flat-bedded to virtually structureless siltstones and claystones; 3) generally regressive marine sandstones deposited in beach and nearshore environments that contain some volcanic detrital grains; and 4) fossiliferous, shallow marine shales with some deeper marine limestones and local water-lain bentonite beds. The volcanic detrital grains in the marine beach sandstones consist of detrital grains of plagioclase feldspars on the southern Colorado Plateau (Cumella, 1981). The four facies are arranged from southwest to northeast parallel to a N60W-striking shoreline that is represented by the regressive beach sands with the terrestrial coal-bearing strata to the southwest and the marine limestones to the northeast (Figure 3).

The general depositional pattern of all Laramie Assemblage strata from 88 to 72 Ma was within a regime of oscillatory regression toward the northeast (Cumella, 1983; Molenaar, 1983). These strata occur above a regional unconformity of basin-wide extent during the lower Niobrara age interval at the base of the T-3 transgression of Molenaar (1983). The best sequence of regressive oscillatory strata of the Laramie Assemblage is in the San Juan Basin of northwestern New Mexico (Peterson and Kirk, 1977; Molenaar, 1983) and this area is designated as a reference area for the Laramie Assemblage.

From oldest to youngest, the formations of the Laramie Assemblage in the San Juan Basin of New Mexico include the Crevasse Canyon Formation, the undivided Mesa Verde Group, Point Lookout Sandstone, Menefee Formation, Cliff House Sandstone, Fruitland Formation and Kirtland Formation (Molenaar, 1977; New Mexico Geological Society, 1982). In Arizona strata of the Laramie Assemblage are present on Black Mesa and include the upper marginal marine sandstone of the Toreva Formation, the coal-bearing Wepo Formation, and the marginal marine Yale Point Sandstone (Repenning and Page, 1956). These formations are listed in Table 3 and are shown on Figure 3.

Structures of the Laramie Assemblage

The principal structural features of the Laramie Assemblage are the shorelines represented by the regressive marine sandstones of the beach facies. The shoreline marking the southwestern edge of the middle to Late Cretaceous epicontinental sea remained remarkably straight and parallel to a N60W strike from 85 to 72 Ma (Cobban and Hook, 1984; Molenaar, 1983). These shorelines are listed in Table 3 and are shown on Figure 3, where each line represents the most landward position of the beach at the time indicated.

In northeastern Arizona on Black Mesa these shorelines are parallel to a N60W-trending set of broad, open anticlines and synclines that deform Wepo and Yale Point formations of upper Santonian to lower Campanian stages (85 to 82 Ma). The folds may have existed during the deposition of strata of the Laramie Assemblage, because the Wepo Formation depositionally thins sharply away from the Maloney synclinal area in northwestern Black Mesa (Peirce and Wilt, 1970). Hence, the downwarps probably existed during Wepo deposition and could have influenced coal deposition (Peirce and Wilt, 1970). Although most of the anticlines and synclines cannot be precisely dated, there is general agreement that these folds precede and are deformed by the north-trending monoclines (Kelley, 1955; Davis, 1975a, 1978a).

Resources of the Laramie Assemblage

Strata of the Laramie Assemblage contain major coal resources on Black Mesa in northeastern Arizona, the Kaiparowits Basin of southeastern Utah, and the San Juan Basin of northwestern New Mexico. In Arizona the Peabody Coal Company is exploiting multiple coal seams 4 to 20 feet thick on Black Mesa within the Wepo Formation (Peirce and Wilt, 1970). The Navajo and McKinley mines of the San Juan Basin have extracted major production from the Clary and Gibson coal seams in the Menefee Formation (Wilson, 1977). In the southern Colorado Plateau region, significant coal accumulation took place after 88 Ma, in contrast to lesser volumes and grades of earlier coals in the Dakota Group. The dramatic increase in volume of coal accumulation may reflect shoaling and lowering of drainage gradients in the southern Colorado Plateau region in response to the initial flattening of the underriding Farallon lithosphere.

Abundant oil and gas production and reserves exist in the beach sandstones of the Laramie Assemblage in the San Juan Basin, particularly in the Pictured Cliffs Sandstone and the Fruitland Formation. Major uranium resources also exist in the San Juan Basin, specifically in the Fruitland Formation and in the Menefee Formation (Chenoweth, 1977).

HILLSBORO ASSEMBLAGE

Name

The name Hillsboro Assemblage was given by Keith (1984) to the earliest Laramide rocks within the Basin and Range Province of Arizona and New Mexico. Lithologic members and mineral systems of the Hillsboro Assemblage are best exposed near Hillsboro in southwestern New Mexico (Hedlund, 1977), and this area is designated as a reference area for igneous rocks of the Hillsboro Assemblage. The central Santa Rita Mountains, which has been well documented by Drewes (1971a,b,c) and Inman (1982), is designated as a reference area for sedimentary rocks of the Hillsboro Assemblage (Figure 3). The north-south compressive deformation of Gilluly (1956) and the early Late Cretaceous disturbance of Hayes (1970) coincide with the tectonics herein assigned to the Hillsboro Assemblage. General characteristics of rocks, structures, and resources of the Hillsboro Assemblage are summarized in Table 4.

Table 4. Characteristics of Hillsboro Assemblage of the early initial Laramide orogeny

SEDIMENTS	MAGMATISM	STRUCTURES	RESOURCES
coarse continental clastics gen. lack volcanic components except in upper parts angular unconf. over mid-Cret. accum. in E-W trending basins adjacent to block uplifts congl. & alluvial fans	not common small volcanic centers small epizonal porphyritic stocks volc. highly brecciated latites & monzonites metaluminous, alkalic gen. Fe-poor, hydrous, oxidized	E-W block uplifts E-W to WNW-ESE striking high-angle reverse vaults (60 deg.) with shortening 5-7 km vertical throw 1-3 km horizontal throw bidirectional transport N- or S-directed or NNE- or SSW-directed either side of block uplifts	epigenetic Cu-Au hydrothermal

Rocks of the Hillsboro Assemblage

The principal rock types of the Hillsboro Assemblage are continental sedimentary rocks consisting predominantly of rounded-clast conglomerate, sandstone and shale; individual sections range up to thousands of feet thick. In their upper parts these strata may contain thin tuff beds, but they generally lack large amounts of volcanic components or large exotic blocks, in contrast to younger Laramide assemblages.

Examples of sedimentary formations assigned to the Hillsboro Assemblage (Table 5 and Figure 3) are the Fort Crittenden Formation of the Santa Rita and Huachuca Mountains in southeastern Arizona (Hayes, 1970; Drewes, 1971c), the Cabullona Group in northeastern Sonora (Taliaferro, 1933; Hayes, 1970), the Ringbone Formation of the Little Hatchet Mountains (Lasky, 1947; Zeller, 1970), possibly the Javelina Formation of the Pedregosa Mountains in southeasternmost Arizona (Epis, 1956), and possibly the American Flag Formation in the northern Santa Catalina Mountains (Creasey, 1967).

Igneous rocks assigned to the Hillsboro Assemblage are not common, although both volcanics and epizonal porphyritic stocks are present and form relatively small volcanic centers. The volcanic rocks of the Hillsboro Assemblage are commonly brecciated, which indicates fairly high flow viscosities and autobrecciation during extrusion of the flows. Rock types are primarily latitic and monzonitic; chemically the rocks are metaluminous in character and plot, with some scatter, in the alkaline fields (especially the quartz alkalic field) on a K20 vs Si02 variation diagram and are generally iron-poor (Keith, this volume).

Examples of igneous rocks that are assigned to the Hillsboro Assemblage include the Copper Flat stock near Hillsboro, New Mexico, possibly the andesite breccia unit of Callaghan (1953) near Silver City, New Mexico, possibly the Oro Grande pluton in southern New Mexico (Beane and others, 1975), and possibly the Mudersbach pluton in the Plomosa Mountains of western Arizona (Scarborough & Meader, 1983).

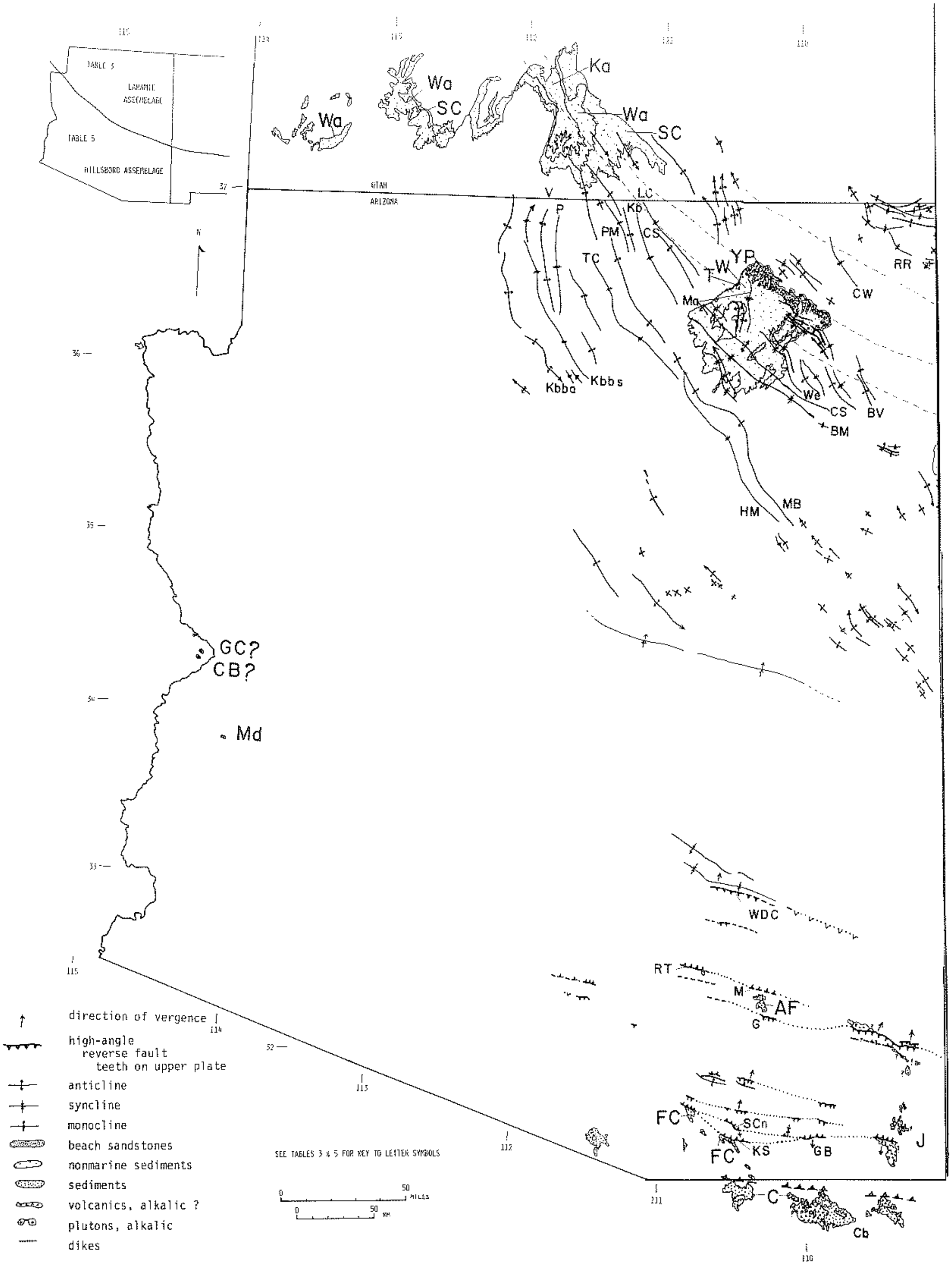
The rocks of the Hillsboro Assemblage unconformably overly strata of the Bisbee Group of probable Albian-Cenomanian age (about 94 Ma) with general angular discordance. The upper contact of the Hillsboro Assemblage with the later Tombstone Assemblage is rarely present. However, in the Little Hatchet Mountains of southwestern New Mexico (Zeller, 1970) the Ringbone Formation, which is herein assigned to the Hillsboro Assemblage, is angularly truncated by Hidalgo Volcanics, which are assigned to the Tombstone Assemblage and are of Maestrichtian age.

Structures of the Hillsboro Assemblage

The structural features of the Hillsboro Assemblage appear to be block uplifts that generally trend east-west to west-northwest (Figure 3). These wedge uplifts are bounded by steep, high-angle, reverse faults with typical dips of about 60 degrees. Vertical stratigraphic throws range from 1 to 6 km with horizontal throws of 1 to 3 km. Available data, though sketchy, indicate that these wedge uplifts are roughly symmetrical with reverse faulting directed both to the north and south respectively on each side of the uplift.

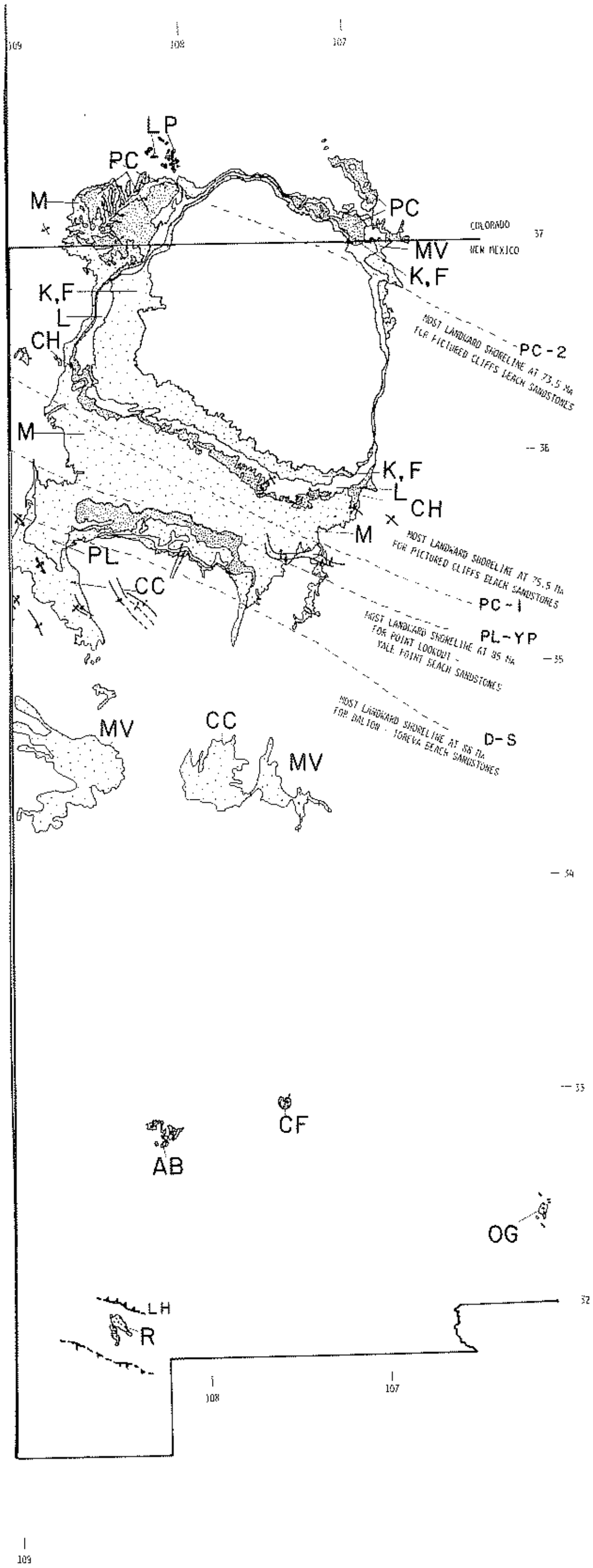
Many of the structures occur along faults that were active in Late Jurassic to Early Cretaceous time during deposition of the Glance Conglomerate (Bilodeau, 1978; Bilodeau and Lindberg, 1983). Many of these faults are parallel to structural elements of the Texas Zone and probably are reactivations of Precambrian faults in the Texas Zone, a west-northwest-trending zone of high-angle faults that probably originated about 1400 Ma (Swan, 1976). One of the best examples of these block uplifts is the Government Butte uplift south of Tombstone; it is bounded on the south by reverse faults in the northernmost Mule Mountains and bounded on the north by the Prompter fault (Gilluly, 1956).

Accumulations of sedimentary rocks of the Hillsboro Assemblage consistently occur along or near



early initial Laramide orogeny

Figure 3. Map of Laramie and Hillsboro Assemblages of the early initial Laramide orogeny in



Arizona and vicinity.

Table 3. Examples of Laramie Assemblage of the early initial Laramide orogeny

	SYMBOL	EXAMPLES	REFERENCES
SEDIMENTS	CC	Crevasse Canyon Fm.	New Mexico Geol. Soc., 1982
	CH	Cliff House Fm.	Hintze, 1973; 1975
	F	Fruitland Fm.	Cumella, 1981, 1983
	K	Kirtland Fm.	Molenaar, 1977, 1983
	Ka	Kaiparowits Fm.	Hintze, 1973; 1975
	L	Lewis Sh.	Cobban & Hook, 1984
	M	Menefee Fm.	Cumella, 1981; NMGS, 1982
	MV	Mesa Verde Fm.	NMGS, 1982
	PL	Point Lookout Ss.	Peterson & Kirk, 1977
	SC	Straight Cliffs Fm.	Hintze, 1973; 1975
	T	upper Toreva Fm.	Repenning & Page, 1956
	W	Wepo Fm.	Repenning & Page, 1956
	Wa	Wahweap Ss	Hintze, 1973; 1975
	YP	Yale Point Ss.	Repenning & Page, 1956
MAG	LP	La Plata, Colo.	Tweto, 1979
STRUCTURES	BM	Black Mesa syncline	Kelley, 1955; Davis, 1975a
	BV	Beautiful Valley syn.	Kelley, 1955; Davis, 1975a
	CS	Cow Springs anticline	Kelley, 1955; Davis, 1975a
	CW	Chinle Wash syncline	Kelley, 1955; Davis, 1975a
	HM	Howell Mesa syncline	Kelley, 1955; Davis, 1975a
	Kb	Kaibito syncline	Kelley, 1955; Davis, 1975a
	Kbba	Kaibab anticline	Kelley, 1955; Davis, 1975a
	Kbbs	Kaibab syncline	Kelley, 1955; Davis, 1975a
	LC	Last Chance syncline	Kelley, 1955; Davis, 1975a
	MB	Mount Beautiful ant.	Kelley, 1955; Davis, 1975a
	Ma	Maloney syncline	Kelley, 1955; Davis, 1975a
	P	Paria syncline	Kelley, 1955; Davis, 1975a
	PM	Preston Mesa anticline	Kelley, 1955; Davis, 1975a
	RR	Red Rock syncline	Kelley, 1955; Davis, 1975a
	TC	Tuba City syncline	Kelley, 1955; Davis, 1975a
	V	Vermilion anticline	Kelley, 1955; Davis, 1975a
	We	Wepo syncline	Kelley, 1955; Davis, 1975a
		Maximum landward shrln.	Cobban, 1974; Molenaar, 1983
	D-S	Dalton-Toreva shln.	Cobban, 1974; Molenaar, 1983
	PC-1	Pictured Cliffs-75.5 Ma	Cobban, 1974; Molenaar, 1983
	PC-2	Pictured Cliffs-73.5 Ma	Cobban, 1974; Molenaar, 1983
	PL-YP	Point Lookout-Yale Point	Cobban, 1974; Molenaar, 1983
RESOURCES		Black Mesa mine	Peirce & Wilt, 1970
		San Jan Basin	Wilson, 1977
		Kaiparowits Basin	Keith, 1970
		uranium in Menefee Fm.	Chenoweth, 1977

Table 5. Examples of Hillsboro Assemblage of the early initial Laramide orogeny

	SYMBOL	EXAMPLES	REFERENCES
SEDIMENTS	AF	American Flag Fm.	Creasey, 1967; Hayes, 1970
	C	Cabullona Gp.	Taliaferro, 1933
	FC	Ft. Crittenden Fm.	Drewes, 1971c; Hayes, 1970
	J	Javelina Fm.	Zeller, 1970
	R	Ringbone Fm.	Zeller, 1970
MAGMATISM	AB	Andesite breccia	Callaghan, 1953
	CB	Copper Basin	
	CF	Copper Flat stock	Thorman&Drewes,1981;Hedlund,1977
	GC	Gene Canyon	
	Md	Mudersbach pluton	Scarborough & Meader, 1983
	OG	Oro Grande stock	Beane and others, 1975
STRUCTURES	Cb	Cabullona basin	Taliaferro, 1933
	G	Geesman flt	Creasey, 1967
	GB	Government Butte	Hayes, 1970
	KF	Kino Springs Flt	Hayes & Raup, 1968
	LH	L. Hatchet Mts.	Zeller, 1970
	M	Mogul flt	Creasey, 1967
	RT	Ragged Top flt	Banks & Dockter, 1976
	SCn	Sawmill Canyon flt	Drewes, 1972b
	WDC	Winkelman-Deer Creek	Simons, 1964
RESOURCES	CF	Hillsboro	Dunn, 1983; Fowler, 1982
		Golden Rule mine	Keith, 1973
		Easter Sunday mine	Keith & others, 1983
		Plomosa Pass	Keith, 1978

faults that trend east-west to west-northwest. The best exposures of these faults suggest that there is at least one episode of reverse separation. Examples of faults which have nearby accumulations of Hillsboro Assemblage sediments (Table 5 and Figure 3) include: the Sawmill Canyon fault zone in the Santa Rita Mountains, where Late Cretaceous movement allowed deposition of the Fort Crittenden Formation (Lutton, 1958; Drewes, 1972b); the Kino Springs fault zone in the northern Huachuca Mountains where Fort Crittenden Formation is preserved (Hayes and Raup, 1968); the Geesman and Mogul fault zones in the Santa Catalina Mountains where American Flag Formation is preserved (Creasey, 1967); and the Ragged Top fault zone in the Silver Bell Mountains where the lower arkose of the Claflin Ranch Formation is preserved (Banks and Dockter, 1976).

In addition, common angular unconformities beneath strata of the Hillsboro Assemblage in the Cabullona basin (Taliaferro, 1933), Little Hatchet Mountains (Zeller, 1970), Winkelman-Deer Creek area (Simons, 1964), northern Empire Mountains (Finnell, 1971), and Government Butte area south of Tombstone (Gilluly, 1956) provide strong evidence for activity along east-west trending faults during sedimentation of Hillsboro Assemblage formations.

Rounded clasts in alluvial fan deposits and debris flow deposits in sedimentary sequences of the Hillsboro Assemblage can be matched with lithologies on the upthrown side of the faults. For example, a major west-northwest-striking fault with reverse separation forms the north boundary of the Sawmill Canyon fault zone in the central Santa Rita Mountains (Lutton, 1958; Drewes, 1972b). In the hanging wall north of the fault are Precambrian granite and 'Pinal Schist, while Fort Crittenden Formation of the Hillsboro Assemblage is exposed south of the fault and contains prominent clasts of the granite and schist.

In southwestern New Mexico the Ringbone Formation of Zeller (1970) angularly overlies the Mojado Formation of Albian-Cenomanian age. The maximum exposed thickness of Ringbone Formation in the vicinity of Playas Peak in the Little Hatchet Mountains is more than 7500 feet. The widespread outcrops of Ringbone in the central Little Hatchet Mountains occur about 4 miles north of a west-northwest striking, steeply south-dipping, reverse fault that juxtaposes porphyritic megacrystic granite of probable Precambrian age (1400 Ma?) against Horquilla Formation of Pennsylvanian-Permian age. Conglomerates that are common near the base and in the upper part of the Ringbone Formation contain abundant cobbles that are mostly derived from Paleozoic limestones. The only presently exposed outcrop of Paleozoics in the Little Hatchet Mountains is just north of the fault and could have been the source of limestone clasts in the Ringbone Formation. It is significant that at least 16,500 feet of Cretaceous strata are regionally present above the Paleozoic section. Thus, at least 17,000 feet of structural relief must have developed after deposition of the Mojado Formation (post-Cenomanian) in order to expose the Paleozoic section south of the Ringbone basin to provide Paleozoic clasts within the Ringbone Formation. In the northern Coyote Hills four miles north of the most northerly outcrops of Ringbone, another large east-west trending zone of folding and faulting has been mapped by Thorman (1977) that could have been the northern boundary of the basin within which the Ringbone Formation was deposited.

Age of the Hillsboro Assemblage

Regional evidence suggests that tectonic features of the Hillsboro Assemblage developed after the Bisbee Group (after Early Cretaceous or after about 95 Ma) and before the Tombstone Assemblage (before Late Cretaceous or before about 80-75 Ma). For example, in the western end of the Tombstone Hills near Bronco Hill and Lewis Springs, Gilluly (1956) observed the Bisbee Formation (middle Cretaceous) had been sharply rotated around east-west strikes and was angularly overlain by Bronco Volcanics (of our Tombstone Assemblage). From this and other relationships Gilluly (1956) interpreted the presence of a first stage, north-south compressive, post-Comanche (Bisbee Group) deformation. Similarly, the exotic block member of the Salero Formation of the Tombstone Assemblage (probably 75-80 Ma) unconformably overlies steeply dipping Bisbee strata that are folded around upright, tight anticlines and synclines in the Empire Mountains (Drewes and Finnell, 1968; Keith and Wilt, 1978).

Direct dates on strata of the Hillsboro Assemblage are mostly those obtained from fossils (freshwater invertebrates, vertebrates such as dinosaur bones, and petrified wood) that have been obtained from the shale member of the Fort Crittenden Formation. The fossils collectively indicate a Late Cretaceous (Santonian to Maestrichtian) age of 85 to 65 Ma for the Fort Crittenden Formation (Drewes, 1971c). A more restricted age of Santonian to early Campanian (85 to 75 Ma) for sedimentary rocks of the Hillsboro Assemblage is more likely as volcanic rocks of the lower part of the overlying Tombstone Assemblage have yielded numerous age dates from 73 to 76 Ma in southeastern Arizona.

Age dates on igneous rocks of the Hillsboro Assemblage show that they become younger eastward. For example, in western Arizona the Mudersbach pluton is dated at about 87 Ma (Chuchla, personal communication, 1983; Reynolds and others, 1985). To the east, in the Hillsboro area of New Mexico, the Copper Flat stock, which is chemically similar to the Mudersbach pluton, has yielded a K-Ar age date on biotite that is near 75 Ma (Hedlund, 1977). Still farther east in the Oro Grande mining district, the chemically similar Oro Grande pluton has yielded a biotite, K-Ar date of 47 Ma (Beane and others, 1975).

Resources of the Hillsboro Assemblage

Mineral resources related to the Hillsboro Assemblage mainly consist of epigenetic, copper-gold, hydrothermal systems that are closely associated with quartz alkalic magmatism. The best documented copper-gold system of the Hillsboro Assemblage is the Copper Flat porphyry copper deposit northeast of Hillsboro in Sierra County, New Mexico (Dunn, 1982). The copper-bearing specularite skarn at Mudersbach in the central Plomosa district of Arizona is another example of quartz alkalic metallogeny.

Late Initial Laramide Orogeny

DENVER ASSEMBLAGE

Name

The name Denver Assemblage is given to sedimentary formations deposited in asymmetrical synclinal downwarps that predominantly occur east of east-facing basement uplifts following the definition of 'Denver-type basins' by Chapin and Cather (1981). The Denver Assemblage is present on the Colorado Plateau and in the Rocky Mountains (Figure 4) and is approximately coeval with the Tombstone Assemblage of the Basin and Range Province. The assemblage is named for rocks deposited in the Denver Basin east of the east-facing Front Range uplift of Maestrichtian age (Morse, 1979). The Denver Basin is designated as a reference area for the Denver Assemblage. Sedimentation of the Denver Assemblage took place with easterly paleoflows and the formations exhibit proximal to distal facies distribution from west to east. Sedimentary rocks of the Denver Assemblage are predominantly coarse-grained arkoses that contain coarse intraformational conglomerates. General characteristics of rocks, structures, and resources of the Denver Assemblage are summarized in Table 6.

Table 6. Examples of Denver Assemblage of the late initial Laramide orogeny

SEDIMENTS	MAGMATISM	STRUCTURES	RESOURCES
coarse arkose & congl. alluvial fans, plains, & meander belts with East flowing paleoslopes asymmetrical synclinal downwarps East of E-facing basement uplifts, wedge-shaped unidirectional facies distribution unconformity at top	igneous rocks not common except as clasts & local volcanic flows	N trending, E-facing basement uplifts N trending monolines N-trending, open, synclinal downwarps deep on West next to steep E face of uplift	

Rocks of the Denver Assemblage

In Arizona no sedimentary components of the Denver Assemblage are preserved, although they are widespread in New Mexico and also occur in Utah and Colorado (Table 7 and Figure 4). In southwestern Utah the Claron Formation was permissively contemporaneous in part with Laramide reverse fault movement on faults with east-directed movement, such as the Grand Wash, Hurricane, Toroweap, Sevier, Beaver Dam Wash, Gunlock, Cedar Pocket Canyon, and Shebit faults (Lovejoy, 1976) and is assigned to the Denver Assemblage. In south central Utah, the Canaan Peak Formation (Bowers, 1972) is assigned to the Denver Assemblage and may have been derived from the northern end of the Kaibab uplift.

In the San Juan basin of northwestern New Mexico, the Ojo Alamo Sandstone is assigned to the Denver Assemblage. The Ojo Alamo Sandstone had a source area to the northwest (Powell, 1973) which could have been the Hogback monocline. The Ojo Alamo Sandstone differed from the later Nacimiento Formation in that it did not include volcanic clasts (Fassett, 1985). Paleoflow data indicate that Ojo Alamo streams flowed over the Nacimiento uplift, which did not appear until Eocene time. Other possible Denver Assemblage formations include the Cub Mountain Formation in south central New Mexico and the Poison Canyon and Raton Formations in northern New Mexico (Figure 4).

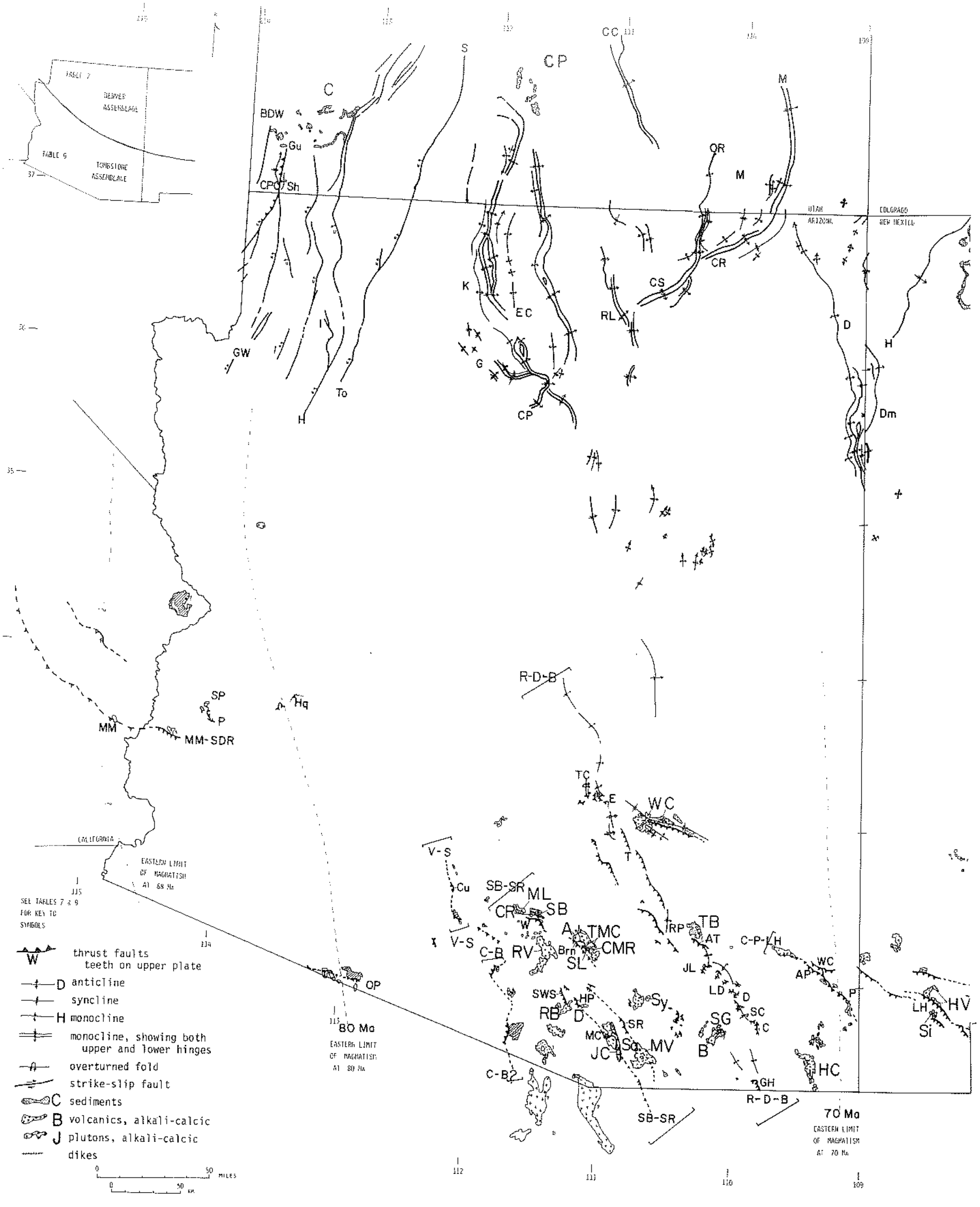
Structures of the Denver Assemblage

Principal structural features of the Denver Assemblage are large, north-trending, east-facing, basement uplifts that are paired with asymmetrical 'Denver-type' basins in the sense of Chapin and Cather (1981). Denver Assemblage uplifts have sharp, generally north-trending, steeply dipping, east-facing monoclines along their east front. Denver Assemblage basins are also asymmetric with the deepest and thickest part of the basin to the west bordering the east side of the uplifts (Chapin and Cather, 1981).

Sedimentation in New Mexico that is associated with east-facing monoclines includes the Cub Mountain Formation east of the Tularosa uplift in central New Mexico and the Poison Canyon and Raton formations east of the Sangre de Cristo uplift in north central New Mexico. In southern Utah the Canaan Peak Formation (Bowers, 1972) is permissively derived from the northeastern extension of the Kaibab uplift.

Table 7. Examples of Denver Assemblage of the late initial Laramide orogeny

	SYMBOL	EXAMPLES	REFERENCES
SEDIMENTS		Dawson Arkose	Chapin & Cather, 1981
		Denver, Arapaho Fm.	Morse, 1979
		Farrer, Tuscher Fm.	Lawton, 1983
	C	Claron Fm.	Lovejoy, 1976; Hintze, 1975
	CM	Cub Mountain Fm.	Hintze, 1975
	CP	Canaan Peak Fm.	Bowers, 1972
	LR	Love Ranch Fm.	Seager, 1975
	OA	Ojo Alamo Fm.	Powell, 1973; Fassett, 1985
	PC	Poison Canyon Fm.	Fassett, 1985
	R	Raton Fm.	Molenaar, 1983
MAG	RC	Rico stock	Tweto, 1979
STRUCTURES	BDW	Beaver Dam Wash flt.	Lovejoy, 1976
	CPC	Cedar Pocket Canyon flt.	Lovejoy, 1976
	GW	Grand Wash flt.	Lovejoy, 1976
	Gu	Guhlock flt.	Lovejoy, 1976
	H	Hurricane flt.	Lovejoy, 1976
	S	Sevier flt.	Lovejoy, 1976
	Sh	Shebit flt.	Lovejoy, 1976
	To	Toroweap flt.	Lovejoy, 1976
	CP	Coconino Point mon.	Davis & Kiven, 1975
	CR	Comb Ridge mon.	Davis & Kiven, 1975
	CS	Cow Springs mon.	Davis & Kiven, 1975
	Dm	Defiance mon.	Davis & Kiven, 1975
	G	Granview mon.	Davis & Kiven, 1975
	H	Hogback mon.	Davis & Kiven, 1975
	K	Kaibab	Davis & Kiven, 1975
	OR	Organ Rock mon.	Davis & Kiven, 1975
	RL	Red Lake mon.	Davis & Kiven, 1975
		Front Range uplift	Bryant & Naesser, 1980
	Ar	Archuleta uplift	N.M.G.S. map, 1982
	CC	Circle Cliffs uplift	Kelley, 1955
	D	Defiance uplift	Davis, 1975, 1978
	EC	Echo Cliffs uplift	Davis, 1975a, 1978a
	L	Lucero uplift	N.M.G.S. map, 1982
	M	Monument uplift	Davis & Kiven, 1975
	Mz	Monzano uplift	N.M.G.S. map, 1982
	SC	Sangre de Cristo up.	Chapin & Cather, 1981
	Tu	Tularosa uplift	N.M.G.S. map, 1982



late initial Laramide orogeny

Figure 4. Map of Denver and Tombstone Assemblages of the late initial Laramide orogeny in Arizona and vicinity.

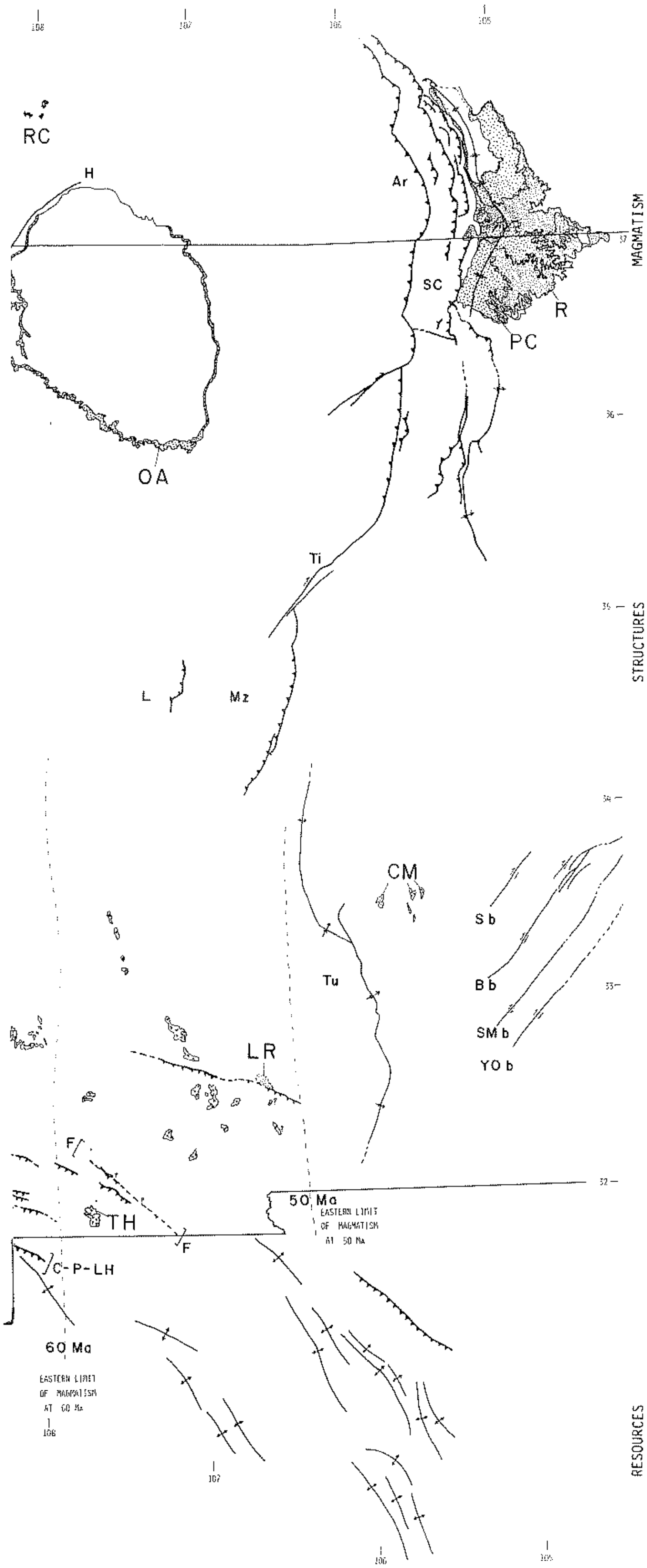


Table 9. Examples of Tombstone Assemblage of the late initial Laramide orogeny

	SYMBOL	EXAMPLES	REFERENCES
MAGMATISM	CR	Claflin Ranch Fm.	Banks & Dockter, 1976
	Sa	low. Salero Fm.	Drewes, 1971a,b,c
	TB	Teran Basin	Grover, in progre:UA MS thesis
	WC	low. Williamson Canyon volc.	Simons, 1964; Krieger, 1968a,b
	TMC	Tucson Mtn. Chaos	Brown, 1939; Hayes & Drewes, 1968
	A	Amole stock	Bolin, 1976
	B	Bronco Volc.	Gilluly, 1956
	CMR	Cat Mtn. Rhyolite	Brown, 1939; Bikerman, 1962
	D	Demetrie Volc.	Thoms, 1966; Cooper, 1971
	HC	Hunt Canyon and.	Epis, 1956
	HV	Hidalgo Volc.	Lasky, 1947; Zeller, 1970
	JC	Josephine Cany. Dior.	Drewes, 1976
	ML	Mt. Lord Volc.	Watson, 1968; Dockter, 1977
	MV	Meadow Valley	Simons, 1972
	RB	Red Boy Rhyolite	Thoms, 1966; Cooper, 1971
	RV	Roskruge Volcanics	Bikerman, 1968
	SB	Silver Bell Fm.	Richard & Courtright, 1960
	SG	Schiefflin Grndior.	Newell, 1977, 1978
	SL	Silver Lily dikes	Drewes, 1970
	Sa	Salero Fm.	Drewes, 1968, 1971
	Si	Silvanite stock	Zeller, 1970; Lasky, 1947
	Sy	Sycamore stock	Finnell, 1971
	TH	Tres Hermanas pluton	Hoffer, 1970
	WC	Williamson Can. Volc.	Simons, 1964; Krieger, 1968a,b
STRUCTURES	Ti	Tijeras flt	
	Bb	Border buckle	New Mexico Geol. Soc., 1982
	SMb	Six Mile buckle	New Mexico Geol. Soc., 1982
	Sb	Serrano buckle	New Mexico Geol. Soc., 1982
	YOb	Y. O. buckle	New Mexico Geol. Soc., 1982
	MM-SDR	Mule Mtns.-S. Dome Rock zone	
	MM	Mule Mts. CA th.flt.	Tosdal, 1982
	P	Plomosa zone	
	Hq	Harquahala Mtns.	Reynolds & others, 1980
	SP	S. Plomosa Mts.	Scarborough & Meader, 1983
	OP	Organ Pipe zone	
	OP	Quitobaquito flt.	Haxel & others, 1984
	V-S	Vekol-Sheridan Mtn. zone	
	Cu	Copperosity th.flt.	Dockter & Keith, 1978
	C-B	Comobabi-Baboquivari zone	
	SB-SR	Silver Bell-Santa Rita zone	
	Brn	Brown Mtn.	Mayo & Davis, 1976
	HP	Helmet Peak	Jansen, 1982
	MC	Montosa Cany. th.flt.	Drewes, 1972b
	SR	Adobe Cnyn flt, S.Ritas	Drewes, 1971a,b
	SWS	SW Sierrita Mts.	Drewes & Cooper, 1973
	W	Waterman Mts.	McClymonds, 1959
	R-D-B	Ray-Dragoon-Bisbee zone	
	AT	Antelope Tank flt.	Cooper & Silver, 1964
	C	Courtland area	Gilluly, 1956; McRea, 1966
	D	Dragoon Mts.	Cooper & Silver, 1964
	E	Emporer flt, Ray	Cornwall & others, 1971
	GH	Gold Hill (Bisbee)	Hayes & Landis, 1964
	JL	Johnny Lyon Hills	Cooper & Silver, 1964
	LD	L. Dragoon Mts.	Cooper & Silver, 1964
	RP	Redington Pass	Thorman & Drewes, 1981
	SC	Silver Cloud fold/thst	Keith & Barrett, 1976; Drewes, 1976a
	T	Tortilla Mts.	Krieger, 1968; 1974, Keith, 1976
	TC	Telegraph Canyon, Ray	Theodore & others, 1978
	C-P-LH	Chiricahua-Peloncillo-Little Hatchet zone	
	AP	Apache Pass flt.	Sabins, 1957
	LH	Little Hatchets	Zeller, 1970
	P	Portal area	Cooper, 1959; Drewes, 1981a,b
	WC	Wood Canyon flt.	Gillerman, 1958
	F	Florida zone	Corbitt & Woodward, 1973
RESOURCES	A	Amole dist.	Brown, 1939; Keith, 1974
	B	Tombstone	Butler & Wilson,1938;Devere,1978
	SR	Mt. Wrightson	Keith, 1975
	Sa	Salero dist.	Schrader, 1915; Keith, 1975
	Si	Eureka & Silvanite, NM	Lasky, 1947

Uplifts in northeastern Arizona (Davis and Kiven, 1975; Davis, 1978a) that lack obvious sedimentation assignable to the Denver Assemblage, but that by analogy are probably related to tectonics of the Denver Assemblage, include the Kaibab, Echo Cliffs, Monument and Defiance uplifts and their associated north-trending monoclines (Figure 4).

Age of Denver Assemblage

Although there is general agreement that the monoclines postdate the northwest-trending anticlines (Kelley, 1955; Davis, 1978a), exact timing via sedimentation for Denver Assemblage uplifts is lacking in Arizona. However, timing of Arizona structures can be inferred by strong analogy to similar structures assigned to the Denver Assemblage that have been well dated in Colorado and Utah. For example in central Colorado, uplifts such as the Sawatch and Front Range uplifts, which are assigned to the Denver Assemblage, began to rise about 67.5 Ma and were uplifted to 7.5 km by 64.3 Ma (Bryant and Naesser, 1980). In central Utah sedimentation of Denver Assemblage is recorded in the Tuscher and Farrer formations which are 74 to 72.5 Ma (Lawton, 1983).

Structural development of Denver Assemblage in Arizona can be inferred by analogy to have begun in Arizona and northwestern New Mexico in Campanian time about 75 Ma. The Kaibab monocline in Arizona-Utah does have a syntectonic sedimentational unit that is permissively assignable to the Denver Assemblage. Sedimentology of the Canaan Peak Formation, which contains Campanian palynomorphs in the lower 65 m of the formation, suggests derivation, at least in part, from the rising Kaibab monocline about 75 Ma (Bowers, 1972).

TOMBSTONE ASSEMBLAGE

Name

The name Tombstone Assemblage was given by Keith (1984) to the rocks of the early part of the Laramide orogeny that postdate the Hillsboro Assemblage. The Tombstone Assemblage is present in the Basin and Range Province of Arizona and New Mexico (Figure 4) and is approximately coeval with the Laramie Assemblage farther north. Rocks, structures, and mineral deposits of the Tombstone Assemblage are well developed near Tombstone, Arizona, (Gilluly, 1956; Newell, 1974; 1978) and this area is designated as a type area for the Tombstone Assemblage. Reference areas are the Deer Creek - Saddle Mountain area in Pinal and Graham Counties (Keith, Ray-Superior area, this volume), the Little Hatchet Mountains (Zeller, 1970; Loring and Loring, 1980), and the Santa Rita Mountains southeast of Tucson (Drewes, 1972b). General characteristics of rocks, structures, and resources of the Tombstone Assemblage are given in Table 8.

Table 8. Characteristics of Tombstone Assemblage of the late initial Laramide orogeny

SEDIMENTS	MAGMATISM	STRUCTURES	RESOURCES
continental clastics, cgl,ss,sltst,volcani-clastics large exotic blocks seds at base of thick volcanics continental fluvial near large volcanic centers unconformable on mid-Cret. strata	abundant pyroclastics some epizonal qtz. monz. porphyritic stocks low= and.-dac. breccia up= dac.-rhy. ignimbrite flows & ash flows metaluminous, subalkaline, alkali-calcic gen. Fe-poor, hydrous, oxidized	NW-striking, NE-directed folds & low-angle thrusts shortening 1-10 km.	mesothermal Pb-Zn-Ag vns and replacement deposits

Rocks of the Tombstone Assemblage

Sedimentary rocks of the Tombstone Assemblage typically occur near the base of the assemblage as continental clastic rocks. The clastic section includes conglomerates with generally well-rounded clasts, volcanic arkoses, and local, fluvially deposited siltstones and shales. The clastic section of Tombstone Assemblage formations are particularly noted for locally significant, exotic blocks of Mesozoic and Paleozoic rocks that are sometimes as large as small buildings. The sedimentary rocks typically grade upward into laterally extensive volcanic piles and locally include intraformational volcaniclastic sedimentary rocks. Thicknesses for sedimentary rocks of the Tombstone Assemblage are highly variable, depending upon the thickness of the associated volcanic piles. Volcaniclastic members can be as much as 2000 to 2500 feet thick.

Examples of sedimentary rocks of the Tombstone Assemblage are shown on Figure 4 and are listed in Table 9. They include the arkosic fanglomerates, quartzites, and redbeds in the lower part of the Salero Formation in the Santa Rita Mountains (Drewes, 1971c), the Claflin Ranch Formation in the Silver Bell Mountains (Richard and Courtright, 1960; Banks and Dockter, 1976), conglomerates, sandstones, and siltstones intercalated within the lower Williamson Canyon volcanics near Saddle Mountain, Pinal County, Arizona (Krieger, 1968a,b; Simons, 1964), and the Tucson Mountain Chaos in the Tucson Mountains (Brown, 1939; Hayes and Drewes, 1968).

VOLCANIC ROCKS. The abundance of volcanic components in the Tombstone Assemblage is in marked contrast to the general lack of volcanics in the earlier Hillsboro Assemblage. Thicknesses of volcanic piles of the Tombstone Assemblage range up to more than 5000 feet. Volcanic rocks of the Tombstone Assemblage are abundant throughout southeastern Arizona and southwestern New Mexico, but are not present west of Casa Grande, Arizona, probably because of subsequent uplift during the latest part of the Laramide orogeny.

Examples of volcanic formations which are assigned to the Tombstone Assemblage are listed on Table 9 and are shown on Figure 4. They include the Williamson Canyon volcanics in the Winkelman to Klondyke areas (Simons, 1964; Krieger, 1968a,b), the Silver Bell Formation (Richard and Courtright, 1960) and Mt. Lord Volcanics (Watson, 1968; Dockter, 1977) of the Silver Bell Mountains, the Cat Mountain Rhyolite of the Tucson Mountains (Bikerman, 1962), the Demetrie Volcanics and Red Boy Rhyolite in the Sierrita Mountains (Thoms, 1966; Cooper, 1971), the welded tuff member of the Salero Formation (Drewes, 1971), the Bronco Volcanics in the western Tombstone Hills (Gilluly, 1956), the Hunt Canyon andesite in the Pedregosa Mountains (Epis, 1956), and the Hidalgo Volcanics in the Little Hatchet Mountains of southwestern New Mexico (Lasky, 1947; Zeller, 1970).

PLUTONIC ROCKS. In addition to widespread volcanism in Tombstone Assemblage rocks, numerous areas contain epizonal, monzo-dioritic to quartz monzonitic plutons that are locally associated with lead-zinc-silver mineralization. Many of these plutons were called 'barren' plutons in porphyry copper literature of the 1970's (Bolin, 1976). Examples of plutons that are assigned to the

Tombstone Assemblage include the Amole pluton in the Tucson Mountains (Bolin, 1976), the Elephant Head Quartz Monzonite and Josephine Canyon Diorite in the Santa Rita Mountains (Drewes, 1976b), the Sycamore stock in the Empire Mountains (Finnell, 1971), the Schiefflin Granodiorite and the Uncle Sam Porphyry of the Tombstone Hills (Gilluly, 1956; Newell, 1978), and the Eureka and Sylvanite stocks of the Little Hatchet Mountains in southwestern New Mexico (Lasky, 1947; Zeller, 1970).

Plutons of the Tombstone Assemblage are commonly porphyritic with more mafic phases containing up to 2% augite, 3-10% hornblende, 3-8% biotite, and accessory sphene, magnetite, and apatite. In the more mafic plutons, major minerals consist of 40-50% plagioclase, 5-15% quartz, and 10-30% orthoclase; the more felsic plutons are typically biotite quartz monzonite and contain 5-10% biotite with accessory sphene, apatite, and magnetite. Modal and chemical data for Tombstone Assemblage magmatism show that the magmatism is metaluminous, iron-poor, alkali-calcic, and hydrous (Keith, this volume).

Structures of the Tombstone Assemblage

Structures of the Tombstone Assemblage consist of folds and thrust faults that strike northwest in contrast to the the more east-west trends of the block uplifts of the preceeding Hillsboro Assemblage. The sense of tectonic transport on Tombstone Assemblage structures is consistently northeast- or east-directed in contrast to the bi-directional, north- or south-directed transport on structures of the Hillsboro Assemblage. Horizontal shortening along structures of the Tombstone Assemblage tended to be greater with shortening on individual low-angle thrust faults on the order of 1 to 10 km where documentation exists.

Examples of structures assigned to the Tombstone Assemblage are listed in Table 9 and are shown on Figure 4. They include: the Mule Mountains of southeastern California where Tosdal (1984) has estimated no more than 10 km of shortening based on offset dikes; the Ray area where no more than 8 km is apparent on the basis of an offset overturned fold (Keith, this volume); the central Dragoon Mountains where there is no more than 2 km of shortening (Keith and Barrett, 1976); and the Little Hatchet Mountains where there is probably no more than 10 km of shortening (cross-sections of Zeller, 1970).

Structures of the Tombstone Assemblage have been best documented in southeastern Arizona (Drewes, 1981b; Keith and Barrett, 1976). In southeastern Arizona folds and thrusts of the Tombstone Assemblage appear to be arranged into several belts separated by about 50-75 km (Table 9 and Figure 4). From west to east these are the Silver Bell - Santa Rita zone, the Ray - Dragoon - Bisbee zone, the Chiricahua - Peloncillo - Little Hatchet zone, and the Florida zone. Structural zones in southeasternmost California and southwesternmost Arizona may, with less certainty, be assigned to the Tombstone Assemblage. From west to east these include the Mule Mountains - Southern Dome Rock zone, the Organ Pipe zone, the Vekol - Sheridan Mountain zone, and the Comobabi - Baboquivari zone. Scattered north-northeast- to northeast-directed thrusts are present in the southern Plomosa Mountains and the Little Harquahala and Harquahala Mountains of western Arizona, but lack the documentation to show lateral connections in regional zones. Their transport direction and relative strato-tectonic position are similar to Tombstone Assemblage structures and they are therefore tentatively assigned to that map (Figure 4).

Age of Tombstone Assemblage

AGE OF STRUCTURES. Many of the northeast-directed thrusts and folds assigned to the Tombstone Assemblage are not stratigraphically well constrained. However, where stratigraphic control is present, the northwest-trending, northeast-directed thrust faults and folds are confined to Tombstone Assemblage strata or are intruded by younger calc-alkalic plutons of the Morenci Assemblage. One of the best examples of these relationships is the Montosa Canyon fault (Drewes, 1972b) which places Permian rocks over Cretaceous Bisbee Group with at least 3 km of stratigraphic throw. This thrust fault is related to the Montosa tear fault which is shown by Drewes (1972b) to be depositionally overlain by the Welded Tuff Member (73 Ma) of the Salero Formation. In the Sierrita Mountains a northwest-striking, southwest-dipping thrust fault is shown on Cooper's (1973) map to be intruded by the Ruby Star Granodiorite, which is dated at 64 Ma and is related to the porphyry copper mineralization of the Morenci Assemblage in the Sierrita-Esperanza and Pima districts.

In the western Tucson Mountains, northeast-directed, generally high-angle, reverse faults that place Recreation Redbeds of Jurassic age against Amole Arkose of Lower Cretaceous age (Mayo, 1968; Mayo and Davis, 1976) are intruded by the Silver Lily dike swarm (70 Ma) (Drewes, 1981b). At the Ray porphyry copper mine in Pinal County, the low-angle Emperor thrust fault, which places Pinal Schist over east-dipping Apache Group of Precambrian age, is part of a family of similar east-directed thrust faults (Metz and others, 1968; Keith, 1983; this volume). The Emperor fault does not displace zoning patterns in the Ray porphyry copper system (Phillips and others, 1974), which indicates the faulting was pre-65 Ma. The Emporer fault was probably pre-70 Ma, because a rhyodacite porphyry intrudes a similar (but now tilted) thrust in the central Tortilla Mountains (Krieger, 1974; Keith, 1983b; Keith and Damon, unpub. data) and intrudes the Tortilla quartz diorite dated at 70 Ma (Banks and others, 1972; Krieger, 1974).

Another similar set of east-directed thrust faults has been mapped in the Little Hatchet Mountains of southwestern New Mexico (Lasky, 1947; Zeller, 1970). These faults occurred after deposition of the Hidalgo Volcanics (66-62 Ma) and were intruded by diorite sills at 58 Ma (Loring and Loring, 1980).

Some of the ductile shear zone deformation in the Whipple Mountains may be assignable to Tombstone Assemblage. Here, southwest-dipping mylonites with dominantly northeast-directed 'S-C' fabric may be synkinematic with metaluminous and peraluminous plutons of 89 to 73 Ma (Davis and others, 1980; Wright and others, 1986). These mylonites are intruded by peraluminous, trondjheimitic aplites that appear from chemistry to be differentiates of the 89 Ma peraluminous plutons (Anderson and Rowley, 1981).

Another area where relatively tight timing is indicated for thrust faults of possible northeast-directed transport is in the Organ Pipe National Monument. Here, Haxel and others (1984) show the Quitobaquito thrust fault cutting a pluton of Santonian age that is probably assignable to the Tombstone Assemblage. K-Ar cooling ages from the Quitobaquito thrust zone are about 55-60 Ma and probably indicate a minimum age for metamorphism and final movement associated with the thrusting (Haxel and others, 1984).

In summary, ages associated with east-directed shearing and thrusting in western Arizona that are possibly assigned to Tombstone Assemblage are about 85 to 75 Ma. In the Tucson region, northeast-directed thrusts are about 75 to 70 Ma; whereas in the Lordsburg region of southwestern New Mexico, northeast-directed thrusting is about 62 to 58 Ma. Thus, there appears to be a definite younging of northeast-directed thrust faults from the west in California across Arizona to the east in New Mexico.

AGE OF MAGMATISM. Igneous rocks of the Tombstone Assemblage have yielded abundant radiometric age dates and also show a clear trend of younger ages to the east. Examples of magmatism with defined magma series chemistry (Keith, this volume) follow. In the Roskruge Mountains west of Tucson, the Roskruge Volcanics are 78 to 74 Ma (Bikerman, 1968). In the Tucson Mountains, rocks of the Tombstone Assemblage (Amole pluton, Cat Mountain Rhyolite) yield numerous K-Ar dates ranging from 76 to 70 Ma (Damon and Bikerman, 1964; Drewes, 1981b). North of Tucson in the Winkelman region, the Williamson Canyon Volcanics have yielded K-Ar dates between 79 and 74 Ma (Koski and Cook, 1982; Reynolds and others, 1985). Farther east in the Tombstone Hills, the Uncle Sam Porphyry and Schieffin Granodiorite have yielded K-Ar age dates ranging from 76 to 72 Ma (Newell, 1978). Still farther east in the Little Hatchet Mountains of New Mexico, the Hidalgo Volcanics have yielded K-Ar dates from 70 to 65 Ma (McDowell, 1971). Finally, magmatism of the Tombstone Assemblage in the El Paso region, namely the Campus Andesite (Hoffer, 1970) and Tres Hermanas pluton (Chapin, pers. comm., 1982), has yielded dates of 51-47 Ma.

Thus, Tombstone Assemblage magmatism in southern Arizona in the general Tucson region is well dated at about 80 to 70 Ma, whereas Tombstone Assemblage magmatism in southwestern New Mexico is 70 to 64 Ma and in the El Paso area is 51-47 Ma. In any one locality, magmatism occupied a 5 to 10 million year interval.

Resources of the Tombstone Assemblage

The mineral resources of the Tombstone Assemblage consist of mesothermal lead-zinc-silver vein and replacement deposits typically associated with alkali-calcic stocks and dikes. The best documented and most famous examples are the silver mines of the Tombstone district in southeastern Arizona (Butler and Wilson, 1938; Devere, 1978). Additional mining districts of the Tombstone Assemblage are shown as Late Cretaceous (LK) on the map of metallic mineral districts of Arizona by Keith and others (1983), together with production data.

MORENCI ASSEMBLAGE

Name

The name Morenci Assemblage was given by Keith (1984) to the rocks of the middle Laramide that postdate Tombstone Assemblage and that predate Wilderness Assemblage within the Basin and Range Province of Arizona and New Mexico. Rocks, structures and mineral deposits of the Morenci Assemblage are especially well developed in the Morenci area (Langton, 1973) and this area is thus designated as the type area for the Morenci Assemblage.

Other well studied reference areas for the Morenci Assemblage are at Ray (Mineral Creek) in Pinal County (Phillips and others, 1974; Banks and others, 1972; Banks and Stuckless, 1973; Banks, 1974, 1977, 1982), in the Central district near Santa Rita in New Mexico (Hernon and Jones, 1968), at the Pima district south of Tucson (Titley, 1982), and the Mineral Park district northwest of Kingman, Arizona (Wilkinson and others, 1982). General characteristics of rocks, structures, and resources of the Morenci Assemblage are listed in Table 10; examples are listed in Table 11 and are shown on Figure 5.

Table 11. Examples of Morenci Assemblage of the medial Laramide

	SYMBOL	EXAMPLES	REFERENCES
MAGMATISM	C	Cornelia Qtz. Monz.	Gilluly, 1946; Dixon, 1966
	CC	Copper Creek grndr.	Simons, 1964
	CM	Cimarron Mtns. pluton	Dockter & Keith, 1978
	CM I	Carrizo Mtns. lac.	
	CW	Chirreon Wash grndr.	Banks & others, 1977
	Cx	Christmas stock	Simons, 1964; Eastlick, 1968
	DC	Dos Cabezas	Drewes, 1981a,c
	GM	Granite Mtn. por. Ray	Ransome,1919; Banks & others,1972
	L	Leatherwood qtz. dior.	Creasey, 1967; Banks, 1976
	Lo	Lordsburg	Thorman & Drewes, 1978
	MP	Mineral Park pluton	Wilkinson & others, 1982
	P	Patagonia batholith	Simons, 1972, 1974
	RM	Red Mountain	Corn, 1975; Bodnar & Beane, 1980
	RS	Ruby Star Qtz. Monz.	Cooper, 1973
	S	Schultze Granite	Peterson, 1962
	SV	Safford Volcanics	Langton & Williams, 1982
	Sa	Sacaton	Balla, 1976
	ShR	Shorts Ranch and.	Damon & Bikerman, 1964
	TC	Texas Canyon	Cooper & Silver, 1964
	UM 1	Ute Mtn laccolith	
STRUCTURES	B	Bagdad	Titley, 1982;Titley & Hicks, 1966
	DS	Dripping Spring Mtns.	Banks & Krieger, 1977
	SB	Silver Bell	Watson, 1968
	T	Tortilla Mtns dikes	Schmidt, 1971; Keith, 1983
RESOURCES	C	Ajo	Gilluly, 1937; Dixon, 1966
	Cx	Christmas, AZ	Koski & Cook, 1982
	GH	Globe Hills, AZ	Peterson, 1962
	H	Helvetia, Rosemont	Schrader, 1915; Keith, 1974
	M	Morenci, AZ	Moolick & Durek, 1966
	MP	Mineral Park	Eidel & others, 1968
	MP	Wallapai	Schrader, 1909
	R	Ray, AZ	Metz & Rose, 1966; Banks, 1982
	RS	Twin Buttes, AZ	Barter & Kelly, 1982
	RS	Esperanza	Lynch, 1968; West & Aiken, 1982
	RS	Pima	Titley, 1982; Cooper, 1960
	SB	Silver Bell	Graybeal, 1982
	SMt	Saddle Mountain	Keith, 1983
	SM	San Manuel	Creasey, 1965; Thomas, 1966
	SR	Santa Rita, NM	Rose & Baltosser, 1966
	Su	Superior, AZ	Hammer & Peterson, 1968
	Ty	Tyrone, NM	Kolessar, 1982
	WC	Washington Camp	Lehman, 1978; Keith, 1978

Table 10. Characteristics of Morenci Assemblage of the medial Laramide orogeny

SEDIMENTS	MAGMATISM	STRUCTURES	RESOURCES
none	numerous epizonal stocks & small batholiths local sporadically preserved volcanics widespread regional NE to ENE striking dike swarms metaluminous subalkaline calc-alkalic Fe-poor, hydrous, oxidized	widespread NE to ENE striking regional dike swarms between E-W to ENE striking structural elements of the Texas Zone that moved in left-slip	large mesothermal disseminated porphyry copper systems locally containing skarns & vns Cu-Zn-Ag vns; Pb-Zn-Ag vns, skarns or replacements marginal to plutons Cu-Zn skarns adjacent to epizonal porphyritic plutons Composite, epigenetic mesothermal, zoned, disseminated porph. copper systems, with sev. zones in a large system

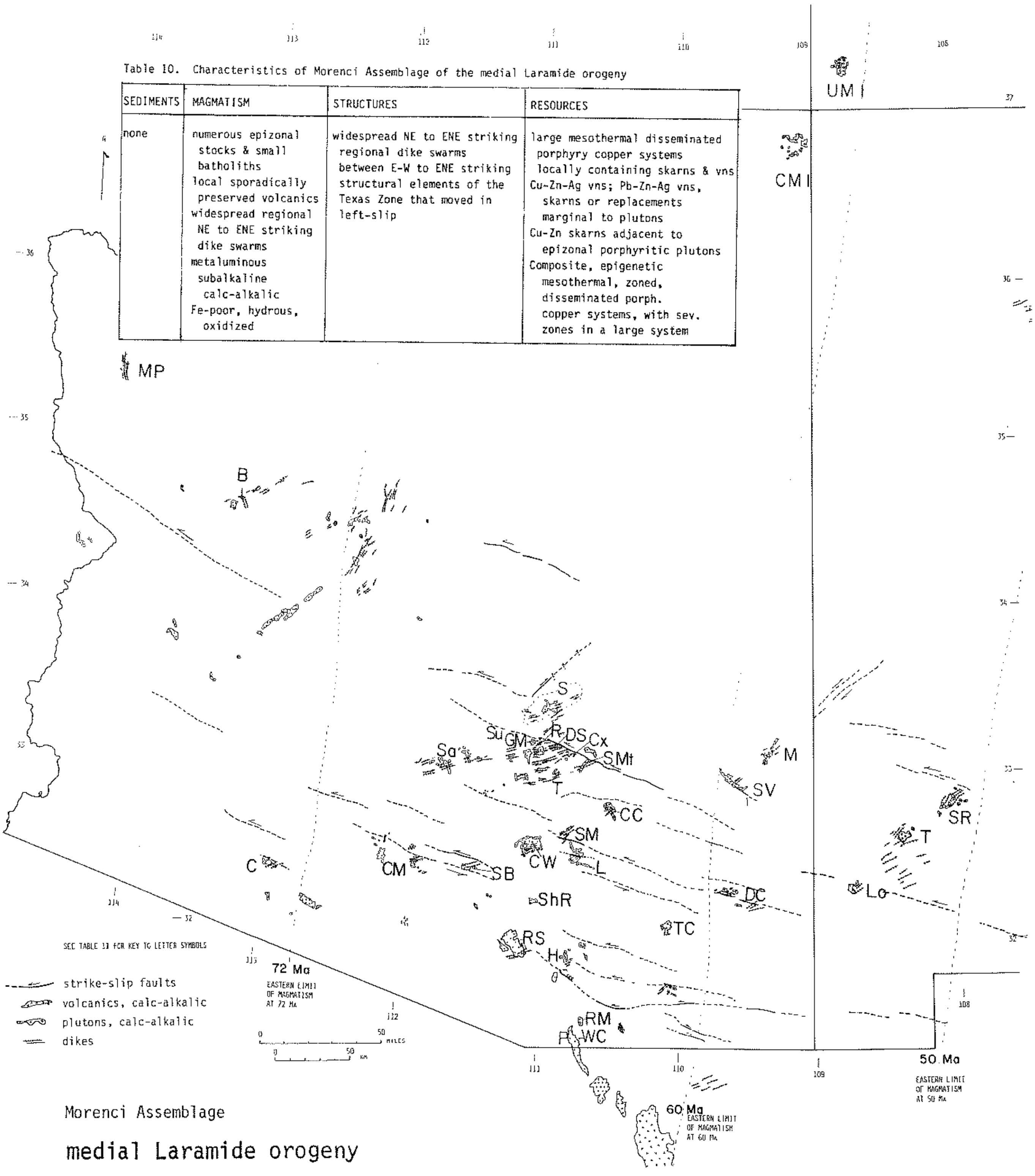


Figure 5. Map of Morenci Assemblage of the medial Laramide orogeny in Arizona and vicinity.

Rocks of the Morenci Assemblage

No sedimentary rocks are known from the Morenci Assemblage, in strong contrast to earlier Laramide assemblages. In fact, on the Colorado Plateau and Rocky Mountains a widespread unconformity is present in most of the basins and represents a hiatus during mid to late Paleocene. An example is the unconformity between the Ojo Alamo Sandstone (Denver Assemblage) and the Nacimiento Formation (Green River Assemblage) in the northern San Juan basin (Fassett, 1985).

The principal rock types of the Morenci Assemblage are plutonic, epizonal, porphyritic stocks of quartz diorite to granodiorite composition. Examples include the Cornelia Quartz Monzonite at Ajo (Gilluly, 1946), the Schultze Granite in the Superior area (Peterson, 1962), the Granite Mountain porphyry at Ray (Banks and others, 1972), the Mineral Park pluton in northwestern Arizona (Wilkinson and others, 1982), the Ruby Star Quartz Monzonite in the Sierrita Mountains (Cooper, 1973), the Leatherwood Quartz Diorite of the Santa Catalina Mountains (Creasey, 1967; Banks, 1976), the Chirreon Wash granodiorite in the Tortolita Mountains (Banks and others, 1977), and the Copper Creek granodiorite in the Galiuro Mountains (Simons, 1964).

Another conspicuous feature of Morenci Assemblage stratigraphy is the general lack of volcanics, although rhyodacitic volcanics of probable Morenci Assemblage exist at Red Mountain in Santa Cruz County (Corn, 1975; Bodnar and Beane, 1980) and are relatively widespread north of Safford (Baboon and Safford Volcanics of Langton and Williams, 1982).

Modal data for Morenci Assemblage plutons suggests that they have more total hydrous minerals (8 to 25% hydrous minerals) than Tombstone Assemblage plutons (6 to 15% hydrous minerals), especially in the more mafic phases. Modal and chemical data for Morenci Assemblage show that the magmatism is metaluminous, calc-alkalic, iron-poor, hydrous, and oxidized (Keith, this volume).

Structures of the Morenci Assemblage

Structural features of the Morenci Assemblage consist of regional, east-west- to northeast-striking dike and vein swarms and prominent, east-west- to east-northeast-striking, through-going joints in and near calc-alkalic plutons of the Morenci Assemblage. Regional aspects of these structural features have been discussed by Rehrig and Heidrick (1972, 1976) and Heidrick and Titley (1982). The dike and vein swarms appear to be concentrated between elements of the Texas Zone that exhibited left-slip movement during medial Laramide orogeny.

Examples of dike and vein swarms of the Morenci Assemblage (Figure 5) include the dike swarms in the Tortilla Mountains (Schmidt, 1971; Keith, 1983b) dike swarms in the Southern Dripping Spring Mountains (Banks and Krieger, 1977), dikes in the Silver Bell district (Watson, 1968), dikes in the Saddle Mountain district (Keith, 1983), and dikes in the Central district of New Mexico (Jones and others, 1967).

Age of Morenci Assemblage

Rocks, structures, and mineral deposits of the Morenci Assemblage have yielded numerous radiometric dates that conclusively show the Morenci Assemblage is older in the west and younger to the east (Figures 1 and 5). At Mineral Park in Mohave County of western Arizona, quartz monzonite in the Mineral Park pit yielded age dates of 71.5 Ma (Damon and Mauger, 1966). Farther east and south, the New Cornelia stock at Ajo is dated at 62.6 Ma (Damon and others, 1964; McDowell, 1971). To the northeast, the Granite Mountain porphyry and associated porphyry copper mineralization in the Ray area yielded K-Ar dates of 59.5 to 63.2 Ma (Rose and Cook, 1965; Moorbath and others, 1967; McDowell, 1971; Banks and others, 1972; Banks and Stuckless, 1973). Twenty km northeast of Ray, the Globe-Miami district is extremely well dated by Creasey (1980), who documents intrusion of the main phase of the Schultze granodiorite at 61.2 ±0.4 Ma and ages of mineralization at 63.3 ±0.5 (Copper Cities), 61.1 ±0.3 Ma (regional quartz sericite veins); 59.3 ±0.3 Ma (Miami-Inspiration orebody), and 59.1 ±0.5 (Pinto Valley).

Numerous dates for mineral deposits within a 60 mile radius of Tucson range from 65 to 58 Ma (Mauger and others, 1965; Johnston, 1972; McDowell, 1971; Banks and others, 1972; Creasey and Kistler, 1962). Farther to the northeast in the Safford to Morenci region, calc-alkalic magmatism and associated porphyry copper mineralization is 62 to 51 Ma (Bennett, 1975; McDowell, 1971; Langton and Williams, 1982). Even farther to the east in southwestern New Mexico, Morenci Assemblage magmatism and mineral deposits in the Tyrone and Central districts yields K-Ar dates between 58 and 54 Ma (McDowell, 1971).

In summary, Morenci Assemblage rocks, structures, and mineral deposits are about 75 to 70 Ma in western Arizona and become younger to the east across Arizona to 60 to 52 Ma in easternmost Arizona and southwestern New Mexico. In any given locality, the Morenci Assemblage magmatism and mineralization occupied a 10 million year interval that post-dated magmatism of the Tombstone Assemblage (Figure 1).

Resources of Morenci Assemblage

Mineral resources of the Morenci Assemblage include the well known and well-studied porphyry copper deposits. The anthologies edited by Titley and Hicks (1966) and Titley (1982) are classics. The porphyry copper deposits of the Morenci Assemblage of the medial Laramide orogeny are the major source of historic copper production in Arizona and the world. In general, the porphyry copper deposits consist of large, disseminated, mesothermal, annular zones of copper-molybdenum mineralization in or adjacent to porphyritic, epizonal, metaluminous calc-alkalic stocks. Some of the systems are extremely large and commonly exhibit zoning outward from the Cu-Mo-rich core to copper-zinc to succeeding zones of zinc-lead-silver-gold, lead-silver, and silver-manganese.

The Globe Hills - Miami - Inspiration - Superior region (Creasey, 1980; Peterson, 1962; 1969) may be a good example of a giant, compositely zoned, porphyry copper system that is approximately centered north of the Schultze granodioritic intrusion (Pinto Valley - Inspiration - Miami - Copper Cities) with copper vein swarms on its northeast fringe in the Globe Hills and at its southwest fringe at Superior. The Mineral

Park - Wallapai district north of Kingman, Arizona (Wilkinson and others, 1982; Eidel and others, 1968; Schrader, 1909) and the Central district of southwestern New Mexico (Hernon and Jones, 1968) are other examples of large, metallogenically zoned, composite porphyry copper systems.

Culminant Laramide Orogeny

The culminant Laramide orogeny is the latest part of the Laramide orogeny and is characterized by the extremes of processes exhibited in earlier phases. Mid-crustal plutonic magmatism is exposed in greater volumes than earlier phases and associated thrust faults appear to have the greatest transport and highest degree of deformation, including mylonitization and metamorphism. Supracrustal Eocene basins also record the coarsest and thickest sedimentary accumulations, reflecting the great magnitude of the profound tectonic event near the end of the Laramide (Chapin and Cather, 1981) in the Colorado Plateau and Rocky Mountain regions.

Culminant Laramide orogeny in Arizona and nearby areas can be subdivided into at least five assemblages (Figure 6). The three assemblages on the Colorado Plateau (the Echo Park, Green River, and Rim Assemblages) are supracrustal sedimentary assemblages that were deposited in different types of basins; the two assemblages in the Basin and Range are intracrustal plutonic (Wilderness Assemblage) and metamorphic (Orocopia Assemblages) assemblages that were emplaced at middle and lower crustal levels respectively. These deep facies would normally not be visible on the surface, but uplift and erosion during the latest phases of the Laramide brought them closer to the surface. During the middle and later parts of the Tertiary, these deep facies were uplifted and arched by events that exposed the lower facies (the mylonitized rocks of the 'metamorphic core complexes') as windows in the upper facies (the nonmylonitized Precambrian crystalline rocks). The assemblages are discussed below from northeast to southwest and from supracrustal to deeper crustal levels.

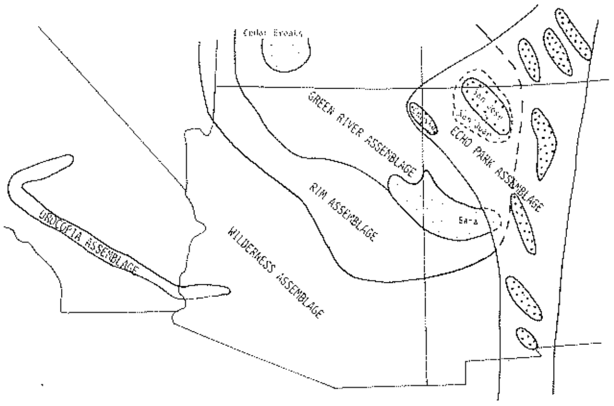


Figure 6. Index map of areas of assemblages of the culminant Laramide orogeny in Arizona and vicinity.

ECHO PARK ASSEMBLAGE

Name

The Echo Park Assemblage as used in this paper is largely synonymous with and is named after the 'Echo Park-type basins' of Chapin and Cather (1981); these basins exist in a north-south belt through central New Mexico and central Colorado. General characteristics of the rocks, structures, and resources of the Echo Park Assemblage are summarized in Table 12; examples are listed in Table 13 and are shown on Figure 7.

Table 12. Characteristics of Echo Park Assemblage of the culminant Laramide orogeny

SEDIMENTS	MAGMATISM	STRUCTURES	RESOURCES
proximal fan facies	general lack	NW-trending, rel. sharp	Uranium
nr basin margin	of volcanics	asymmetric syn. downfolds	
mainly arkosic alluv. fans		bounded on East sides	
fans fining upward		by steep E dipping	
lack of volcanic clasts		reverse faults	
except near Paleocene fields		N-S trending zones with	
scarp-related breccia sheet-		NW-trend en echelon folds	
wash facies at E. margins		N-S trending zones of	
of basins		NE-striking normal faults	

Rocks of the Echo Park Assemblage

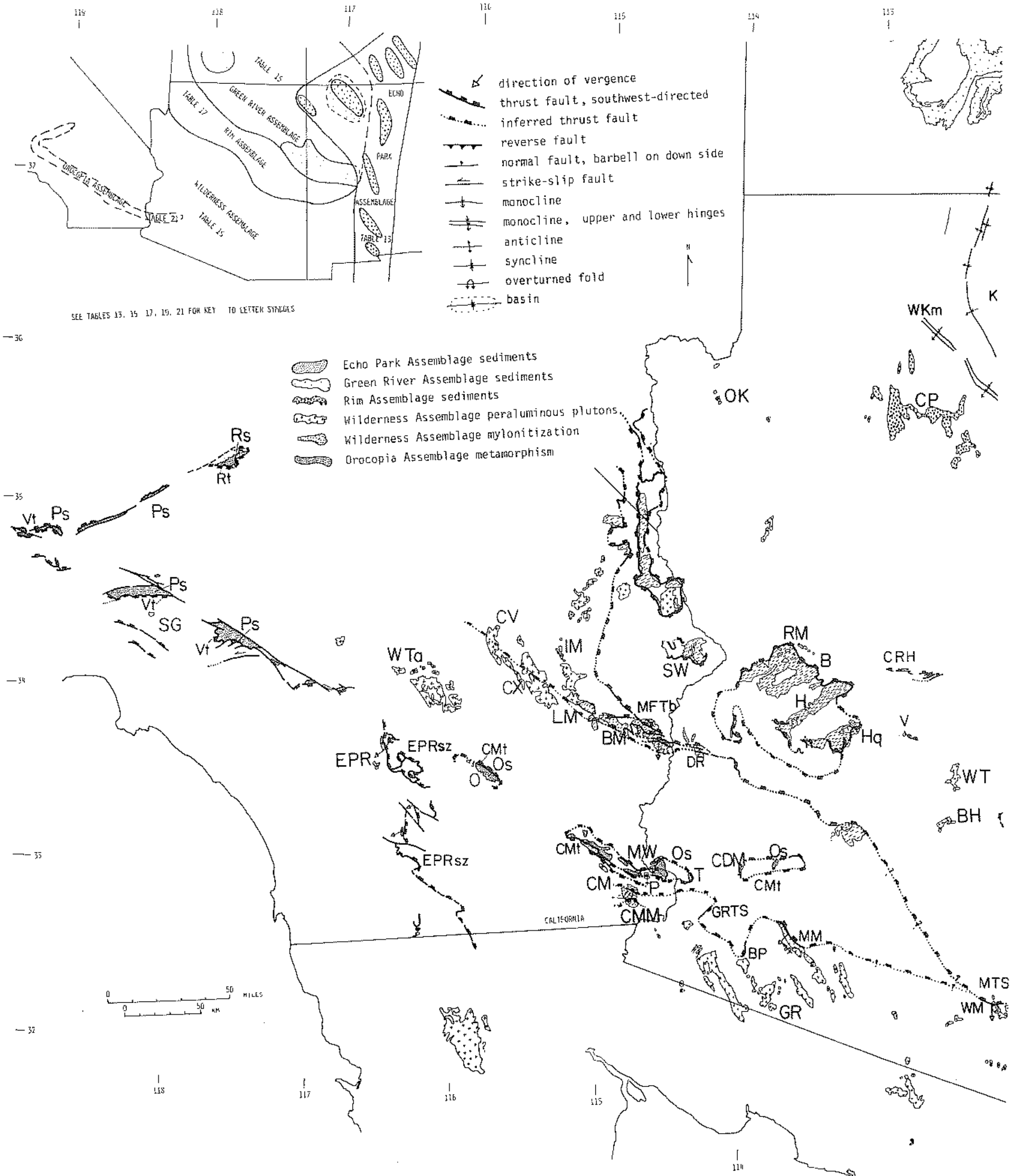
According to Chapin and Cather (1981) sediments of the Echo Park Assemblage consist mainly of arkosic alluvial fan deposits that become finer upward with proximal fan facies near the eastern basin margin and finer grained facies towards the central parts of the basins. Breccia deposits of sheet wash facies occur at the eastern margin of basins and represent deposits related to steep, topographic scarps. Echo Park Assemblage sedimentary rocks generally lack volcanic clasts, except near Paleocene volcanic fields.

Examples of Echo Park Assemblage sedimentary rocks are the Echo Park Formation in central Colorado, the San Jose Formation of Eocene of the San Juan basin in northwestern New Mexico, and possibly the Chuska Sandstone of northeastern Arizona (Figure 7). The San Jose Formation of Eocene age in northwestern New Mexico probably accumulated in a northwest-trending, synclinal trough west of the Nacimiento uplift in a broader, somewhat atypical, Echo Park-type basin. Less well-defined rocks assignable to Echo Park Assemblage may be present as the Love Ranch Formation of south central New Mexico and the Palm Park Formation of southern New Mexico (Smith and others, 1985).

Structures of the Echo Park Assemblage

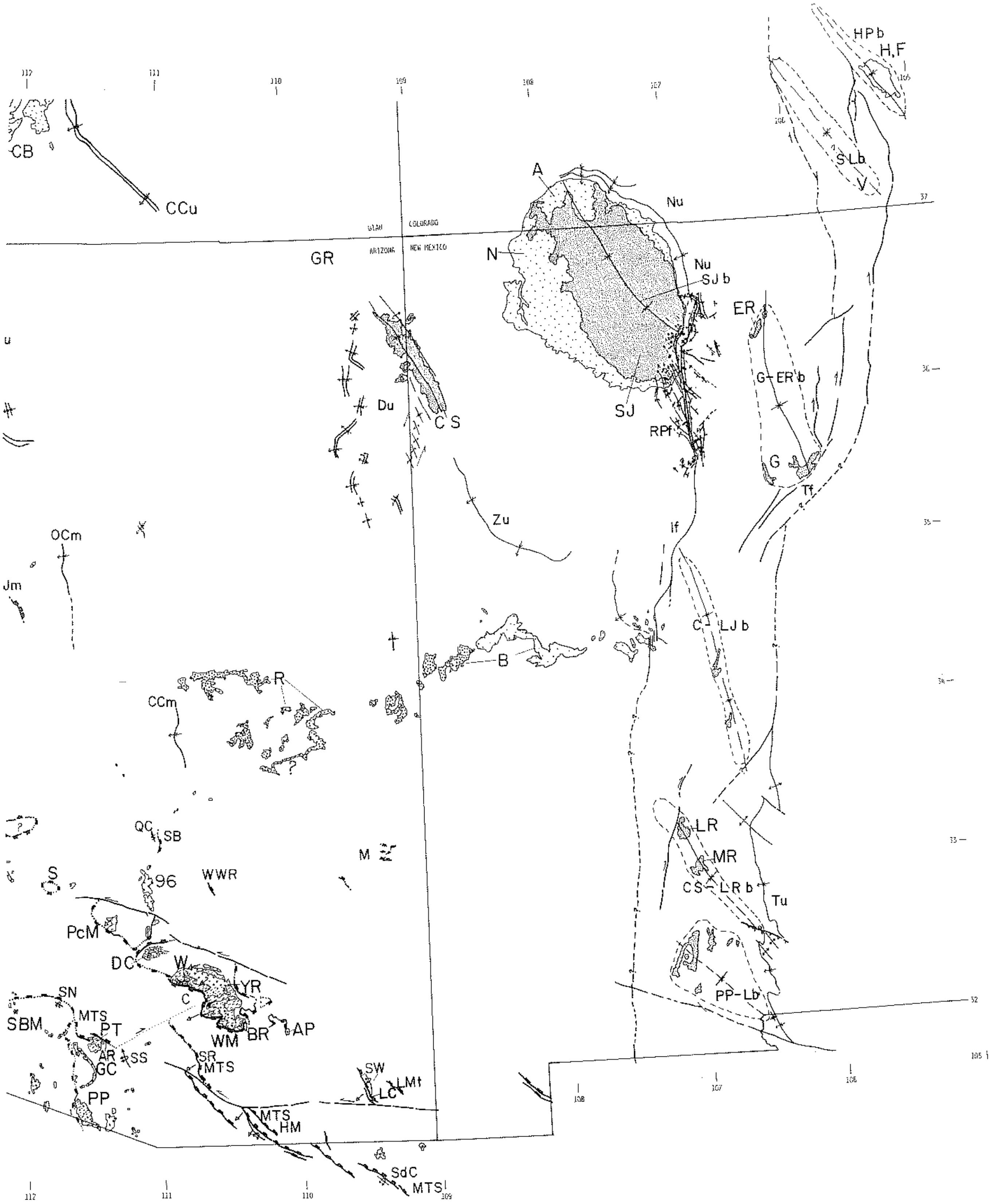
The principal basins of the Echo Park Assemblage are north-northwest-trending, relatively sharp, asymmetric, synclinal downfolds that are bounded on the east sides by steep, east-dipping, reverse faults. The more southerly basins are shown in Figure 7 and include the Huerfano Park and San Luis Basins in southern Colorado and the Galisteo-El Rito, Carthage-La Joya, and Cutter Sag-Love Ranch basins in New Mexico along the Rio Grande Rift (Chapin and Cather, 1981).

West of the Rio Grande Rift, the San Jose Formation in southern Colorado and the Chuska Sandstone in northeastern Arizona and northwestern New Mexico were deposited in broad, northwest-



culminant Laramide orogeny

Figure 7. Map of Echo Park, Green River, Rim, Wilderness and Orocopia Assemblages of the culminant Laramide



orogeny in Arizona and vicinity.

trending synclines associated with en echelon zones of northwest-southeast trending folds. In the northeast part of the San Juan basin, the San Jose Formation has been deposited in a broad, northwest trending syncline. The southeastern end of the syncline is part of a distinctive, north-south trending zone of en echelon folds along the west edge of the Nacimiento uplift (Baltz, 1967). These folds deform rocks as young as the San Jose Formation. Similarly, the Chuska Sandstone, which is pre-25 Ma (Trevena, 1979), occurs in a northwest-trending syncline that is clearly superimposed across the trace of the east-facing Defiance monocline of the Denver Assemblage. Also, south of the Chuska syncline, the Defiance monocline is deformed by a north-south zone that contains a set of northwest trending en echelon folds.

Less commonly, zones of northeast-striking normal faults may be developed as part of the Echo Park Assemblage. The en echelon, northeast-striking normal faults of the Rio Puerco fault zone in north central New Mexico (Slack and Campbell, 1976) are also tentatively assigned to the Echo Park Assemblage. The Rio Puerco fault zone occurs just south of the en echelon fold zone at the western edge of the Nacimiento uplift and appears to be a continuation of strain effects related to the Nacimiento uplift.

Chapin (1983) has recently compiled evidence that suggests the regionally aligned, north-south zone of Echo Park-type basins through central New Mexico and Colorado may be linked by an anastomosing fault system of regional extent that trends north-south parallel to the Rio Grande Rift. Chapin infers these faults would have a strong component of right slip. Some of the faults postulated by Chapin are shown on Figure 7.

Table 13. Examples of Echo Park Assemblage of the culminant Laramide orogeny

	SYMBOL	EXAMPLES	REFERENCES
SEDIMENTS		Echo Park Fm.	Chapin & Cather, 1981
	CS	Chuska Ss.	Trevena, 1979
	ER	El Rito Fm.	Lucas, 1984
	F	Farasita Congl.	Johnson & Wood, 1956
	G	Gallisteo Fm.	Lucas, 1984; Baltz, 1978
	H	Huerfano Fm.	Johnson & Wood, 1956
	LR	Love Ranch Fm.	Smith & others, 1985
	MR	McRae Fm.	Chapin & Cather, 1981
	SJ	San Jose Fm.	Fassett, 1985
	V	Vallejo Fm.	Upson, 1941
	MAGMATISM	none	
STRUCTURES		North Park-Middle Park bas.	Chapin & Cather, 1981
		Echo Park basin	Chapin & Cather, 1981
		South Park basin	Chapin & Cather, 1981
	C-LJ b	Carthage-La Joya bas.	Smith & others, 1985
	CS-LR b	Cutter sag-Love Ranch bas.	Seager, 1975
	G-ER b	Galisteo-El Rito bas.	Gorham & Ingersoll, 1979
	HP b	Huerfano Park basin	Johnson & Wood, 1956
	PP-L b	Palm Park-Lobo basin	Corbitt & Nials, 1975
	SJ b	San Jose basin	Fassett, 1985
	SL b	San Luis basin	Tweto, 1979; Baltz, 1965
	CCu	Circle Cliffs uplift	Kelley, 1955
	Du	Defiance uplift	Kelley, 1955
	Ku	Kaibab uplift	Davis & Kiven, 1978
	Nu	Nacimiento uplift	Baltz, 1967
	Tu	Tularosa uplift	Kelley, 1955
	Zu	Zuni uplift	Kelley, 1955
	If	Ignacio fault	Kelley, on NMGS map, 1982
	RPf	Rio Puerco fault zone	Slack & Campbell, 1976
	Tf	Tijeras fault	Lisenbee & others, 1979

Resources of the Echo Park Assemblage

Significant uranium resources occur in the Tallahassee Creek area of Colorado. In the Tallahassee Creek district uranium mineralization occurs in stratabound bodies within arkoses of the Echo Park Formation and also in the Oligocene Tallahassee Creek Formation. Published reserves as of 1978 were 30 million pounds of U308 for the Hansen orebody.

GREEN RIVER ASSEMBLAGE

Name

The Green River Assemblage as used in this paper is only partially synonymous with and is named after the 'Green River-type basins' of Chapin and Cather (1981) in the Colorado Plateau and Rocky Mountains. According to Chapin and Cather (1981) "the Green River-type basins are large, ellipsoidal to equidimensional in shape, are bounded on three or more sides by various combinations of the previously described uplifts, and occur on, or northward of, the Colorado Plateau. They exhibit a quasiconcentric zonation of facies and commonly contain volumetrically significant lacustrine deposits. Examples of Green River-type basins include the San Juan, Uinta, Piceance, Wind River, Bighorn, Powder River, Baca, and greater Green River basins." In addition, many of the basins show a depositional asymmetry with the thickest portions on the north or east sides of the basins against south- or west-facing uplifts.

The term 'Green River Assemblage' differs conceptually from the 'Green River-type basins' of Chapin and Cather (1981) because it emphasizes basins developed west and south of uplifts and includes fine-grained sediments deposited in lacustrine environments. The term Green River-type basins as employed by Chapin and Cather (1981) represents basins that, in our classification, have a composite tectonic history of Denver, Green River, and Echo Park Assemblages. General characteristics of the rocks and structures of the Green River Assemblage are summarized in Table 14. Examples of rocks and structures are listed on Table 15 and are shown on Figure 7.

Table 14. Characteristics of Green River Assemblage of the culminant Laramide orogeny

SEDIMENTS	MAGMATISM	STRUCTURES	RESOURCES
fanglom. facies near North &/or East margins near uplifts grading laterally into alluvial plains, mudflats and lakes with large volumes of carbonates & fine seds.	scattered tuffs	large NW- to N-S trending asymmetrical uplifts bounded on W and SW sides by major thrust faults E- to NE-dipping, low-angle to intermediate-angle	oil shale trona

The San Juan basin of northwestern New Mexico is an excellent example of overprinted strato-tectonic assemblages. Here, the Ojo Alamo Sandstone of the Denver Assemblage is unconformably overlain by Nacimiento or Animas Formations of the Green River Assemblage, which is overlain with local unconformity by the San Jose Formation of the Echo Park Assemblage. In the San Juan basin, Denver Assemblage was succeeded by Green River Assemblage, which was succeeded by Echo Park Assemblage in the same area.

The facies relationships and transport directions record a change from southeastward transport to southwestward transport to westward transport. Sediments of the Ojo Alamo Sandstone were transported southeastward off the northeast-trending Hogback monocline to the west in early Paleocene (Denver Assemblage). Nacimiento sediments were transported southwestward off the north end of the southwest-facing Archueleta uplift in late Paleocene (Green River Assemblage). San Jose sediments were transported southwestward and westward off the north-trending and west-facing Nacimiento and south-southwest-facing Archueleta uplift (Echo Park Assemblage). The assemblage boundaries are enhanced by local unconformities, particularly away from the basin center, between the Ojo Alamo Sandstone, the Nacimiento Formation, and the San Jose Formation (New Mexico Geological Society, 1982; Fassett, 1985). In the Uinta basin, Tuscher-Farrer Formations of the Denver Assemblage are unconformably succeeded by the Colton-Wasatch and Green River Formations (Fouch and others, 1983) of the Green River Assemblage.

Our definition of Green River Assemblage emphasizes sedimentation during latest Paleocene to middle Eocene that is derived from southwest-facing monoclines to southwest-directed thrust uplifts that developed during culminant Laramide orogeny. We consider the type area for Green River Assemblage to be the Green River basin south and west of the Wind River uplift in central Wyoming. Reference areas would be the Uinta Basin-Uinta uplift pair and the Owl Creek - Wind River basin pair in central Wyoming.

Sediments and Basins of Green River Assemblage

The Green River Assemblage in Arizona includes sediments in the thinned, southwestern edge of the Baca basin (Figure 7). The main Baca basin is to the northeast in New Mexico, where it was probably bounded on the north by the southern end of the Defiance uplift, the southwestern edge of the Zuni uplift, and the western edge of the Lucero monoclinal uplifts, and was bounded on its east and southeast sides by the Sierra basement uplift (Cather, 1980; Johnson, 1978).

Table 15. Examples of Green River Assemblage of the culminant Laramide orogeny

	SYMBOL	EXAMPLES	REFERENCES
SEDIMENTS		Green River Fm.	Chapin & Cather, 1981
	B	Baca Fm.	Cather,1983; Cather & Johnson,1984
	N	Nacimiento Fm.	Fassett, 1985
	A	Animas Fm.	Fassett, 1985
	CB	Cedar Breaks Fm.	Hintze, 1975
		Flagstaff Ls.	Hintze, 1975
MAGMATISM		none	
STRUCTURES		Green River basin	Chapin & Cather, 1981
		Powder River basin	Chapin & Cather, 1981
		Wind River basin	Chapin & Cather, 1981
		Uinta basin	Chapin & Cather, 1981
		Piceance basin	Chapin & Cather, 1981
	N, A	San Juan basin	Baltz,1967; Lucas & Ingersoll,1981
	B	Baca basin	Cather & Johnson, 1984
	Ku	Kaibab uplift	Davis & Kiven, 1975
	OCm	Oak Creek mon.	
	CCm	Cherry Creek mon.	
	WKm	West Kaibab mon.	Davis & Kiven, 1975

The Cedar Breaks Formation in southern Utah is also assigned to the Green River Assemblage and may represent a lacustrine pond of late Paleocene to mid Eocene age between the west-facing Circle Cliffs monocline on the east and the erosional remnants of the Sevier thrust belt on the west. The Cedar Breaks Formation may be a southern extension or equivalent of the Flagstaff Limestone of latest Paleocene to earliest Eocene age to the north. The Flagstaff Limestone also accumulated in a lacustrine pond between the west margin of the San Rafael Swell and the erosional remnants of the Sevier thrust belt on the west.

Formations in the San Juan basin of northwestern New Mexico that are assigned to the Green River Assemblage include the Nacimiento Formation and the Animas Formation. The Nacimiento Formation of Paleocene age exhibits facies relationships extending to the southwestward away from the San Juan uplift (Fassett, 1985). In the northern San Juan basin, Nacimiento Formation interfingers with the volcaniclastic Animas Formation and is deposited directly on Kirtland-Fruitland Formations of the Laramie Assemblage with the Ojo Alamo Sandstone of the Denver Assemblage removed erosionally (Fassett, 1985). Paleoflow for the Nacimiento Formation is towards the southwest, at right angles to the paleoflow directions for the Ojo Alamo Sandstone. The Animas-Nacimiento formations represent deposition in a Green River Assemblage basin that was superimposed on a Denver Assemblage basin during and after metaluminous magmatism (similar to Morenci and Tombstone Assemblages) began in the southwest part of the Colorado Mineral belt about 65-58 Ma.

Structures of the Green River Assemblage

Structures responsible for uplifts and basins that record the Green River Assemblage include the classic southwest-facing Wind River uplift of central Wyoming. In Arizona on the Colorado Plateau and Transition Zone, some west-facing monoclines may possibly have developed at this time by analogy with the better studied uplifts to the north. Possible examples include the west side of the Kaibab uplift, the north-south monocline on the Mogollon Rim near Oak Creek, and possibly the west-facing monocline along Cherry Creek in the Sierra Ancha Mountains (the west side of the Apache uplift of Davis, 1978a).

Resources of the Green River Assemblage

In the Green River basin, oil shales formed due to increased algal productivity in shallow, relatively fresh waters during high stands of lake levels. Trona deposition occurred during low stands via the seasonal dessication of hypersaline brines in a small, basin-center lake (Eugster and Hardie, 1975). Some of the oil from the early Eocene oil shales may have migrated into anticlinal traps beneath south- or west-directed thrust faults that border south-and west-facing thrust uplifts. The thrust overhangs on the Wind River uplift (Gries, 1980) are especially provocative.

RIM ASSEMBLAGE

Name

The name Rim Assemblage was given by Keith (1984) and Keith and Wilt (1985) to the gravels along the Mogollon Rim in southern Coconino County and southern Navajo and Apache Counties. The assemblage was named for the 'Rim gravels' of Peirce and others (1979) and earlier workers. Because of the good exposures, accessibility, and documentation in the literature, the Mogollon Rim south of Show Low is designated as a type area for the Rim Assemblage. The exposures in southern Coconino County, such as the Frasier Well gravels, are now known to be Eocene in age (Young, 1979; 1982) and are designated as a reference area for the Rim Assemblage. General characteristics of rocks and structures of the Rim Assemblage are summarized on Table 16. Outcrops of Rim Assemblage are shown on Figure 7 and are listed in Table 17. They occur northeast of and were eroded from the Mogollon Highlands that were reuplifted by the southwest-directed thrust faulting in a broad zone across southwestern Arizona (Keith and Wilt, 1985; Nations and others, 1985).

Table 16. Characteristics of Rim Assemblage of the culminant Laramide orogeny

SEDIMENTS	MAGMATISM	STRUCTURES	RESOURCES
fluvial gravels with very well round. clasts grade laterally into alluvial plain facies general lack of lacustrine facies	none	shallowly inclined NE-dipping paleoslope W-facing monoclines	none

Rocks of the Rim Assemblage

Lithologically, the Rim Assemblage consists of fluvial gravels with very well-rounded clasts which can be as large as boulders. These fluvial gravels grade laterally into alluvial plain facies and generally lack lacustrine facies. Structurally, the Rim gravels overlie a regional, very gently inclined, northeasterly dipping paleoslope. In the Mogollon slope region the unconformity below the 'Rim gravels' truncates successively older rocks to the south (Peirce and others, 1979), such that a possible 'Rim gravel' equivalent rests on Precambrian granites south of the Mogollon Rim at Four Peaks at an elevation of 7200 feet (Wilson and others, 1969). The gravels below the Mogollon Rim are similar to the 'Rim gravels' and were included as Rim Assemblage in (Keith, 1984). Their present elevation 2000 feet below the Rim may imply Oligocene collapse and drainage reversal along the Colorado Plateau margin (Peirce, 1985).

The 'late Eocene erosion surface' of Epis and Chapin (1975) is a common feature throughout the western United States (Gresans, 1981). This erosion surface, also called the Telluride surface, is overlain by the Mogollon-Datil volcanics dated at 37 Ma, which also overlie the Eocene Baca Formation (Epis and Chapin, 1975). The 'Rim gravels' of the Rim Assemblage are possibly partly correlative with the Baca Formation of the Green River Assemblage in northwestern New Mexico (Cather and Johnson, 1984). They differ in that the Rim Assemblage sediments are very coarse grained and were possibly derived from the uplifted thrust margin to the southwest, whereas the Green River Assemblage sediments are finer grained and were derived from wedge uplifts to the north or northeast.

Table 17. Examples of Rim Assemblage of the culminant Laramide orogeny

PROPERTY	SYMBOL	EXAMPLES	REFERENCES
SEDIMENTS	R	Rim Gravels	Peirce & others, 1979
	E	Eager Fm.	Cather & Johnson, 1984
	CP	Coconino Plateau grav.	Young, 1979, 1982
	MM	Mazatzal Mtns. grav.	Wilson & others, 1969
MAGMATISM		none	
STRUCTURES	WKm	W side Kaibab mon. N-S monocline Mog. Rim	Davis & Kiven, 1975

Age of the Rim Assemblage

The Rim Assemblage is probably of middle to late Eocene age (52 to 43 Ma). The 'Rim gravels' at Round Top Mountain contain andesite and latite boulder clasts of Laramide volcanics that yield K-Ar dates as young as 54 Ma; they are overlain by a rhyolite ignimbrite dated at 28 Ma (Peirce and others, 1979). Near Eager, gravel deposits that are probably correlative with Rim gravels have yielded middle Eocene vertebrate teeth (Young and Hartman, 1984). Similarly, the Frasier Well gravels, a probable Rim gravel equivalent in the western Mogollon Rim, have also yielded a middle Eocene age on a gastropod fauna (Young, 1982). Thus, rocks that cap the Mogollon Rim segment of the Colorado Plateau could be middle Eocene in age and would lie above the Paleocene-Eocene unconformity and rest beneath the late Eocene-early Oligocene unconformity associated with the Oligocene drainage reversal (Peirce and others, 1979; Peirce, 1985).

WILDERNESS ASSEMBLAGE

Name

The name Wilderness Assemblage was given by Keith (1984) to a set of peraluminous igneous rocks of Paleocene-Eocene age and related mylonitic and recrystallized metamorphic rocks that occur throughout the Basin and Range Province of Arizona and nearby areas. The name Wilderness was chosen for well-exposed, well-documented, peraluminous plutonic rocks of middle Eocene age in the Wilderness of Rocks area of the Santa Catalina Mountains near Tucson. These rocks were originally informally called Wilderness granite by Doug Shakel in 1972 and were referred to in print by Budden (1975) and formally adopted by Keith and others (1980) as part of the Wilderness suite of plutons in the Santa Catalina-Rincon-Tortolita batholithic complex. The Wilderness granite and its related deformation in the main range of the Santa Catalina Mountains north of Tucson is designated as the type area of the Wilderness Assemblage. Other well-studied reference areas for the Wilderness Assemblage magmatism and related deformation are the northern Coyote Mountains (Wright and Haxel, 1982) and the Sierra Blanca Mountains (Haxel and others, 1984). General characteristics of the rocks, structures, and resources of the Wilderness Assemblage are summarized in Table 18.

Table 18. Characteristics of Wilderness Assemblage of the culminant Laramide orogeny

SEDIMENTS	MAGMATISM	STRUCTURES	RESOURCES
none	widespread, (2-mica) garnet-muscovite, granitoid stocks, batholithic sills, aplo-pegmatite dikes peraluminous, calc-alkalic & calcic Fe-poor to Fe-rich, hydrous, oxidized Sr init. ratios = .7085 to .725	SW-directed, low-angle thrusts widespread, shallowly dipping mylonitic zones general SW shear	hypo-mesothermal to mesothermal Pb-Zn-Ag veins minor Cu-Au veins Au in qtz vns kyanite

Examples and characteristics of rocks and structures of the Wilderness Assemblage are listed in Table 19 and are shown on Figure 7. Examples of Wilderness assemblage plutons include the well-studied Wilderness Granite batholithic sill complex in the Santa Catalina Mountains (Keith and others, 1980; Keith and Reynolds, 1981) and the Pan Tak granite (58 Ma) in the Coyote Mountains (Wright and Haxel, 1982).

Rocks of the Wilderness Assemblage

VOLCANIC GAP. In strong contrast to the earlier Laramide and later Galiuro assemblages (Keith and Wilt, 1985), there are no sedimentary or volcanic rocks in the Wilderness Assemblage. A prominent 'magma gap' from 55 to 38 Ma in southeastern Arizona had long been recognized as Eocene (Damon and Mauger, 1966; Damon, 1971; Snyder and others, 1976; Coney and Reynolds, 1977; Keith, 1978). However, this 'magma gap' has been closed in recent years with a newly recognized kind of magmatism -- the muscovite- and garnet-bearing, peraluminous granites (Keith and others, 1980; Miller and Bradfish, 1980; Keith and Reynolds, 1981; Wright and Haxel, 1982). Although the 'magma gap' of earlier work is now largely occupied by the peraluminous granitoids, it is important to point out that in the surface stratigraphy there is a gap in volcanism for the interval formerly called the 'magma gap'. Thus, the term 'volcanic gap' is probably a more appropriate term for what was originally called 'magmatic gap'.

MAGMATISM. In Arizona the peraluminous granitoids assigned by Keith (1984) to the Wilderness Assemblage are now recognized to be the most widespread and most voluminous product of Laramide magmatism. Magmatism of the Wilderness Assemblage consists entirely of peraluminous, muscovite- and garnet-bearing granitoids that commonly contain well developed alasko-pegmatite complexes, especially near the roofs of the plutons. Wilderness Assemblage plutons generally occur as sills with low-volume, late phases occurring as dikes that are discordant to the earlier sills. Many Wilderness Assemblage plutons are commonly associated with well-developed mylonitic fabrics in or adjacent to the plutons and appear to be synkinematically intruded into mylonitic shear zones (especially southwest- to south-directed mylonitic shear zones).

MINERALOGY. Mineralogic data for Wilderness Assemblage plutons shows that they contain 4 to 13% hydrous minerals, which are represented by micas

Table 19. Examples of Wilderness Assemblage of the culminant Laramide orogeny

	SYMBOL	EXAMPLES	REFERENCES
MAGMATISM	96	96 Hills pluton	Bradfish, 1978
	AP	Adams Peak leucogranite	Cooper & Silver, 1964
	AP	E. edge Texas Canyon	Cooper & Silver, 1964
	B	Buckskin Mtns.	Shackelford, 1979, 1980
	BH	Buckeye Hills	Keith, 1984
	BM	Big Maria Mts., CA	Martin & others, 1982
	BR	Barney Ranch pluton	Lingrey, 1982
	C	Coxcomb range	Calzia, 1982
	CMM	Cargo Muchacho Mtns.	Keith, unpub.data; Dillon,1976
	CV	Cadiz Valley batholith	Howard & others, 1982
	DC	Tortolita Mts.	Banks & others, 1977
	DC	Derrio Canyon granite	Banks & others, 1977
	EPR	E. Peninsular Range	Simpson, 1984
	GC	Gu Chuapo granite	Wright & Haxel, 1982
	GR	Gunnery Range batholith	Shafiqullah & others, 1980
	Ha	E. end Harquahala Mts.	Keith, 1983
	IM	Iron Mountain	Brand & Anderson, 1982
	J	Jacumba pluton	Walawender, M.J., pers. comm.
	MW	Marcus Wash pluton	Haxel, 1977
	OK	Gold Basin	Theodore & others, 1982
	OK	O K pluton	Theodore & others, 1982
	PM	Picacho Mountains, AZ	Rehrig & Reynolds, 1980
	PP	Presumidio Peak	Wright & Haxel, 1982
	PT	Pan Tak granite	Wright & Haxel, 1982
	PT	Coyote Mtns.	Wright & Haxel, 1982
	RM	Rawhide Mtns.	Shackelford, 1979, 1980
	RP	Redington Pass	Keith & others, 1980
	SBM	Sierra Blanca Mts.	Haxel & others, 1984
	SW	Sweetwater, Whipples	Miller & others, 1982
	W	Wilderness pluton	Keith & others, 1980
	WT	White Tank Mts.	Brittingham,in progress,ASU
	WTa	White Tank adamellite	Brand & Anderson, 1982
	YR	Youtcy Ranch pluton	Keith & others, 1980
STRUCTURES	AR	Ajo Road fault	Haxel & others, 1984
	BM	Big Maria Mtns.	Hamilton, 1982
	BP	Baker Peak	Pridemore & Craig, 1982
	BR	east Rincon Mtns.	Lingrey, 1982
	C	Catalina flt.	Banks,1977; Drewes,1972,1977
	CRH	Congress, Rich Hill	Herald & Russ, 1985
	DR	Dome Rock Mountains	Yeats, 1985
	EPR	E. Peninsular Range	Simpson, 1984; Sharp, 1967
	EPRsz	E. Penin. Rg. shear zone	Simpson, 1984; Sharp, 1967
	GRTS	Gunnery Range thr. sys.	Keith and Wilt, 1986
	HM	E. Huachuca Mts. thst	Hayes & Raup,1968; Davis,1978b
	Hq	Harquahala Mtns.	Reynolds & others, 1980
	Jm	Jerome area	Lindberg, pers. com.
	LC	Lyle Canyon thrust	Keith, unpub. map.
	LM	Little Maria Mtns.	Martin & others, 1982
	LMt	Limestone Mtn thrust	Epis, 1956
	M	Morenci area	Langton, 1973
	MFTb	Maria fold thrust belt	Reynolds & others, 1986
	MM	Mohawk Mountains	Mueller & others, 1982
	MTS	Maricopa thrust system	Keith & Wilt, 1985; 1986
	QC	Queen Creek fold	Keith,this vol.; Peterson,1969
	S	lower plate, Sacaton	Cummings, 1982
	SB	Sleeping Beauty	Keith, this vol.
	SN	Sil Nakya Hills	Haxel & others, 1984
	SR	Box Canyon, Santa Rita	Keith and Wilt, 1983
	SS	SW Sierrita Mts. fold	Drewes, 1974; Thoms, 1966
	SW	Swisshelm Mts.	Cooper, 1959
	SdC	Sierra de Cabullona	Rangin, 1977
	V	Vulture Mountains	White, 1985
	WM	Wrong Mountain pluton	Drewes, 1972a
	WMW	Window Mountain Well	Haxel & others, 1984
	WWR	Whittaker Wash Ranch flt.	Keith, 1983; Krieger, 1968
RESOURCES		Boriana	Myers, 1983
		Reef, Las Guijas	Dale & others, 1961
		Cobabi	Williams, 1963
		Mesquite	
	OK	Gold Basin	Theodore & others, 1982
	CMM	Cargo Muchachos	
	P	Picacho, CA	Van Nort and Harris, 1984

only. In the lower portions of the plutons, the principal mica mineral is biotite with accessory magnetite (up to 2 volume %) and zero to minor muscovite and trace garnet. The upper portions of Wilderness Assemblage sill complexes are commonly two-mica granites with muscovite and biotite in approximately equal amounts and with garnet as a well-developed accessory mineral (1 to 2 volume % garnet). The two-mica granite portions of Wilderness Assemblage plutons locally grade upward into aplo-pegmatite complexes up to 1 km thick that generally are dominated by muscovite with zero to minor biotite. Garnet is a very common accessory mineral in the alasko-pegmatite phases and locally forms spectacular garnet schlieren bands, as in the Lemmon Rock leucogranite, which is a roof phase of the Wilderness granite (Keith and others, 1980).

In strong contrast to earlier Laramide magmatism and later Galiuro and San Andreas magmatism (Keith and Wilt, 1985), Wilderness Assemblage magmatism does not contain metaluminous mafic minerals such as olivine, pyroxene, or hornblende, or mafic metaluminous igneous inclusions. Wilderness Assemblage plutons contain microcline K-feldspars with perthitic Na-plagioclase rather than orthoclase K-feldspars. Trace accessory minerals include apatite, monazite, and rarely corundum.

MAGMA CHEMISTRY. Chemically, plutonic rocks of the Wilderness Assemblage are peraluminous, calcic (Sweetwater Facies) to calc-alkalic (Gold Basin Facies), iron-poor to weakly iron-rich, hydrous, and oxidized (Keith, this volume). Their strontium initial ratios generally range from 0.7085 to 0.725, which are distinctly higher than earlier Laramide metaluminous magmatism (0.7042 to 0.7090) or later Galiuro metaluminous magmatism (0.705 to 0.710) and distinctly higher than San Andreas metaluminous magmatism (mostly 0.7022 to 0.705 for the basalts) (Keith and Wilt, 1985). At any given silica composition Wilderness Assemblage plutons are more aluminous [have higher molecular $Al_2O_3/CaO+Na_2O+K_2O$ ratios] and more sodic [have higher Na_2O/K_2O ratios] than metaluminous magmatism of the earlier Laramide, later Galiuro, or later San Andreas assemblages. Manganese appears to increase with increasing differentiation as a function of garnet content in the Wilderness Assemblage plutons, whereas manganese decreases with increasing differentiation in metaluminous magmatism of the other strato-tectonic assemblages.

DEPTH OF EMPLACEMENT. Evidence that the two-mica granites formed at great depth, probably equal to or greater than 10 km, comes from a variety of phenomena. Seven lines of petrologic evidence independently indicate thrust burial of 8 to 12 km or more. Firstly, the lack of surface volcanism suggests that the Wilderness Assemblage plutons did not intrude close enough to the ground surface to produce a volcanic expression on the surface and must have been deeper than .5 km. Secondly, fluid inclusion data from mineral deposits or from pegmatites and leucogranite phases associated with Wilderness plutons commonly display high CO_2 densities (greater than 0.70) requiring a considerable pressure correction for depths to at least 4.5 km. For example, high CO_2 fluid densities occur in fluid inclusions from veins in the OK peraluminous pluton of the Gold Basin district (Theodore and others, 1982).

A third depth indicator is the widespread distribution of phenocrysts of magmatic muscovite of celadonitic composition which indicates depths greater than 10 km (Anderson and Rowley, 1981). Fourthly, recent geobarometry on garnet and feldspar in peraluminous plutons indicates deep crystallization depths; for example depths of 20 km or more in the Whipple Mountains (Anderson, 1985). Fifth, because Wilderness Assemblage plutons have numerous and abundant pegmatites, their water content must have been extremely high. Burnham and Jahns (1962) estimate that water contents for pegmatitic granites are between 8 and 10 weight % H_2O; they constructed water depth curves that indicate pH_2O of 10 weight % in a pegmatite would equilibrate with the overriding pressure of the lithostatic load at about 13 km (Burnham and Jahns, 1962).

A sixth depth indicator is the presence of metamorphic minerals such as kyanite and staurolite in the metamorphic aureoles of several of the Wilderness Assemblage plutons. For example, staurolite is reported by Waag (1968) in the metamorphic aureole of the pelitic Apache Group metasediments in the Catalina Mountains at the roof of the Wilderness pluton. Minimum depths for staurolite stability at amphibolite grade temperatures are about 8 km. Kyanite occurs in the metamorphic aureoles of the Brown's Canyon pluton in the Harquahala Mountains, along the American Girl thrust in the Cargo Muchacho Mountains, and near pegmatites associated with southwest-directed thrusts in the Big Maria Mountains. At amphibolite grade temperatures (450 o C) the kyanite stability requires approximate minimum depths of 12 km (Holdaway, 1971).

A seventh depth indicator is the inference from geochronologic data that the thickness of cover removed during the mid-Tertiary is about the same as the thickness of thrust plates added during the late Laramide. Numerous mid-Tertiary ages by the K-Ar method have been obtained from rocks that are older by other age dating methods in the crystalline 'pseudo-cores' of the 'metamorphic core complexes'. In the Santa Catalina Mountains, K-Ar ages for hornblende or large muscovite grains from these rocks are either not reset or are only partially reset (Keith and others, 1980). This indicates that ambient temperatures in the lower plate beneath possible thrust plates that served as thermal blankets prior to 30 Ma were not greater than 400 degrees C. However, K-Ar determinations on biotite and fission track determinations on zircon and sphene from several complexes (especially the Whipple Mountains and the Santa Catalina Mountains) consistently yield reduced ages between 28 and 24 Ma. This strongly suggests that by 24 Ma crystalline rocks in the 'pseudo-cores' had cooled below 200 degrees C, which represents uplift of 8 km assuming a normal crustal geothermal gradient of 25 degrees C/km. If the reduced ages are related to uplift refrigeration of K-Ar clocks, then between Eocene and mid-Oligocene the complexes with reduced 28-24 Ma K-Ar and fission track ages cooled from 400 to 200 degrees. By 18 Ma fission track ages on apatite are reset suggesting that another 4 km of uplift had occurred between 22 and 18 Ma for a cumulative total of 12 km.

If it is assumed that the normal crustal geothermal gradient was 25 degrees C/km, a cumulative uplift of about 12 km is required to explain the refrigeration dates. Much of that 12 km is probably represented by erosional removal of overlying thrust plates during Oligocene uplift of the tectonized crystalline basement terranes during medial Galiuro orogeny (Keith and Wilt, 1985). If it is acknowledged that the Marble Peak porphyry copper skarn in the crystalline core of the Santa Catalina Mountains represents a system emplaced no deeper than 3 km about 65 Ma, then a thrust loading of 9 km after 65 Ma was followed by an erosional removal of a minimum of 9 km of thrust cover during mid-Tertiary uplift and denudation of the probably Eocene-aged thrust plates.

CONTACT RELATIONSHIPS. Stratigraphically, where Wilderness Assemblage plutons are in mutual contact with metaluminous plutons of older Sevier and Laramide assemblages, the peraluminous plutons generally cross-cut the older metaluminous plutons. For example, in the Tortolita and Santa Catalina Mountains plutons of the Leatherwood suite (Morenci Assemblage) are intruded by plutons of the Wilderness suite (Keith and others, 1980). In the Little Dragoon Mountains, the peraluminous Adams Peak leucogranite (aplite phase of Cooper and Silver, 1964) intrudes metaluminous, biotite quartz monzonite (main phase of Texas Canyon pluton of Cooper and Silver, 1964).

Structural Features of Wilderness Assemblage

STRUCTURES. Structures of the Wilderness Assemblage consist of mylonitic zones, southwest-directed thrust faults, and synkinematic peraluminous plutons. The widespread, regionally developed, shallowly dipping mylonitic zones exhibit a general southwest-directed shear. 'S' surfaces of the mylonites invariably contain a N50E-N70E to S50-70W mineral lineation. These shear zones are commonly associated with low-angle, southwest-directed thrust faults and synkinematic, peraluminous plutons (Keith, 1982a). Regional seismic data (Keith, 1980; Reif and Robinson, 1981) strongly suggest that many of the seismic reflectors can be correlated with surface outcrops of the mylonites. Many of the mylonitic zones are shallowly dipping and are northeasterly inclined towards and beneath Precambrian crystalline rocks along the southwestern boundary of the Colorado Plateau (Otton, 1981).

In Arizona and adjacent regions, several major southwest-directed thrust systems occur within the North American crust. These thrust systems are shown on Figure 7 and are described from west to east as follows. The Peninsular Range shear zone occurs along the eastern side of the Peninsular Range batholith and along its presumed extension in the San Gabriel Mountains to the northwest. Farther to the northeast a zone of possible south-southwest-directed thrusts, herein named the Gunnery Range thrust system, may be traced from the Cargo Muchacho Mountains to the Mohawk Mountains in southwestern Arizona. Farther to the northeast, a major zone of thrusting, named the Maricopa thrust system by Keith and Wilt (1985), may extend from the Coxcomb and Little Maria Mountains area in southeastern California southeast into northeastern Sonora (Figure 7). Windows of the Maricopa thrust system may be exposed in the northwest-trending belt of so-called 'metamorphic core complexes that occurs northeast of the trace of the Maricopa thrust system. Northeast of a this zone of 'thrust windows', a diffuse system of south- to southwest-directed reverse faults and folds is present in the southern part of the Transition Zone between the Basin and Range and Plateau provinces.

All of the above structures are consistently associated with peraluminous granitoid magmatism of the Wilderness Assemblage. In western exposures (such as the Peninsular Range and Gunnery Range thrust systems) the thrust systems are associated with peraluminous calcic magma series (Gold Basin Facies), whereas in northeastern exposures (such as the Maricopa thrust system and its uparched windows) the thrust systems are associated with calc-alkalic magma series (Sweetwater Facies). Each of the above thrust systems is shown on Figure 7 and Table 19 and is described from west to east in more detail below.

PENINSULAR RANGE THRUST ZONE. In southern California, a major, northeast-dipping shear zone was originally mapped by Sharp (1967). This shear zone extends from the Palm Springs area southeastward through the Santa Rosa Mountains and has placed metamorphic rocks that are older than mid-Cretaceous (possibly of Paleozoic and Mesozoic age) over the eastern margin of the Peninsular Range batholith. The shear zone has been offset by several strike slip faults of younger Cenozoic age in the Anza-Borrego State Park area farther to the south. In all the above areas, the shear zone is marked by thick zones of mylonite that exhibit southwest-directed 'S-C' shear fabric (Simpson, 1984). The 'S-C' fabrics provide strong evidence for the thrust nature of the zone.

The Peninsular Range shear zone deforms metaluminous calc-alkalic igneous rocks of the Peninsular Range batholith that are as young as 79 Ma (Silver and others, 1979). Potassium-argon cooling ages (Krummenacher and others, 1975) from the Santa Rosa Mountain region suggest that the mylonites were kinematically cold by 75 Ma (Figure 1). The Peninsular Range shear zone is intruded by several synkinematic peraluminous muscovite- and/or garnet-bearing sill-like sheets west of Borrego Springs and south of Palm Springs (Anderson and Erskine, pers. comm.).

Farther to the northwest mylonitic belts in the southeastern San Gabriel Mountains have been interpreted by May (1985) to be the remnants of the Late Cretaceous sinistral transcurrent shear zone that operated as a tear fault within a southwest-directed thrust network. Thrusts related to this network occur in the Fraser Mountain area and Mount Gleason area to the northwest of the sinistral shear zone.

GUNNERY RANGE THRUST SYSTEM. A diffuse zone of southwest- to south-southwest-directed thrusts may be found in scattered outcrops from the Cargo Muchacho Mountains west of Yuma to the Mohawk Mountains east of Yuma. In the Cargo Muchacho Mountains near American Girl Canyon, the American Girl thrust mapped by Dillon (1976) locally exhibits south-southwest-directed shear fabric and places the Jurassic monzo-diorite plutonic complex over a younger sequence of quartzo-feldspathic meta-arkoses of possible mid-Cretaceous age.

East of Yuma in the vicinity of Baker Peaks, a major detachment fault places clastic sedimentary rocks of middle Tertiary age over a lower plate of Precambrian? to Mesozoic crystalline rocks (Pridemore and Craig, 1982). Clast data from the mid-Tertiary sediments suggest that they were derived from a granitic source (Pridemore and Craig, 1982).

Farther to the northeast in the Mohawk Mountains, a similar fault places granitic rocks called the Mohawk and Owl granites by Mueller and others (1982) of indeterminate age over a lower plate consisting of gneisses of undetermined age. The upper plate granitic rocks are unconformably overlain by a mid-Tertiary conglomerate - sandstone sequence similar to the lithologies at Baker Peaks.

Thus, available data suggest that the low-angle faults in the Baker Peaks area and in the Mohawk Mountains are part of the same regional low-angle structure. Fabric data from gneisses in the lower plate suggest southwest-directed ductile tectonic transport. Also, a large folded pegmatite complex at the southern end of the Mohawk Mountains exhibits a southwest-directed sense of overturning (Mueller, pers. comm., 1982). As documented by Pridemore and Craig (1982) and Mulhler and others (1982), tilt directions in the mid-Tertiary sedimentary sequences suggest northeast-directed normal transport. However, fabric data from crystalline rocks in the lower plate suggest southwest-directed transport. Thus, as in many other locations, the Gunnery Range thrust system has at least two episodes of motion.

South of the Gunnery Range fault system, extensive pegmatites and/or batholithic plutons have been intruded into crystalline rocks of the lower plate. The Gunnery Range batholith is Paleocene to earliest Eocene in age (Haxel, pers. comm.; Arnold, written comm., 1984). Possible pegmatite apophyses of the Gunnery Range batholith are involved in apparent southwest-directed folding in the southeastern Mohawk Mountains (Mueller, pers. comm., 1982). The peraluminous magma series are conspicuously lacking in crystalline rocks of the inferred upper plate of the Gunnery Range thrust system between the the Gunnery Range thrust system and the Maricopa thrust system to the northeast. The general lack of peraluminous plutons in the upper plate of the Gunnery Range fault system is a characteristic feature of many of the southwest-directed thrust systems.

MARICOPA THRUST SYSTEM. In Arizona a major northwest-trending zone of southwest-directed thrust faults of the Wilderness Assemblage is named the Maricopa thrust system (Keith and Wilt, 1985). The Maricopa thrust system consists of numerous southwest-directed thrusts and southward-overturned folds and nappes (Table 19 and Figure 7).

The western portion of the Maricopa thrust system is manifested as thrust faults in California in the Big and Little Maria Mountains (Frost and Martin, 1982). Here, cratonic sequences of Paleozoic through Mesozoic rocks have been spectacularly folded into huge, ductile nappes the size of a mountain. In the overturned middle limb of one fold, the entire Paleozoic-Mesozoic section has been thinned to much less than one percent of its original thickness (Hamilton, 1982). During the thinning, however, each stratigraphic unit (especially the Paleozoic units) were remarkably well preserved. Structural analysis of folding of minor structures in the Big Maria Mountains by Ellis (1982) suggest that much of the deformation is related to south-southwest tectonic transport. Certainly, the overturning sense of the large nappe structures is south-southwestward.

In the Big Maria Mountains, a great swarm of generally north-northeast-trending pegmatite dikes is present in the central and northern parts of the range. Mapping by Hamilton (1982) has presented evidence that the dikes are late kinematic with respect to much of the this deformation in the Big Maria Mountains. In the northern and structurally highest part of the range, the dikes that probably belong to this swarm are moderately deformed and boudinaged parallel to much of the regional foliation fabric. However, in the southern and structurally lower parts of the range, the dikes appear to cut cleanly through the regional foliation and the extremely attenuated Paleozoic sections.

A biotite K- Ar age of 75 Ma (Martin and others, 1982) provides a minimum age for this dike swarm in the Big Marias and also provides a minimum to late kinematic age for the completion of the southwest-directed ductile deformation and metamorphism. Martin and others (1982) present numerous K-Ar dates for the Big Maria Mountains that conspicuously cluster between 50 and 70 Ma. As in many other locations, the 50 to 70 Ma ages can be interpreted as minimum ages for kinematic activity related to the thrusting.

Farther to the east, a probable continuation of the Maricopa thrust system eastward from the Big Marias has been mapped in the northern Dome Rock Mountains (Yeats, 1985). Analysis of fabric data by Yeats (1985) reveals that most of the thrusting in the northern Dome Rock Mountains is southwest-directed.

Farther east in the central and southern Plomosa Mountains several low-angle faults may be interpreted as southwest-directed thrust faults and may represent an eastward continuation of the Maricopa thrust zone. In the Plomosa Pass area of the central Plomosa Mountains, Scarborough and Meader (1983) have mapped a major low-angle fault that cuts up structural section to the south. It truncates older, east-directed thrusts and probably truncates the 87 Ma Mudersbach pluton (Keith and Wilt, 1983). South-dipping Paleozoic strata in the upper plate contain south-vergent folds and occur structurally beneath a major thrust. This thrust is now also tilted to the south and places porphyritic granite similar to the 1400 Ma megacrystic granites over the Paleozoic section. A kinematic model for this thrusting is presented by Keith and Wilt (1983a, p. 31A). In the central Plomosa Mountains south of Interstate 10 another thrust cuts up structural section to the south (Miller, 1970; Davis, 1985). Recent mapping by Davis (1985) indicates that this thrust is south-directed.

The western part of the Maricopa thrust system in western Arizona and southeastern California has recently been studied in detail by Reynolds and others (1986), who call it the Maria fold thrust belt. The more ductile style of the Maria fold thrust belt compared to the more brittle style of the eastern part of the Maricopa thrust system in southeastern Arizona is probably due to the greater amounts of post-thrust erosion in the Colorado River region which has exposed deeper levels of the thrust system. Similar ductile structural style is found down dip from the leading edge of the Maricopa thrust system in southeastern Arizona. This ductile deformation is present in the Santa Catalina-Rincon thrust window north and east of Tucson and closely resembles that in the Maria fold thrust belt of Reynolds and others (1986).

Southeastward extensions of the Maricopa thrust system from the Plomosa Mountains are difficult to document. On Figure 7 a large concealed area is indicated between the exposures in the Plomosa Mountains and the next well-documented south-directed thrusting along the strike of the Maricopa thrust sytem in the Sierra Blanca Mountains in the Papago Indian Reservations. However, exposures in the western Gila Bend Mountains near Cortez Peak may possibly be related to the Maricopa thrust system. Here, northeast-dipping fabric cuts a quartz dioritic gneiss of undetermined age and locally contains a faint northeast-trending lineation. Float of well-lineated, mylonitic, muscovite granite is present in many of the washes that drain Cortez Butte. Northwest of Cortez Butte, Wilson and others (1969) show a granitic outcrop of Precambrian? age. However, this granitic rock strongly resembles mylonitic muscovite granites that could be late Laramide in age and may possibly be related to southwest-directed thrusting. More work needs to be done in this area to confirm the presence of the Maricopa thrust system.

Farther to the southeast along the strike of the Maricopa thrust system, southwest-directed thrusting is present in the Papago Indian Reservation. These southwest-directed thrust faults are interpreted by us to represent the possible southeastward extension of the Maricopa thrust system from the Plomosa Mountains region. In the Papago Indian Reservation, outcropping thrust faults mapped by Haxel and others (1984) that probably comprise parts of the Maricopa thrust system include the Window Mountain Well thrust in the Sierra Blanca Mountains, a possible thrust north of the Sil Nakya Hills that would have been responsible for southwest-overturned strata there, and a similar situation at the Ajo Road fault north of the Coyote Mountains.

The Sierra Blanca Mountains contain the best evidence of south-southwest-directed thrusting that is synkinematic with the emplacement of the Sierra Blanca muscovite granite pluton. Mapping summarized by Haxel and others (1984) shows that early phases of the Sierra Blanca granite pluton are cut by fabric that is probably related to their Window Mountain thrust structure. However, late phases of the garnet-muscovite granite cut some of the fabric. Fold data from the Sierra Blanca area indicate south- or southwest-directed vergence (Davis, 1980) for the thrusting.

From the Papago Indian Reservation, the Maricopa thrust system may be traced southeastward across southern Arizona to the area south of Tucson. Southwest of Tucson in the southwestern Sierrita Mountains, Thoms (1966) has mapped a northeast-trending thrust fault with southwest-directed transport. Southeast of Tucson in the northern Santa Rita Mountains, thrusting originally mapped by Drewes (1972) has been reinterpreted by Keith (1983) and Bilodeau (1979) as being related to southwest-directed thrusting. This interpretation applies, in particular, to a major thrust zone that juxtaposes two plates containing Glance Conglomerate with different clast composition. An upper plate of Paleozoic rocks overlain by Glance Conglomerate containing Paleozoic clasts has been thrust over a lower plate of lower Paleozoic and Precambrian rocks overlain by Glance Conglomerate containing Precambrian clasts. This thrust zone, which was named the Santa Rita thrust by Keith (1983), crops out in upper Box Canyon (NE1/4, Sec. 12, T19S,R15E) and may be traced northward to the vicinity of the Mount Fagin Ranch (W1/2, Sec.35, T17S,R15E).

Farther to the southeast, the Maricopa thrust system is marked by several major, southwest-directed thrust faults in the Huachuca Mountains (Davis, 1978b). This zone of thrusting has been intruded by alaskite dikes which have yielded a 47 Ma K-Ar date (Shafiqullah and others, 1980). Farther to the east in the Swisshelm Mountains, a spectacular, large, overturned syncline of nappe dimension is present and is overturned to the southwest. Numerous southwest-directed thrust faults have been mapped in southeastern Cochise County.

From southeastern Arizona, the Maricopa thrust zone continues southeast into northeastern Sonora for about 60 miles to where it is unconformably buried beneath the Oligocene ignimbritic volcanics of the northern Sierra Madre Occidental. Major structures originally mapped by Rangin (1977) that show southwest-directed vergence are present on Sierra de Cabullona twenty miles south of Agua Prieta and at Cerro de la Marita ten miles southwest of Agua Prieta.

<u>WINDOWS INTO THE LOWER PLATE.</u> Northeast of the Maricopa thrust system a northwest-trending belt of highly tectonized (commonly mylonitic), plutonized, and metamorphosed crystalline rocks are exposed as windows beneath unmetamorphosed, unmylonitized upper plate that is composed mainly of Precambrian crystalline rock (Figure 8). The plutonized and tectonized crystalline terranes are generally separated from their 'cover' by profound low-angle fault zones that circumscribe the crystalline rocks and produce a 'pseudo-cored' aspect. The term 'pseudo-core' is appropriate because recent drill hole results summarized by Reif and Robinson (1981) suggest that the plutonized and tectonized basement

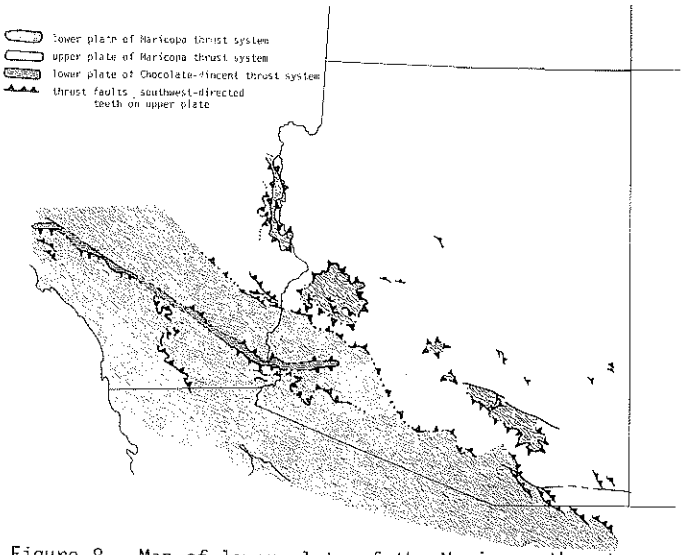


Figure 8. Map of lower plate of the Maricopa thrust system, showing the windows previously called 'metamorphic core complexes'.

exists beneath unmetamorphosed cover throughout a broad region. The 'pseuco-cored' aspect of the crystalline complexes led to nomenclature such as 'gneiss dome' in pre-1977 literature and 'metamorphic core complex' in post-1977 literature (Davis and Coney, 1979; Crittenden and others, 1980).

Portions of the profound low-angle faults that surround the underlying crystalline 'pseudo-cores' have experienced low-angle, normal separation during the mid-Tertiary (Davis, 1983; Davis and others, 1980) when the tectonized and plutonized basement was uplifted around large, anticlinal fold axes (Keith and Wilt, 1985). However, compelling evidence shows that large, low-angle reverse or thrust faults juxtaposed 'upper plate' over crystalline basement of the lower plate crystalline basement during the latest part of the Laramide orogeny (Thorman, 1977; Drewes, 1981; Keith, 1982a; Haxel and Grubensky, 1984). In our view, the so-called 'metamorphic core complexes' or 'pseudo-cores' are simply windows or fensters into a regionally extensive crystalline plate that was deformed, plutonized and tectonized by thrust faulting in the latest Laramide. The lower plate was then uplifted in the mid-Tertiary and exposed in the culminations of large, broad, openly folded, northwest-trending, antiformal arches (Keith and Wilt, 1985).

An example of a window into the crystalline basement is in the Rincon Mountains east of Tucson. Ductile, southwest-directed, flexural-flow, fold deformation of Paleozoic rocks is present on the east side of the range (Lingrey, 1982). This fold deformation is cut by the Barney Ranch pluton, which is at least 37 Ma old; this pluton was assigned to the Wilderness suite of plutons by Keith and others (1980). This deformation occurs in the lower plate of a regional low-angle fault that juxtaposes nonmylonitic Precambrian crystalline rocks over deformed Paleozoic and Cretaceous sections on both sides of the mountain range (Drewes, 1974, 1977; Thorman and Drewes, 1981; Keith, 1983a). Similar, large-scale, older over younger, low-angle fault juxtapositions occur in the Tortolita Mountains (Banks and others, 1976) and in the Rawhide and Buckskin Mountains of west central Arizona (Shackelford, 1979; 1980; Otton, 1982).

Northeast of the zone of 'thrust windows' is a diffuse system of south- to southwest-directed reverse faults and folds. This diffuse belt consists of numerous small scale thrusts and folds widely scattered throughout the northern part of the Basin and Range Province and the Transition zone. These structures are shown on Figure 7 and extend from the Vulture Mountains and Congress and Rich Hill mining districts on the west to the Morenci area on the east.

TIMING OF THRUSTING. Excellent relationships in the Santa Catalina and Rincon Mountain crystalline complexes indicate southwest- to west-southwest-directed tectonite fabrics and southwest-directed thrusting are synchronous with peraluminous magmatism, although the plutons tend to be late kinematic. Near Mount Lemmon in the Santa Catalina Mountains the Leatherwood quartz diorite (70 Ma) and the early, shallowly-dipping phases of the leucogranite phase of the Wilderness granite (45-50 Ma) have been deformed by west-southwest-directed, 'S-C' mylonitic fabrics. These fabrics are intruded by steeply dipping, later dikes of the leucogranite showing that the mylonitic fabric developed slightly before and during emplacement of the Wilderness suite of middle Eocene age.

To the southeast in the Rincon Mountains, Lingrey (1982) has shown that Paleozoic rocks have been ductilely deformed by southwest-directed flexural flow folds that predate the intrusion of the Barney Ranch peraluminous pluton of at least 37 Ma (assigned by Keith and others (1980) to the Wilderness suite). In the western and southern Rincon Mountains, Paleozoic slivers along the previously mentioned Catalina fault zone beneath Precambrian crystalline rocks in the upper plate contain flexural slip to flexural flow folds (Davis, 1975b) that are consistent with regional southwest-directed shear (Davis, 1983).

In the Redington Pass area between the Santa Catalina and Rincon Mountains, a fault similar to the Catalina fault has been intruded by parts of the Youtcy Ranch muscovite-bearing, peraluminous pluton that is at least 42 Ma and is probably part of the Wilderness suite of plutons of Eocene age (Keith and others, 1980). Throughout the southern and western parts of the Santa Catalina and Rincon mountains, peraluminous sills of the Wilderness suite are pervasively affected by southwest-directed, 'S-C' mylonitic fabric. In the forerange of the Catalinas in Bear Canyon, some of this fabric is cross cut by moderately to steeply dipping, garnet-bearing pegmatite dikes of probable Wilderness Assemblage. Thus, the overall relationships between thrusting, mylonitic fabric, and peraluminous, two-mica granitoids of Eocene age in the Santa Catalina and Rincon Mountains strongly suggest that these elements are synchronous.

Other areas showing strong evidence of synchroneity of the thrusting, mylonitization, and peraluminous plutonism include the Eastern Peninsular Ranges (Simpson, 1984; Anderson, 1983; Dokka and Frost, 1978), the Big Maria Mountains (Hamilton, 1982; Martin and others, 1982), the central Harquahala Mountains (Reynolds and others, 1980), and the Gunnery Range and Papago Indian Reservations (Haxel and others, 1984).

In summary, southwest-directed mylonitic shear zones, southwest-directed thrust faults and folds, and peraluminous plutons of the Wilderness Assemblage all seem to be broadly synkinematic, although the plutons tend to be late kinematic. These events occur in southeast California between 85 and 75-70 Ma, between 70 to 60 Ma in western Arizona, and between 60 to 45 Ma in southeastern Arizona.

REGIONAL MAGNITUDE OF THRUSTING. Both geometric reconstructions and petrology of peraluminous magmatism provide strong evidence for the regional magnitude of southwest-directed thrusting. Where southwest-directed thrusting is present, very large amounts of horizontal transport are suggested by the difficulty of matching upper plate lithologies with those in the lower plate throughout southern Arizona and southeastern California. The amount of tectonic transport of upper plate relative to lower plate along southwest-directed thrust faults of the Wilderness Assemblage appears to have been much larger than that associated with northeast-directed folds and faults of the Tombstone Assemblage of the earlier Laramide. Where southwest-directed thrusting is or may be present, very large amounts of horizontal transport are indicated, because upper plate rocks are difficult to match or cannot be matched with lower plate rocks anywhere in the region.

For example in the Rincon Mountains east of Tucson, nonmylonitic Precambrian rocks (generally granodiorite of 1625 Ma) in the upper plate of the Catalina fault and their probable analogs in the eastern Rincons and Johnny Lyon Hills can be found on both the west and east sides of the mountain range. These nonmylonitized rocks of the Precambrian upper plate cannot be matched anywhere in the mountain range with unmylonitized crystalline rocks of the lower plate; all Precambrian rocks in the lower plate are generally mylonitic (generally granite of 1400 Ma). To remove the nonmylonitic upper plate from the generally mylonitic or deformed lower plate along a line parallel to the lineation would require cumulative transport of at least 35 km, which is the exposed outcrop width of lower plate rocks parallel to lineation. How much of this transport is related to southwest-directed culminant Laramide thrusting or how much is related to southwest-directed culminant Galiuro detachment faulting (Keith and Wilt, 1985) is not yet clear. However, most of the overlap is probably due to southwest-directed thrusting of the culminant Laramide, because similar mismatches occur regionally, even where there are no mid-Tertiary detachment faults.

In the Papago Indian Reservation west of Tucson, a major lithologic boundary exists (Haxel and others, 1980; 1984). Stratigraphy north of the boundary generally consists of fairly widespread Precambrian crystalline rocks that are unconformably overlain by the younger Precambrian Apache Group, which are unconformably overlain by Paleozoic rocks. The Paleozoic rocks are unconformably overlain by Bisbee Group equivalents of mid-Cretaceous age, and all of the earlier rocks are intruded by Morenci Assemblage plutons and their associated porphyry copper deposits. Significantly, igneous rocks of the early to middle Jurassic magmatic arc are not present in the northern area. Rocks south of the boundary consist only of the Mesozoic magmatic arc, unconformably overlain by clastic sedimentary rocks that are mostly mid-Cretaceous in age. This assemblage is intruded by extensive, peraluminous plutons of the Wilderness Assemblage of Paleocene age, which do not intrude rocks north of the boundary.

The boundary between northern and southern terranes could partly represent the Maricopa thrust system that places Precambrian rocks in the northern Papago Indian Reservation over Jurassic-Cretaceous rocks in the southern Papago Indian Reservation along a regional, shallowly north- to northeast-dipping thrust. The widespread presence of peraluminous plutons of the Wilderness Assemblage south of the currently exposed leading edge of the Maricopa thrust system may indicate that the upper plate was originally present over much of the southern Papago Indian Reservation and has subsequently been removed by Eocene and later erosion.

Northwest of the Papago Indian Reservation in the Harquahala Mountains 60 miles west-northwest of Phoenix, extensive lithologic differences or mismatches occur between the upper and lower plates along the Hercules and Harquahala thrusts, both of which are southwest- to south-directed thrust faults. At least 10 km of low-angle structural overlap along a SSW-NNE line are required to remove Proterozoic crystalline rocks in the upper plate of the Harquahala thrust from the nonmatching, upside down, Paleozoic section in the lower plate. At least 20 km of overlap parallel to a similar SSW-NNE line is required to remove the mostly Precambrian crystalline rocks in the upper plate of the Hercules thrust from the mostly Mesozoic rocks in the lower plate. (See Fig. 1 in Spencer, 1984).

In the Rawhide, Buckskin, and Northern Plomosa Mountains extensive lithologic mismatches occur between Precambrian crystalline rocks, which are predominantly mylonitic without 1400 Ma granites in the lower plates and which are nonmylonitic with widespread 1400 Ma granites in the upper plates. In the Buckskin Mountains and Rawhide Mountains Shackelford (1979, 1980) has mapped a 'middle plate' of tectonized Paleozoic and Mesozoic rocks above the Rawhide-Buckskin detachment fault. In one area in the northern Rawhide Mountains, Shackelford shows that these Paleozoic rocks are structurally overlain by Precambrian crystalline rocks. The Precambrian crystalline rocks in that upper plate are in turn unconformably overlain by mid-Tertiary volcanic and clastic rocks. Thus, Paleozoic and Mesozoic strata are erosionally missing above the Precambrian in the upper plate, although they are present, though tectonized, above the Precambrian in the middle plate. A similar relationship exists in the northern Plomosas where a complexly faulted Paleozoic and probable Mesozoic metasedimentary section occurs in the upper plate of the Plomosa detachment fault (Scarborough and Meader, 1983).

Thus, juxtapositions of older over younger rocks are similar in both the northern Plomosa and northern Rawhide Mountains. If the nonmylonitic Precambrian-bearing upper plate existed as a regional sheet from the Rawhide to the Plomosa Mountains, then 35 km of overlap is implied along a line parallel to the widespread N50E-S50W lineation in the lower plate. Similar extensive lithologic mismatches exist between upper and lower plates in the Whipple, Chemehuevi, Sacremento, Dead, and Newberry Mountains of southeastern California and southernmost Nevada.

The mismatches between the nonmylonitic Precambrian crystalline rocks in the upper plate and the mylonitic rocks in the lower plate are commonly attributed entirely to middle Tertiary detachment faulting (Davis and others, 1980; Rehrig and Reynolds, 1980). However, the juxtaposition of upper plate crystalline rocks in the Whipple Mountains may have originally been produced by deep level, northeast-dipping Maricopa system thrusting of the nonmylonitic Precambrian (Mogollon Highlands) plate on the north over the mylonitic lower plate of the Whipples; this thrust was later reutilized in mid-Miocene time. Recent work by Greg Davis and Lawford Anderson (pers. comm., 1985) indicates that the high angle fabric that was formerly thought to be Precambrian by Davis and others (1980, 1982) is now known to be mid-Cretaceous because the high-angle fabric cuts the low-angle mylonitic sills (dated at 85-75 Ma) and is cut by the low-angle mylonitic fabric (Wright and others, 1986). Because the fabric is Cretaceous rather than Precambrian, then the rocks that the fabric deforms may not be Precambrian either.

The presence of Mesozoic protoliths in the lower plate is becoming increasingly more apparent. For example, in the southwestern end of the Buckskin Mountains, nonmylonitic Mesozoic metasedimentary rocks gradationally become more mylonitic (Marshak, 1980). Mesozoic protoliths have recently been recognized elsewhere in the lower plate of the Buckskin Mountains (Reynolds, pers. comm., 1985) and may exist in the Cunningham Pass area of the Harcuvar Mountains where numerous amphibolite grade lenses of calc-silicate rocks are present. The occurrence of Mesozoic protoliths in the mylonitic lower plate beneath well-documented nonmylonitic Precambrian rocks in the upper plate indicates an older over younger thrust-relationship over a broad region in western Arizona.

Ultimate amounts of transport could have been much greater than the minimum 10 to 35 km of southwest-directed transport deduced from the overlap of nonmatching lithologies. The upper plates of the Maricopa thrust system throughout southwestern Arizona mainly consist of nonmylonitic Precambrian crystalline rocks that are unconformably overlain by mid-Tertiary clastics and volcanics. This terrane is typical of the 'Mogollon Highlands' of Cooley and Davidson (1963) where Paleozoic and Mesozoic strata were stripped away by erosion during the Mesozoic and Tertiary. The 'Mogollon Highlands' plate of Tertiary sediments and volcanics deposited on nonmylonitized Precambrian granites (1400 Ma) is the structurally highest plate in the Riverside, Whipple, Rawhide, Buckskin, Harquahala, Big Horn, Harquvar, and Plomosa Mountains. The lower plates in the same region consist of tectonically imbricated plates of mylonitic rocks, including Precambrian, Paleozoic, and Mesozoic strata. These mylonitic rocks occur in the crystalline 'pseudo-cores' of the Tortolita, Catalina, Harquahala, Harcuvar, Rawhide, and Buckskin Mountains. They can be visualized as 'windows' through the nonmylonitic upper plate into the mylonitic lower plate.

If the Maricopa thrust is taken as the leading edge of the Mogollon Highlands plate, then present lithologic overlap between the Mogollon Highlands plate and the lower plate containing Paleozoic and Mesozoic protoliths would be at least 90 km projected to and along the line of the lower plate lineation (which is N50E-S50W). This would be the amount of transport required to remove the overlap; it is the distance between the Riverside Mountains in southeastern California (the southwesternmost exposures in the upper plate where Paleozoic rocks are missing and middle Tertiary rocks unconformably overlie Precambrian) and the northern Rawhide Mountains (the northernmost exposures in the lower plate where metamorphosed Paleozoic sections occur).

Restoration of mid-Tertiary, northeast-directed, normal motion along portions of the thrust that have been reutilized magnifies the overlap problem. For example, Reynolds and Spencer (1985) speculate that large-scale, northeast-directed, normal motion of Proterozoic rocks in the upper plate Bullard detachment fault in the Harcuvar-Harquahala region may have been as much as 50 km. If so, the configuration before low-angle normal faulting put the upper plate (Mogollon Highlands plate) 35 km farther southwest of its present position relative to lower plate Mesozoic-Paleozoic strata. This increases the southwest-directed transport during Laramide thrusting to a speculated 125 km.

Amounts of southwest-directed thrusting may also be estimated from the petrologic data. For example, using a petrologically estimated thickness of thrust plate above a given Wilderness Assemblage pluton of about 8 km and a regional dip from seismic data of the Maricopa thrust system beneath the Colorado Plateau of about 3o, then about 150 km of thrust overlap is required using the sine function. This figure roughly agrees with lithological overlap evidence presented earlier.

THICKNESS OF THRUST PLATES. A crustal thickening of 6-8 km is required to explain the emplacement depth of Wilderness Assemblage plutons discussed earlier. The peraluminous plutons of the Wilderness Assemblage formed at 10 km intrude earlier Laramide plutons of the Morenci Assemblage that formed at depths shallower than 3.5 km. These earlier metaluminous plutons were drier (2 to 4 weight % H2O), epizonal plutons and were commonly associated with mesothermal hydrothermal mineral deposits that formed at depths shallower than 3.5 km.

For example in the Santa Catalina Mountains, the Leatherwood suite plutons (which are locally porphyritic plutons of the Morenci Assemblage that are in places associated with porphyry copper-skarn mineralization that probably formed at depths of less than 3 km) are intruded by the Wilderness granite (Keith and others, 1980), which probably crystallized at depths of 10 km or more.

Thus, where shallow level, metaluminous plutons of the Morenci Assemblage were directly intruded by deeper level peraluminous plutons of the Wilderness Assemblage, the shallower level plutons had to be deeply buried in order to be in contact with the deeper level intrusions. Between the time of the Morenci Assemblage and the Wilderness Assemblage in any given area (no more than 10 million years), at least 6 km of crust must have been added above the Morenci Assemblage. The only way to accomplish this is to thicken the crust after Morenci Assemblage and before or during Wilderness Assemblage. A logical mechanism to thicken the crust is by major thrusting of older rocks over younger rocks during culminant Laramide orogeny.

Field relationships in several areas also indicate that the preserved thickness of the upper plate beneath the earliest Oligocene unconformity was at least 3 km and possibly as much as 12 km thick. For example on the Papago Reservation, Haxel and others (1984) suggest that the upper plate of the Baboquivari thrust system (which is part of the Maricopa thrust system in this paper) was on the order of 5 to 8 km thick and was emplaced after porphyry copper related intrusions (Morenci Assemblage metaluminous magmatism) and before or during two-mica granite intrusions (Wilderness Assemblage peraluminous magmatism). In the Johnny Lyon Hills 40 km east of Tucson, about a thickness of 6 km of upper plate (consisting of undeformed Precambrian, Paleozoic, and Cretaceous sediments) may be preserved above a fault that generally dips east and is analogous to the Catalina fault. This fault juxtaposes undeformed Precambrian Johnny Lyon granodiorite in the upper plate over deformed Paleozoic and Mesozoic sediments in the lower plate.

In western Arizona the thickness of the rotated Precambrian plate above the imbricated Paleozoic section in the northern Rawhide Mountains is at least 3 km thick (Davis and others, 1980). If the structural restorations by Howard and others (1982) for the Mohave Mountains are correct, as much as 12 km of tilted crystalline Precambrian rocks are present above the Whipple low-angle fault. In many other areas, the preserved thickness of the upper plate is considerably less because of erosion during the late Eocene through Miocene.

Seismic, geochronological, geochemical, and lithological data from the Arizona State A-1 well (Reif and Robinson, 1981) also suggest a thick upper plate overlapped a significantly different lower plate in central Arizona. In the A-1 well, Reif and Robinson report the upper 2.3 km is megacrystic granite that is 1400 Ma; it overlies a unit of muscovite granite dated at 47 Ma which contains inclusions of biotite hornblende gneiss that is older than 1500 Ma. The contact between the upper two units can be considered as both a major lithologic break and a major tectonic break between two plates. The upper plate is at least 2.3 km thick and consists of 1400 Ma granite (part of the Mogollon Highland plate of this paper); the lower plate consists of probably mylonitic gneisses containing sills of peraluminous granite of the Wilderness Assemblage. Significantly, this inferred tectonic break is also broadly coincident with the low-angle, northeast-dipping boundary between an upper plate package that is non-reflecting and a lower plate seismic package that contains numerous continuous seismic reflectors. (See figures in Keith, 1980, and Reif and Robinson, 1981).

The contact in the well discussed above between the two lithologic and seismic units would be part of the Maricopa thrust system that is at depth and northeast of its currently exposed leading edge in southwestern Arizona (Figure 7). The biotite-hornblende gneiss of the lower plate is lithologically and geochemically dissimilar to the 1400 Ma granite of the upper plate, implying a major lithologic mismatch of Precambrian lithologies in the two plates. This relationship is similar to significant differences between upper and lower plates in the Sacaton Mountains encountered during drilling for porphyry copper mineralization between Tucson and Phoenix. There the upper plate consists of Precambrian (mostly 1400 Ma) and Laramide plutons and the lower plate consists of schistose rocks.

Age of Wilderness Assemblage

CROSS-CUTTING RELATIONSHIPS. Where the metaluminous and peraluminous Laramide plutons are not in contact, but are in close geographic proximity, the peraluminous plutons generally yield younger radiometric age dates. For example in the Papago Indian Reservation, the metaluminous Cimarron Mountains pluton has yielded an U-Pb zircon date of 68 Ma (Smith and Eaton, 1979), whereas the peraluminous Pan Tak and Gu Achi granites in the Coyote and Quinlan Mountains about 30 km to the southeast have yielded near concordant zircons of 58 Ma(Wright and Haxel, 1982).

Conversely, metaluminous plutons or dikes of the younger Galiuro assemblages cross-cut Wilderness Assemblage plutons. For example, the Santa Catalina-Tortolita plutons (26 Ma) intrude peraluminous pegmatites (45-50 Ma) of the Derrio Canyon granite and leucogranite of the Wilderness granite. In the Harquahala Mountains 28 to 25 Ma microdiorite dike swarms cross-cut peraluminous plutons in the eastern Harquahala Mountains that are probably Eocene in age (Keith and others, 1983).

EASTWARD YOUNGING. In common with earlier Laramide metaluminous magmatism, peraluminous granitoids of the Wilderness Assemblage are generally older in the west and younger in the east. In the Old Woman Mountains of southeastern California, Miller and Bradfish (1980) report a Rb-Sr isochron of approximately 80 Ma for the Sweetwater Wash pluton. Peraluminous plutons in the Whipple Mountains have also yielded U-Pb dates of 85-75 Ma (Anderson, pers. comm., 1984). To the east, U-Pb data from the Pan Tak pluton in the Coyote Mountains yield an age date of about 58 Ma (Wright and Haxel, 1982). About 60 km further to the east in the Santa Catalina Mountains, the Wilderness granite is 44-50 Ma (Catanzaro and Kulp, 1964; Shakel and others, 1977; Keith and others, 1980).

On a regional scale, the peraluminous plutons occupy the youngest part of the west to east magmatic sweep on the time-distance curve of Coney and Reynolds (1977). The peraluminous plutons exhibit a paired relationship with the metaluminous plutons of the older Laramide. In any given time slice, the peraluminous plutons occupied a diffuse plutonic belt west of the older metaluminous magmatism and moved eastward with the metaluminous magmatism in a coordinated, paired fashion (Keith and Reynolds, 1981). Because the peraluminous plutons and associated southwest-directed thrust faults of the Wilderness Assemblage are part of the eastward migration of Laramide magmatism, they should be considered part of the Laramide orogeny. More specifically, Wilderness Assemblage magmatism in any given area represents the culmination of Laramide orogeny.

REDUCED ISOTOPIC AGES. Another distinctive feature of the Wilderness Assemblage is regional low-grade metamorphism or heating expressed by reduced radiometric dates. In any given area Wilderness Assemblage plutons have been emplaced into older rocks that commonly yield reduced K-Ar and fission track ages that are about the same age as or slightly younger than the emplacement of the peraluminous granites. As with peraluminous plutons of the Wilderness Assemblage and magmatism of Laramide strato-tectonic assemblages in general, reduced ages assigned to Wilderness Assemblage become younger eastward. For example, in the Transverse Ranges of southeast California, Miller and Morton (1982) have obtained numerous reduced K-Ar dates that range from 85 to 72 Ma. To the east in the Big Maria Mountains K-Ar cooling ages on Precambrian through Mesozoic metasedimentary rocks range from 72-50 Ma (Martin and others, 1982). In western Arizona numerous reduced K-Ar ages cluster between 60-44 Ma (Shafiqullah and others, 1980; and Hardy, 1984 in the Harquahala and Harcuvar Mountains). In all of the above mentioned areas, regionally reduced age dates by the K-Ar and fission track methods coincide with emplacement ages of peraluminous plutons of the Wilderness Assemblage.

Resources of the Wilderness Assemblage.

Wilderness Assemblage magmatism contains metallogeny distinctly different from earlier

Laramide metallogeny, of which the porphyry copper deposits associated with the Morenci Assemblage epizonal, porphyritic plutons are the most well-known. Tungsten deposits and lead-zinc-silver deposits containing minor copper and gold occur as veins and replacements associated with two-mica granitoids or pegmatites of the Wilderness Assemblage. The plutons associated with the base-metal rich deposits (Sweetwater Facies) are more alkalic than the plutons associated with gold-related deposits (Gold Basin Facies), though both represent hypo-mesothermal to mesothermal emplacement depths.

Small amounts of kyanite for refractory uses have been locally been produced from kyanite-rich accumulations in and near the thrust zones adjacent to the gold deposits in the Cargo Muchacho Mountains. Many occurrences of kyanite have been found near oxidized, peraluminous calcic pegmatites or plutons.

The more calcic rocks of the Wilderness Assemblage (Gold Basin Facies) have great economic potential and may contain more gold resources than have been produced from any other Laramide or Tertiary assemblage in Arizona. The recent discoveries of Mesquite (Glamis) and Picacho in southeastern California associated with two-mica- and garnet- bearing pegmatites and gold-quartz veins emphasize the potential of the Wilderness Assemblage for future gold production. Resources recently announced by Goldfields at Mesquite amount to at least 63.5 million tons of gold ore at 0.058 oz Au/ton.

OROCOPIA ASSEMBLAGE

Name

The name Orocopia Assemblage was given by Keith (1984) to Laramide recrystallization phenomena in older schistose rocks that possibly were Jurassic metagraywackes and that now occur in the lower plate of the regional Chocolate Mountain thrust system of southeastern California and southwestern Arizona. Laramide recrystallization is indicated by numerous reduced K-Ar ages that record termination of a metamorphic event that was possibly associated with the final emplacement of the schistose rocks, such as the Orocopia, Rand, and Pelona schists summarized by Haxel and Dillon (1978). The term Orocopia Assemblage was chosen for recrystallization phenomena in the Orocopia Schist beneath the Chocolate Mountain thrust within the Orocopia Mountains 30 km east of Indio in southeastern California. General characteristics of rocks and structures of the Orocopia Assemblage are summarized in Table 20 and examples are listed in Table 21 and are shown on Figure 7.

Metamorphism of Orocopia Assemblage

There are no sedimentary, volcanic, or plutonic rocks in the Orocopia Assemblage. Rather, Orocopia Assemblage 'rocks' consist of metamorphism and recrystallization phenomena in rocks that predate Orocopia Assemblage tectonism. Orocopia Assemblage metamorphism consists of greenschist-grade metamorphism of metagraywackes that had previously been metamorphosed to blueschist grade (Ehlig, 1968; Graham and England, 1976).

Table 20. Characteristics of Orocopia Assemblage of the culminant Laramide orogeny

METAMORPHISM	MAGMATISM	STRUCTURES
greenschist metamorphism of mostly blueschist grade Franciscan metagraywackes of orig. mid-Jurassic to mid-Cretaceous age ?	none	very large, poss. SW-dir., very shallowly NE-dipping regional thrust faults (Chocolate-Vincent thrust system) foliation fabric within schists of lower plate has NE-SW trending lineation schistose rocks contain numerous fold styles of uncertain kinematics

Petrographic and chemical data (Keith, unpub. data) is consistent with original deposition in a basin or possibly a trench that was marginal to the North American continent. The original blueschist-grade metamorphism could have occurred in an accretionary melange wedge developed above the subduction zone from Late Jurassic through mid-Cretaceous time. The greenschist metamorphism of the Orocopia Assemblage would then be related to emplacement via thrusting beneath the North American plate.

The original metamorphism of the schists is no older than 163 Ma, which is the date of a pre-metamorphic pyroxene-hornblende diorite dike that intrudes metagraywackes of the lower plate (Mukasa and others, 1984) and may pre-date final emplacement subsequent to 85 Ma. Numerous reduced K-Ar ages between 47 to 60 Ma reflect cooling and termination of metamorphism of the Orocopia Schist perhaps during the last phases of emplacement. For example, the Pelona Schist beneath the Vincent thrust in the San Gabriel Mountains was metamorphosed during the Paleocene (Ehlig, 1968; 1984). The concentration of K-Ar and Rb-Sr isotopic ages from the Pelona Schist and Vincent thrust in the interval between 50 to 60 Ma suggested to Haxel and Dillon (1978) that the metamorphism occurred in Paleocene time.

Table 21. Examples of Orocopia Assemblage of the culminant Laramide orogeny

	SYMBOL	EXAMPLES	REFERENCES
SEDIMENTS		none	
METAMORPHISM	CM	Chocolate Mountains	Dillon, 1976
	GR	Garnet Ridge	Helmstaedt & Doig, 1975
	MW	Marcus Wash granite	Haxel, 1977, 1978
	O	Orocopia Mtns.	
	Os	Orocopia Schist	Haxel & Dillon, 1978
	P	Picacho, CA	Haxel, 1977, 1978
	Ps	Pelona Schist	Crowell, 1981
	R	Randsburg	Silver & others, 1984
	Rs	Rand Schist	Graham & England,1976; Ernst,1971
	SG	San Gabriel Mtns.	Dibblee, 1982; Ehlig, 1981
	SG	San Gabriel Mtns.	Carter & Silver, 1972
	T	Trigo Mountains	Haxel, 1984
	CDM	Castle Dome Mountains	Haxel, 1984
MAGMATISM		none	
STRUCTURES	CMt	Chocolate Mts. thrust	Haxel & Dillon, 1982
	Rt	Rand thrust	Crowell, 1981
	Vt	Vincent thrust	Tosdal & Haxel, 1982

Structural Features of the Orocopia Assemblage

STRUCTURES. Structures herein assigned to the Orocopia Assemblage consist of the regional thrust faults of the Chocolate-Vincent-Rand thrust system, which is regionally present throughout southeastern California and southwestern Arizona (Haxel and Dillon, 1978; Crowell, 1981). Principal thrusts are the Rand thrust in the Rand Mountains of northeastern Kern County, the Vincent thrust in the San Gabriel Mountains of northern Los Angeles County, and the Chocolate Mountain thrust in Riverside and Imperial Counties of southeastern California and southern Yuma County in southwestern Arizona.

These structures are very large, very shallowly northeast-dipping, possibly southwest-directed, regional thrust faults. The foliation fabric within schists of the lower plate below the thrusts generally have northeast-southwest trending lineation. Mineral assemblages in the Pelona Schist are transitional between blueschist and greenschist facies (Graham and England, 1976). The upper plate of the Orocopia-Vincent thrust system is commonly affected by thrust-related mylonitic fabric that cuts retrograded granulites, amphibolite-grade paragneiss and orthogneiss of Precambrian through possibly mid-Cretaceous age. The thrust-related mylonites in the upper plate commonly contain a northeast-southwest-trending lineation parallel to lineation in the lower plate schistose rocks. Tectonic transport directions for the upper plate mylonites yield contradictory results. Based on Hansen slip-line analysis, Haxel and Dillon (1978) suggest that upper plate was transported northeast relative to lower plate in the southeast Chocolate Mountains. Southwest-directed transport is indicated along other segments of the thrust, for example in the Orocopia Mountains.

MAGNITUDE OF THRUSTING. Subhorizontal transport along Orocopia Assemblage thrust faults dwarf those of all other Cretaceous and Cenozoic assemblages in the region. Shortening for the Wilderness Assemblage thrust faults discussed earlier was suggested to be as much as or greater than 125 km. Lateral transport along Orocopia Assemblage thrust faults probably was at least 150 km and may have been as much as 725 km or more.

The metagraywackes, minor metapelites, cherts, and mafic metavolcanic rocks in the lower plates of thrust faults of the Orocopia Assemblage have no lithologic analogs anywhere in the upper plate. That is, there are no correlatives in the North American plate above the Orocopia Assemblage thrusts, such as above the Vincent or Chocolate Mountain thrust faults. In southeastern California and southern Arizona, an overlap of North American upper plate rocks over lower plate metagraywackes of the Orocopia Schist and correlatives can be reasonably inferred to be at least 150 km projected parallel to a N50E-S50W line, which is the average trend of lineation in the lower plate schistose rocks.

An overlap between upper plate (North American plate) rocks and lower plate schistose rocks can be tenuously extended to at least 270 km based on petrologic data from Wilderness Assemblage plutons that may have been derived from metagraywacke protoliths such as the Orocopia Schist. For example in the White Tank Mountains, Brittingham (1985) reports geochemical, trace element, and measured strontium isotopic data ($^{87}Sr/^{86}Sr=.7048$) that is consistent with a metagraywacke source for the Wilderness Assemblage peraluminous pluton in the northeastern White Tank Mountains. Similar data on the Gunnery Range pluton of southwestern Arizona obtained by Arnold (pers. comm.) suggests that the Gunnery Range pluton may also be largely derived from a metagraywacke protolith. The calcic, peraluminous pluton in the White Tank Mountains represents the farthest northeastern extent yet documented of calcic, peraluminous magmatism. If the inference that it was derived from a protolith of metagraywacke is correct, then the White Tank Mountains are also the farthest northeastern extent of graywacke protolith beneath the North American plate. The inferred presence of metagraywacke beneath the White Tank Mountains would extend the amount of lithologic overlap of metagraywacke beneath the North American plate to a distance of at least 270 km along a northeast-southwest line.

Perhaps the most provocative data for continent-scale underthrusting of Franciscan-like materials beneath North America was reported by Helmstaedt and Doig (1975). They obtained samples of blueschist eclogite from inclusions in the nepheline alkalic diatremes of mid-Tertiary age at Garnet Ridge and Moses Rock in the Four Corners Region of Arizona and Utah. The affinity between the eclogite inclusions and the Franciscan-like rocks was affirmed by lawsonite cores and jadeite cores within pyroxene and amphibole phenocrysts from the eclogite inclusions. Helmstaedt and Doig (1975) state that the only way to get a high-pressure, low-temperature assemblage beneath a continental area such as the Colorado Plateau was to invoke massive continent-scale underthrusting of Franciscan-like materials beneath North America. If it is assumed that the Franciscan-like eclogite inclusions are indeed underthrust Franciscan, then the amount of implied lithologic overlap would be at least 625 km.

The potential overlap of upper and lower plates can be extended to 725 km by locating the farthest west occurrence of metagraywackes in the lower plate. In 1968 Robert Yeats suggested that the Catalina Schist, which occurred beneath ophiolitic basic metavolcanic rocks and Jurassic metavolcanic rocks on Catalina Island in southern California might correlate with the Orocopia Schist and its correlatives in the Transverse Ranges. If it is assumed that Yeats (1968) correlation is correct and that Helmstaedt and Doig (1975) are correct, then possible overlap of Franciscan material beneath the North American plate could be 725 km from southwest to northeast.

MISSING CRUST. One of the most remarkable structural features of the Orocopia Assemblage thrusting is that deep level schistose terranes or metagraywacke packages have been commonly juxtaposed against surficial assemblages of the North American plate. Deeper North American crust, such as the granulite layer which would be expected in a normal crustal profile, is missing. For example, in the southeastern Chocolate Mountains, the Castle Dome Mountains, and the Kofa Mountains, the Chocolate Mountain thrust places deep level Orocopia Schist in direct contact for long distances with supercrustal rocks of Slumullion, which is a sequence of Jurassic redbeds, clastic sedimentary rocks and alkaline volcanic rocks (Haxel, in press). In other places, such as the southeastern Chocolate Mountains, eastern San Gabriel Mountains, southern and western Rand Mountains of California, rocks of upper crustal levels, such as Precambrian orthogneiss (1400 Ma? granites), Jurassic? orthogneiss, and Cretaceous mesozonal (3-6 km?) plutons, are in direct contact with deeper level, schistose terranes of the lower plate.

Granulitic materials and deep level anorthosite bodies of the lower crust locally occur in the upper plate juxtaposed against deep level schists in the lower plate of the thrusts. For example, Mendenhall gneiss of granulitic grade in the San Gabriel Mountains and anorthosite-syenite complexes dated about 1100 Ma occur locally in the upper plate of the thrust in the San Gabriel and Orocopia Mountains. Thus, there are places where the granulite lower crust is locally preserved in the upper plate, but for the most part the granulite crust is missing in the upper plate. In effect, the North American crust throughout much of the western Mojave desert region is a rootless, crystalline 'flake' that is resting allochthonously on probable schistose basement.

This interpretation is consistent with some of the deep crustal COCORP seismic data recently shot across the western Mojave block (Frost and others, this volume). These seismic sections show numerous reflecting horizons at depth beneath the western Mojave that could in part represent the schistose basement. Based on the seismic data, the base of the present crust in the western Mojave region occurs no deeper than 20 to 25 km, which is about half of the expected thickness for normal continental crust. Thus, the crust has been thinned 100% and the possibility exists that the lower 20 km of the crust that had been present in middle Cretaceous time was removed by decretion thrusting in the early Cenozoic (Keith and Livaccari, 1985).

Age of Orocopia Assemblage

Relative age relationships and geochronologic calibration along the various thrust faults suggest thrusting occurred post-85 Ma and terminated about 60 Ma. In the San Gabriel Mountains hornblende-biotite quartz diorite in the upper plate that is in contact with the Vincent thrust yields K-Ar dates on hornblende of 67 Ma (Miller and Morton, 1980). Petrographically similar plutons in the upper plate immediately to the east have the same chemistry as the calc-alkalic plutonism of 85 to 105 Ma in the Transverse Ranges and in the Southern California batholith. One of the plutons in the San Gabriel Mountains has yielded a U-Pb date on zircon of 80 ±10 Ma (Carter and Silver, 1972). These same plutons also yield numerous K-Ar dates of 68 to 75 Ma (Miller and Morton, 1980). Thus, available evidence in the San Gabriel Mountains indicates emplacement of the Vincent thrust after 85 Ma.

In the Randsburg area, Silver and others (1984) report a U-Pb date of about 86.5 Ma on zircon from a granite in the upper plate that is cut by the Rand thrust zone. This date strongly suggests that thrust emplacement of the schist beneath the Rand thrust is younger than 85 Ma. In the Tehatchapi Mountains north of the Garlock fault, granitoid rocks of the southern Central California batholith that resemble the 85-105 Ma, metaluminous, calc-alkalic plutons are in fault contact with the Pelona Schist in the northern Garlock fault zone and therefore predate thrusting. In the southeasternmost Chocolate Mountains, minimum ages for rock juxtapositions along the Chocolate Mountains thrust are Paleocene based on K-Ar data on the Marcus Wash Granite, which cross-cuts the thrust (Haxel, 1977).

In summary, available radiometric and stratigraphic data for cross-cutting relationships associated with the Rand-Vincent-Chocolate Mountain thrust system of the Orocopia Assemblage suggests the thrusting occurred between 85 and 60 Ma. The younger age limit for the thrusting is also supported by the Paleocene-Eocene cooling ages for thrust-related metamorphism. In any given area, Orocopia assemblage tectonism appears to post-date Wilderness assemblage tectonism. In several areas of southern California, peraluminous alaskites of the Wilderness Assemblage are truncated by the Chocolate-Vincent thrust system of the Orocopia Assemblage.

Resources

There are no metallic ore deposits discovered to date associated with the metamorphism of the Orocopia Assemblage. In the western San Gabriel Mountains Ehlig (1984) reports that many of the quartz veins in the Pelona Schist beneath the Vincent thrust contain anomalous gold concentrations. However, none of these gold-bearing veins has yet been proven commercial.

PLATE TECTONIC INTERPRETATIONS

The foregoing sections have described a sequential array of empirically defined strato-tectonic assemblages. The orderly and sequential overprinting of the various Laramide strato-tectonic assemblages is a result of the plate tectonic process and constitutes a detailed record of that process. The superposition of the assemblages may be viewed as the sequential record of magmatic, structural, sedimentologic, and resource phenomena that are coordinated to and reflect the flattening of the underriding Farallon plate beneath the North American plate from 89 Ma to 43 Ma (Keith, 1982b).

Initial flattening in Arizona and adjacent regions in the early initial Laramide is recorded by the Hillsboro Assemblage in the Basin and Range Province of southern Arizona and New Mexico and by the Laramie Assemblage on the Colorado Plateau. These assemblages represent the earliest evidence of eastward migration after 89 Ma of the Laramide orogenic front from the position of the Sevier orogenic front in southeastern California and western Arizona. Thus, initial flattening on the Colorado Plateau was reflected by a dramatic straightening of shorelines and an overall shoaling effect that dramatically increased the volume and area of continental sedimentation and coal formation in the Laramie Assemblage. Weak regional compression was manifested on the Colorado Plateau by broad, open, symmetrical folding that may have influenced coal deposition.

In the Basin and Range Province of Arizona and New Mexico, the initial flattening in the early initial Laramide was marked by wedge uplifts and accompanying sedimentation in the Hillsboro Assemblage. The vertical nature of the uplifts suggests that shortening produced by the regional compression was minimal. The initial eastward migration of the metaluminous magmatic arc is also manifested by metaluminous, quartz alkalic magmatism and attendant copper-gold mineralization. This magmatism signals the first eastward shift of metaluminous magmatism from its former position in the eastern Peninsular Range batholith (105-89 Ma) of the Sevier orogeny.

As flattening progressed during late initial Laramide orogeny, increased shortening related to increased regional compression in a NE-SW direction was recorded as the Denver Assemblage on the Colorado Plateau and the Tombstone Assemblage in the Basin and Range Province. In contrast to the early initial Laramide assemblages (Hillsboro and Laramie assemblages), structural development during late initial Laramide orogeny displayed a distinct northeast- to east-directed vergence. Continued flattening of the subducting slab was manifested by less alkaline, alkali-calcic metaluminous magmatism and associated lead-zinc-silver mineralization of the Tombstone Assemblage in the Basin and Range Province and the central Colorado Mineral Belt.

During medial Laramide orogeny, progressive flattening of the subducting slab was represented by eastward passage of the main volume of metaluminous calc-alkalic magmatism and associated copper-molybdenum mineralization. In contrast to initial and culminant Laramide strato-tectonic assemblages, the medial Laramide assemblages do not display evidence of compressive deformation. Rather, extensive dilational phenomena expressed as regional, northeast- to east-northeast-striking dike swarms were emplaced between west-northwest-striking zones distributed left shear in the Basin and Range Province. In the Basin and Range Province the arc thermal axis is represented by the Morenci Assemblage.

Extreme flattening during the culminant Laramide orogeny is represented by extremes of sedimentation, compressive deformation, and volumes of magmatism. Although extreme structural phenomena are recorded throughout the western United States, Arizona contains evidence of magmatic phenomena only in the southwestern half of the state and of sedimentation phenomena only in the northeastern half.

In northeastern Arizona, locally coarse clastic sediments of the Echo Park Assemblage were deposited in a zone of en echelon, northwest-trending, narrow synclinal basins that approximately coincide with the present day Rio Grande Rift. The Echo Park-type basins probably formed as en echelon, transpressional basins within a regional zone of north-south distributed right shear that affected the eastern part of the Laramide orogen in middle Eocene time. Kinematic analysis of the Echo Park type basins by Chapin and Cather (1981) and Chapin (1983) suggest that during the middle Eocene, the Colorado Plateau was driven north-northeastward and was tectonically coupled to the flatly subducting, underriding Farallon plate. The north-northeastward translation of the Colorado Plateau block was accompanied by regional right shear along its eastern margin and by south-southwest-directed thrusting (such as Wind River and Uinta thrust uplifts) along the northern margin of the greater Colorado Plateau (Gries, 1983). The south-southwest-directed thrusting and accompanying sedimentation in Green River-type basins is part of the Green River Assemblage.

Farther to the southwest, locally coarse clastic sedimentation of the Rim Assemblage was deposited on a northeast-dipping paleoslope called the Mogollon slope. The Mogollon slope may have drained a highland over the Basin and Range Province that existed above and just northeast of the outcrop edge of a regional thrust system called the Maricopa thrust system. The Colorado Plateau may have been thrust as much as 200 km southwestward along the Maricopa thrust system during culminant Laramide orogeny. Downdip along the Maricopa thrust system, numerous peraluminous plutons of the Wilderness Assemblage were synkinematically emplaced into south- to southwest-directed shear zones.

At deeper crust levels now exposed in southwestern Arizona, peraluminous calcic magmatism and associated, locally significant, gold mineralization were emplaced just above an even more extensive, southwest-directed thrust system called the Chocolate-Vincent-Rand thrust system. At least 700 km of southwest-directed transport could have taken place along the Chocolate-Vincent-Rand thrust system. Such large amounts of transport ultimately may have placed Franciscan-like eclogites beneath the Colorado Plateau in the Four Corners region. During the southwest-directed thrusting along the Chocolate-Vincent-Rand thrust system, major slices of lower crust may have been detached and laterally transferred eastward beneath the Colorado Plateau region and beyond into the Great Plains region. Thrusting along the Chocolate-Vincent-Rand thrust system thus represents the most extreme expression of Laramide tectonic processes in Arizona and adjacent regions and may ultimately reflect the process of Cordilleran decretion during the flattest stages of subduction (Keith and Livaccari, 1985).

During the final and lowest angle stages of flattening subduction, isostatic response to plate thickening during the southwest-directed thrusting may have produced widespread uplift in the late Eocene, refrigeration of low-retentivity radiometric systems, and the development of regional erosional surfaces over the entire western United States.

CONCLUSION

The tectonic events outlined above may be viewed as facies related to the arc thermal axis. The medial Laramide assemblages such as the Morenci Assemblage with its metaluminous calc-alkalic magmatism represent the magmatic arc that lacks evidence of strong compressional tectonism. Northeast-directed thrust tectonics of the initial Laramide orogeny were manifested east of the arc thermal axis, whereas southwest-directed thrust tectonics with extreme amounts of shortening are recorded west of the arc thermal axis in the assemblages of the culminant Laramide orogeny. Eastward migration of the metaluminous arc thermal axis was a geometric consequence of flattening of the subducting Farallon plate and resulted in the complex, but orderly and sequential, overprinting of strato-tectonic assemblages described above.

This paper has demonstrated that strato-tectonic analysis is a powerful tool with which to unravel Cordilleran orogenic phenomena. In particular, the Laramide orogeny, a subject of considerable controversy in previous literature, can be understood as an orderly progression of tectonic events that are not an inference of flat subduction, but that establish flat subduction as fact.

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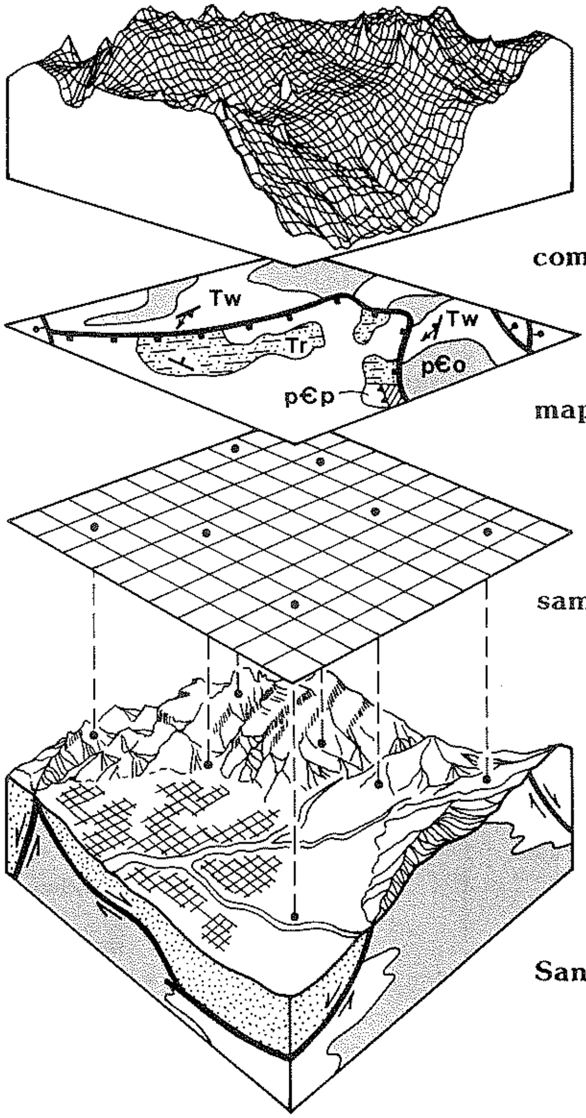
FRONTIERS IN GEOLOGY AND ORE DEPOSITS OF ARIZONA AND THE SOUTHWEST



Edited by Barbara Beatty and P.A.K. Wilkinson

ARIZONA GEOLOGICAL SOCIETY DIGEST VOLUME XVI

Tucson, Arizona 1986