ROCKY MOUNTAIN SECTION - S.E.P.M.
CENOZOIC PALEOGEOGRAPHY OF WEST-CENTRAL UNITED STATES
R.M. FLORES AND S.S. KAPLAN, EDITORS
DENVER, COLORADO 1985

LATE CRETACEOUS AND CENOZOIC OROGENESIS OF ARIZONA AND ADJACENT REGIONS: A STRATO-TECTONIC APPROACH

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ABSTRACT

Strato-tectonic analysis of Late Cretaceous - Cenozoic stratigraphy, structure, and resources of Arizona and adjacent regions reveals the presence of three major diachronous orogenic events: 1) Laramide orogeny of late Cretaceous to late Eocene; 2) Galiuro orogeny (new) of late Eocene to mid-Miocene, which was formerly called the mid-Tertiary orogeny; and 3) San Andreas orogeny (new) of late Miocene to present, which includes Basin-Range nomenclature.

Laramide orogeny in the Basin and Range Province consists of five major, eastward-younging, sequential assemblages that include, from oldest to youngest: 1) metaluminous, quartz alkalic, hydrous magmatism; Cu-Au porphyry deposits; and E-W to WNW-trending, wedge uplifts and folds (Hillsboro assemblage); 2) metaluminous, alkali-calcic, hydrous magmatism; Pb-Zn-Ag vein and replacement deposits; and NE-directed folds and thrusts (Tombstone assemblage); 3) metaluminous, calc-alkalic, hydrous magmatism; large zoned porphyry Cu-Mo systems; and E-W to NE-striking dikes and distributed left shear on WNW-striking faults (Morenci assemblage); 4) peraluminous, subalkaline, hydrous plutonism; regional-scale, SW-directed thrust faults and related mylonitic deformation (Wilderness assemblage); and 5) greenschist-grade, mostly sodic, metagraywacke beneath crustal-scale, SW-directed, thrusts (Orocopia assemblage).

Galiuro orogeny consists of three major, westward-younging, sequential assemblages that include, from oldest to youngest: 1) low-energy sedimentation in reverse(?)-faulted basins (Mineta assemblage); 2) extensive, metaluminous, calc-alkalic and alkali-calcic, hydrous ignimbritic magmatism; Au-Ag-W and Pb-Zn-Ag veins and replacements; local, coarse clastic sedimentation with megabreccia units; and crustal-scale, NW-SE-trending, broad folds, and NW-striking reverse(?) faults (Galiuro assemblage); and 3) metaluminous, alkalic, hydrous magmatism; Au-Ag veins and minor Cu replacements; coarse clastic sedimentation; major low-angle normal (detachment) faults, minor reverse faults, and continued crustal-scale warping (Whipple assemblage).

San Andreas orogeny consists of two orogenic assemblages: 1) NE-SW to E-W trending folds (Transverse assemblage); and 2) metaluminous, alkaline, anhydrous, iron-rich, magmatism; N-S trending horsts and grabens; internally drained, lacustrine basins with fringing coarse clastics; and industrial mineral deposits (Basin and Range assemblage).

INTRODUCTION

In spite of a general agreement on a tripartite division of late Cretaceous-Cenozoic orogenesis in Arizona and adjacent regions, there is considerable disagreement on the tectonic style and dynamics of each orogenic event. Several recent developments provide new constraints for structural and dynamic interpretations of the various orogenic events. Perhaps the most significant development is the discovery of the Cordilleran two-mica granites (Miller and Bradfish, 1980; Keith and others, 1980). Several thousand line miles of deep seismic sections were shot in 1979 to 1981 during the southern Arizona oil play. The 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).

Results of recent mapping in western Arizona and adjacent southeastern California (Haxel and Dillon, 1978; Reynolds and others, 1980; Frost and

Martin, 1982; Haxel and others, 1984) have documented the regional extent of several events of low-angle thrusting that range in age from late Jurassic to early Tertiary. In addition, recent mapping and geochronological studies have shown the low-angle normal faults of middle Miocene age are distributed through a broad region (Davis, 1980; Shakelford, 1980; Frost and Martin, 1982). Since 1980, several hundred chemical analyses and several hundred new radiometric dates (Shafiqullah and others, 1980; 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 abundance of quantitative data, concepts of late Cretaceous and Tertiary orogenesis must be adjusted to fit the new data.

Approach and Methodology

The resynthesis of late Cretaceous - Cenozoic orogenesis presented in this paper is based on a detailed strato-tectonic approach. A strato-tectonic correlation chart consisting of 100 strato-tectonic columns from limited geographic areas was prepared with the columns projected to a ENE-WSW line, approximately perpendicular to the North American plate margin. Data used included stratigraphy and structural data from detailed quadrangle mapping, geochronological data, igneous rock chemical composition, and metal contents of associated mineral deposits. The igneous rocks were categorized according to a new chemical classification of igneous rocks based on magma series chemistry and metal contents of associated mineral deposits currently being developed by Keith.

After compilation of the large, strato-tectonic, correlation chart, the data were organized in a manner similar to that used by Coney (1972) into strato-tectonic assemblages that contained unique arrays of lithologies, structures, mineral resources, isotopes, and magma chemistry. These assemblages are named for particular type areas and are shown on a summary strato-tectonic chart (Fig. 1) and are also presented in a series of assemblage maps (Fig. 2-7). Where rock and resource features differed, but were associated with the same structural features, the strato-tectonic assemblages were subdivided into facies. On a larger scale, similar strato-tectonic assemblages were grouped into broader orogenic phases that reflect different stages of orogenic development. All of the above strato-tectonic facies, assemblages, and phases of a given orogeny are generally diachronous (Fig. 1).

Results

Analysis of the strato-tectonic correlation chart revealed three major orogenies in the late Cretaceous and Cenozoic that can be subdivided into orogenic phases and strato-tectonic assemblages (Table 1). The orogenies are: 1) Laramide orogeny (85-43 Ma); 2) Galiuro orogeny (37-13 Ma); and 3) San Andreas orogeny (13-0 Ma). Where necessary, the strato-tectonic assemblages of the orogenies were subdivided into different facies. More detailed characteristics of the various assemblages and their facies are shown in Tables 2-4 and are discussed below in order of decreasing age.

OROGENY	OROGENIC PHASE	ASSEMBLAGES	MAGMATISM	TECTONICS	MINERAL RESOURCES	EPOCH	TIME
SAN ANDREAS	Basin & Range	Basin & Range	basaltic volcanism	grabens	salt, cinders, sand gypsum, zeolites	PLIOCENE	0-13
	Transverse	Transverse	none or rare	en echelon folds trending NE-SW	petroleum, gas	PLIOCENE	0-13
GALIURO	Culminant Galiuro	Whipple	local qtz. alkalic volcanics	gravity slide detachments	Cu-Au-Ag in detach. flts; Au vns	mid-MIOCENE	28-13
	Medial Galiuro	Galiuro	alkali-calcic volc. & dikes	NW-trend folds NW dikes	Pb-Zn-Ag vns Au vns	up OLIGOCENE MIOCENE	38-18
	Initial Galiuro	Mineta	rare volcanics coarse clastics	local basins little data	U, Cu clastics	up OLIGOCENE low MIOCENE	38-28
LARAMIDE	Culminant Laramide	Echo Park Green River Rim Wilderness Orocopia	peraluminous calcic & calc-alk.	SW-dir. thrusts	Au vns & dissem. W, base metals	EOCENE	56-43
	Medial Laramide	Morenci	calc-alkalic dikes & stocks	NE dikes & veins	porphyry copper	EOCENE PALEOCENE	75-50
	Initial Laramide	Denver Tombstone	alkali-calcic volc. & stocks	NE dir. folds & thrusts	Pb-Zn-Ag	CRETACEOUS PALEOCENE	80-60
		Laramie Hillsboro	alkalic stocks & volcanics	NE-shorelines E-W wedge uplifts	coal Cu-Au	CRETACEOUS	85-65
SEVIER			alkalic stocks	S or E dir. thrusts	Au-Cu	CRETACEOUS	105-85

Table 1. General framework of Cretaceous and Cenozoic orogenesis in Arizona.

OROGENIC PHASE	ASSEMBLAGE	SEDIMENTATION	MAGMATISM	STRUCTURAL FEATURES	MINERAL RESOURCES	AGE (Ma)
Culminant LARAMIDE	Echo Park	arkosic alluv. 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 surfaces)	none	56-43
	Wilderness	none	calc-alkalic and calcic, hydrous peraluminous 2-mica granitoids	shallow-dipping mylonite zones low-angle SW-dir. thrusts large amount of transport	Au disseminations & veins W veins, minor Ag-Pb-Zn	80-43 AZ 80-38 ? AZ 50-43 NM
	Orocopia	none	none greenschist meta. of metagraywackes	large regional thrusts Chocolate-Vincent thrust vy. large amt shortening	quartz pods w/ local anomalous 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
Initial LARAMIDE	Denver	cse. clastics in asym. basins E of E-facing basement uplifts	local nepheline alkalic magmatism	N-trend, E-facing monoclinal uplifts		74-72 UT 68-64 AZ 70-65 CO
	Tombstone	continental clastics large exotic blocks interbd volcani-clast.	alkali-calcic, hydrous plutonism & pyroclast. volcanism, metalumin.	NW strike, NE-dir. folds & thrusts with 1-10 km shortening	Pb-Zn-Ag veins & replacement deposits	80-70 AZ 70-64 NM
	Laramie	regress. marine-nonmar. ss, sh, ls, bentonite	none vy few volc. clasts	N60W trend shorelines broad N60W folds	coal abundant oil, uranium	85-72 AZ 85-65 NM
	Hillsboro	coarse contin. clastics congl. & alluv. fans	alkalic hydrous volc. & small stocks metaluminous	E-W wedge uplifts & basins WNW-ESE strik., high-angle reverse faults on uplifts	epigenetic Cu-Au porphyries	85-65

Table 2. Summary of assemblages of the Laramide orogeny in Arizona.

This paper presents a summary description of the various orogenies and their component assemblages. Detailed documentation and dynamic and plate tectonic interpretation of the different assemblages, and comparison with previous work will be presented later. For example, detailed documentation, dynamic analysis, and plate tectonic significance of the Laramide strato-tectonic assemblages will be presented in Keith and Wilt (1986).

LARAMIDE OROGENY

In any given area the Laramide orogeny can generally be subdivided into three broad phases that sequentially overprint earlier phases in a systematic manner (Table 2). On a regional basis the orogenic phases are diachronous in that all phases of the Laramide orogeny become generally younger in a west to east direction (Fig. 1). Only the culminant phase (Paleocene-Eocene) of Laramide orogeny is summarized in detail in this paper. However, for completeness, the earlier Laramide phases are briefly summarized below.

Initial Laramide Orogeny

The initial Laramide orogeny is subdivided into two strato-tectonic assemblages in both the Colorado Plateau and Basin and Range provinces. In the Basin and Range Province, initial Laramide orogeny consists of the Hillsboro assemblage, followed by the Tombstone assemblage. In the Colorado Plateau Province, initial Laramide orogeny consists of the Laramie assemblage, post-dated by the Denver assemblage.

With respect to time, Laramie and Hillsboro assemblages are equivalent. 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 detritus with volcanic components and exhibit facies relationships with straight, N60W-trending shorelines that are parallel to broad folds with coal accumulations in the synclines. The Hillsboro assemblage (Keith, 1984) 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, commonly double-sided, wedge uplifts. The magmatic component of the Hillsboro assemblage consists of quartz-bearing, alkalic, metaluminous volcanics and epizonal stocks that are associated with copper-gold mineral deposits.

With respect to time, the Denver and Tombstone assemblages are equivalent. The Denver assemblage was named for the 'Denver basin type' of Chapin and Cather (1981) and occurs mainly in Colorado and New

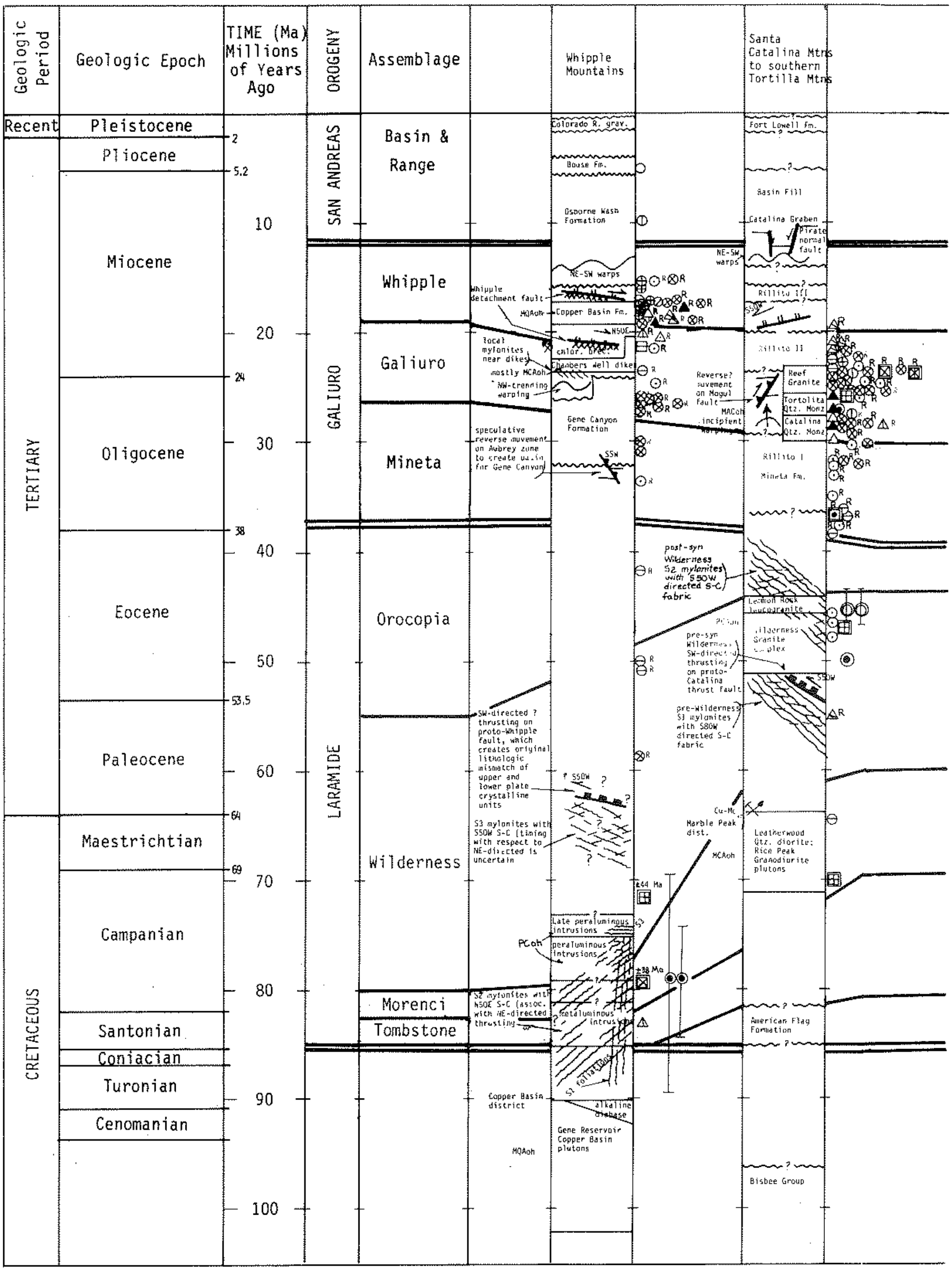
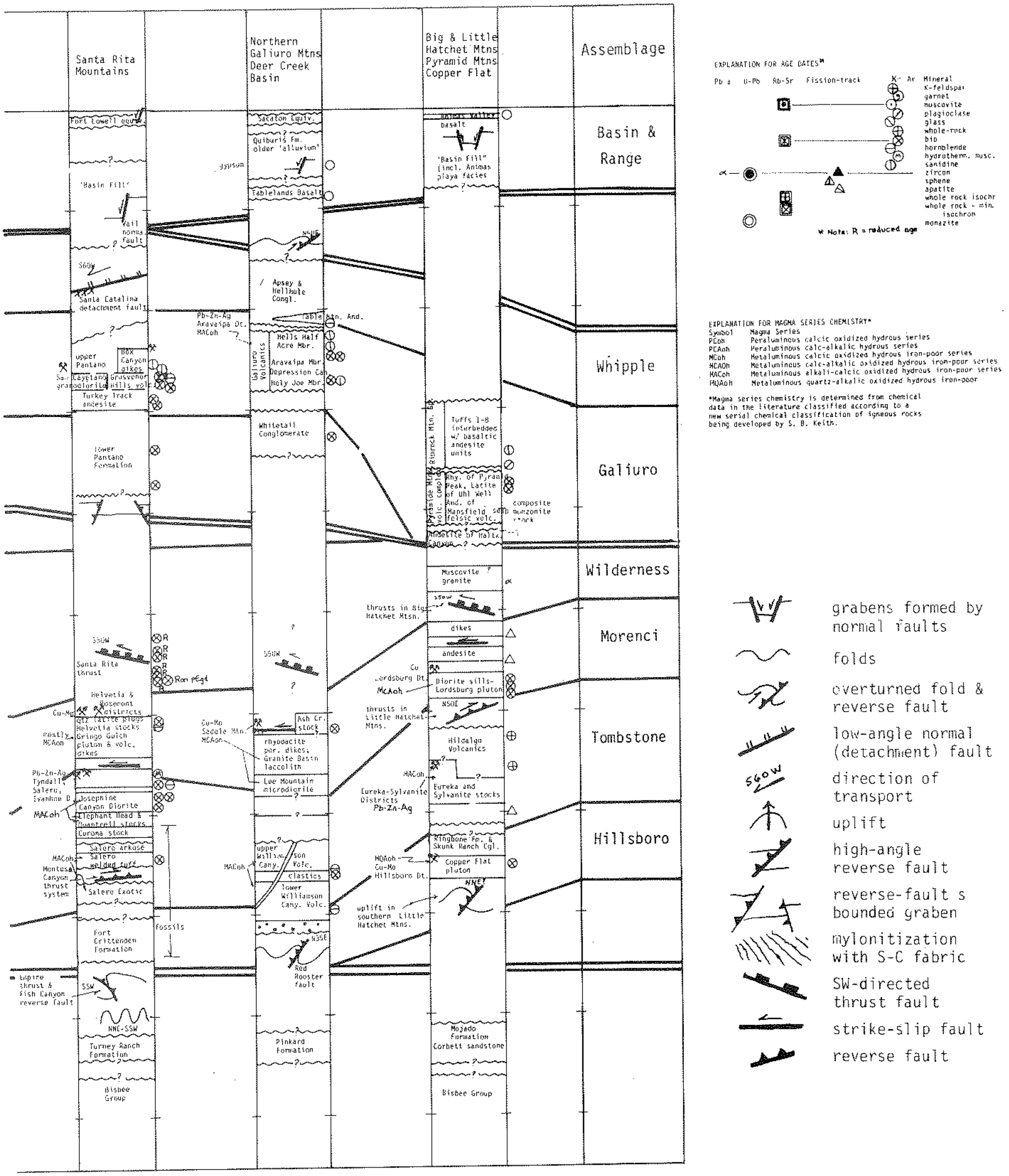


Figure 1. Summary strato-tectonic correlation diagram for late



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
MCAOh	Metaluminous calc-alkalic oxidized hydrous iron-poor series
MACoh	Metaluminous alkali-calcic oxidized hydrous iron-poor series
MQAoh	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.

Cretaceous-Cenozoic orogenesis in Arizona and vicinity.

Mexico. There, it consists of coarse arkoses and conglomerates deposited in asymmetrical synclinal downwarps that are generally east of east-facing basement uplifts that were formed during Maestrichtian to Paleocene time. In Arizona the Tombstone assemblage of Keith (1984) is late Cretaceous (85-69 Ma) and consists of alkali-calcic, metaluminous igneous rocks, with minor volcani-clastic sedimentary rocks, lead-zinc-silver mineralization, and northeast-directed folding and thrust faulting.

Medial Laramide Orogeny

Medial Laramide orogeny in the Basin and Range Province of Arizona only consists of the Morenci assemblage of Keith (1984). Here, the Morenci assemblage is late Cretaceous to early Paleocene in age (75-50 Ma) and consists of calc-alkalic, metaluminous, epizonal plutons and associated large, zoned, porphyry copper-molybdenum systems. Sedimentation is conspicuously absent. The principal structures of the Morenci assemblage are the regional, dike swarms that strike east-west to northeast. The dikes generally occur between west-northwest-striking structural elements of the pre-existing Texas Zone which underwent regional, left shear during medial Laramide orogeny.

Culminant Laramide Orogeny

Green River Assemblage

The Green River Assemblage is largely synonomous with, and is named after the 'Green River-type basins' of Chapin and Cather (1981); these basins exist in a northwest-trending belt through northwest New Mexico, western Colorado, northern Utah, and central Wyoming. In Arizona, the southwestern outcrops of the Baca Formation represent the southwesternmost extension of the Baca Basin, which is mainly developed to the northeast in west-central New Mexico (Chapin and Cather (1981).

Echo Park Assemblage

The Echo Park assemblage is largely synonomous 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. In Arizona, a possible candidate for an Echo Park assemblage is the pre-25 Ma Chuska Sandstone which occurs in a northwest-trending syncline that post-dates the east-facing Defiance monocline of the Denver assemblage.

Rim Assemblage

The name Rim assemblage was given by Keith (1984) 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.

Lithologically, the Rim assemblage consists of fluvial gravels with very well-rounded clasts which can be as large as boulders. Structurally, the Rim gravels overlie a regional, very gently inclined, northeasterly dipping paleoslope, the 'Eocene erosion surface' of Epis and Chapin (1975). In the Mogollon slope region the unconformity below the 'Rim gravels' truncates successively older rocks to the south (Peirce and others, 1979).

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 and 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 are most likely middle Eocene in age. The 'Rim gravels' rest on the Paleocene-Eocene unconformity and overlie an unconformity of late Eocene-early Oligocene age that is associated with the Oligocene drainage reversal (Peirce and others, 1979).

Wilderness Assemblage

The name Wilderness assemblage was given by Keith (1984) to 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 main range of the Santa Catalina Mountains near Tucson (Keith and others, 1980). This area is designated as the type area of the Wilderness assemblage.

Rocks of the Wilderness Assemblage

There are no sedimentary or volcanic rocks in the Wilderness Assemblage. A prominent 'magma gap' in southeastern Arizona during the Eocene from 55 to 38 Ma had long been recognized by numerous workers (Damon and Mauger, 1966; Snyder and others, 1976; Coney and Reynolds, 1977; Keith, 1978). However, this gap has been filled 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; Wright and Haxel, 1982). Although the 'magma gap' of older work is now largely occupied by the peraluminous granitoids, there is a gap in volcanism in the surface stratigraphy so term 'volcanic gap' could be substituted for 'magma gap'.

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 (Fig. 2).

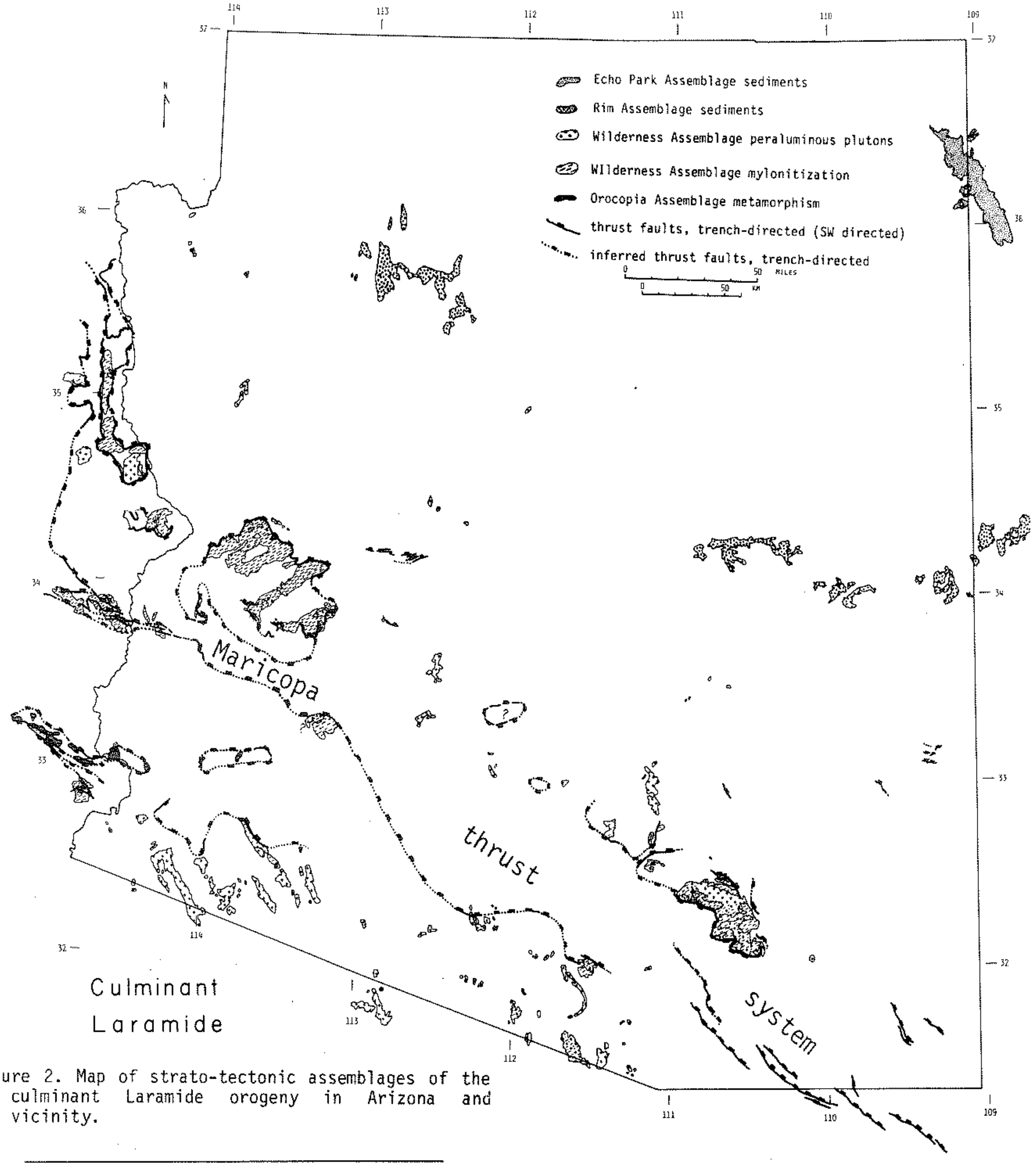


Figure 2. Map of strato-tectonic assemblages of the culminant Laramide orogeny in Arizona and vicinity.

Wilderness assemblage plutons generally occur as sills with low-volume, late phases occurring as dikes that are discordant to the earlier sills. Magmatism of the Wilderness assemblage consists of peraluminous, muscovite- and garnet-bearing granitoids that commonly contain well-developed alasko-pegmatite complexes in their upper portions. The lower portions of the complexes contain biotite as the principal mica mineral while the upper parts are dominated by muscovite and garnet. In strong contrast to other Cretaceous and Cenozoic magmatism, Wilderness assemblage plutons do not contain mafic minerals such as olivine, pyroxene or hornblende. Chemically, they are peraluminous, calcic to calc-alkalic, iron-poor to weakly iron-rich, hydrous, and oxidized with strontium initail ratios ranging from 0.7085 to 0.725, which is distinctly higher than other Cenozoic magmatism.

Petrologic evidence strongly suggests that the two-mica granites crystallized within the crust, probably at depths equal to or greater than 10 km. Firstly, the lack of surface volcanism suggests that the Wilderness assemblage plutons did not intrude close enough to the ground surface to produce volcanism; magmatism at depths of less than 5 km commonly produces volcanism. Secondly, fluid inclusion data from mineral deposits or from pegmatites and leucogranite phases associated with Wilderness plutons indicate high CO2 densities (greater than 0.70) requiring a considerable pressure correction for depths to at least 4.5 km (as in the OK pluton of Theodore and others, 1982). A third depth indicator is the widespread distribution of phenocrystic, magmatic muscovite of celadonitic composition which indicates depths of greater than 10 km (Anderson and Rowley, 1981). Fourthly, recent geobarometry on garnet, feldspar, and mica in peraluminous plutons in Arizona indicates deep crystallization depths; for example depths of 10 km or more (Wilderness granite in Santa Catalina Mountains; L. Anderson, pers. commun., 1985). Fifth, because Wilderness assemblage plutons have numerous and abundant pegmatites, the water content was probably high. Burnham and Jahns (1962) estimate that water contents for pegmatitic granites are between 8 and 12 weight percent H_2O; they constructed water depth curves that indicate pH_2O of 10 weight percent in a pegmatite would equilibrate with the overriding lithostatic load at about 13 km. 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, as in the Catalina, Harquahala, and Cargo Muchacho mountains. Minimum depths for staurolite stability at amphibolite grade temperatures are about 8 km. At amphibolite grade temperatures (450° C) the kyanite stability requires approximate minimum depths of 12 km (Holdaway, 1971).

Structural Features of the Wilderness Assemblage

Structures of the Wilderness assemblage consist of mylonitic zones, southwest-directed thrust faults of regional extent, and synkinematic peraluminous sills. The widespread, regionally developed, shallowly dipping, mylonitic zones exhibit a general southwest-directed shear. 'S' surfaces of the mylonites invariably contain a mineral lineation that trends N50-70E to S50-70W. These shear zones are commonly associated with low-angle, southwest-directed thrust faults and synkinematic, peraluminous plutons (Keith, 1982). 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 northeasterly inclined towards and beneath Precambrian crystalline rocks along the southwestern boundary of the Colorado Plateau (Otton, 1981).

In Arizona a major northwest-trending zone of southwest-directed thrust faults of the Wilderness assemblage may be present and is herein named the Maricopa thrust system (Fig. 2). Within the Maricopa thrust system are numerous southwest-directed thrusts and southward-overturned folds, many of which are nappe dimension. The western portion of the Maricopa thrust system is well-displayed in California in the Big and Little Maria mountains. 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 and possible thrust north of the Sil Nakya Hills that would be responsible for southwest-overturning strata there. The zone continues southeast of Tucson and is marked by major, southwest-directed thrusting in the Huachuca Mountains (Fig. 2) and continues into northeast Sonora, Mexico, to Sierra Cabullona.

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 an unmetamorphosed, unmylonitized, upper plate composed mainly of Precambrian crystalline rocks. 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 applied because recent drill hole results summarized by Reif and Robinson (1981) suggest that the plutonized and tectonized basement exists regionally beneath unmetamorphosed cover. Portions of the profound low-angle faults that surround the underlying crystalline 'pseudo-cores' have experienced low-angle, normal separation during the mid-Tertiary, as widely recognized (Davis, 1983; Davis and others, 1980). However, compelling evidence discussed below shows that regional, low-angle, thrust faults juxtaposed nonmylonitic crystalline basement over mylonitic crystalline basement prior to middle Tertiary (Drewes, 1981; Keith, 1982; Haxel and Grubensky, 1984).

An example of a window into the crystalline basement of the lower plate is in the Rincon Mountains where ductile, southwest-directed, flexural-flow, fold deformation of Paleozoic rocks on the east side of the range (Lingrey, 1982) is cut by the Barney Ranch pluton (at least 37 Ma) that was assigned by Keith and others (1980) to the Wilderness suite of plutons. This fold deformation occurs in the lower plate of a regional, low-angle fault that juxtaposes nonmylonitic Precambrian crystalline rocks (1400 Ma or older) over deformed Paleozoic and Cretaceous sections on both sides of the mountain range (Drewes, 1974, 1977; Keith, 1983). Similar, large scale, older over younger, low-angle, fault juxtapositions occur in the Tortolita Mountains (Keith, 1983) and in the Rawhide and Buckskin Mountains of west central Arizona (Shackelford, 1980).

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 both the 70 Ma Leatherwood quartz diorite and the early, shallowly-dipping phases of the 45-50 Ma leucogranite phase of the Wilderness granite 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. Other areas showing strong evidence of synchroneity of thrusting, mylonitization, and peraluminous plutonism include the Eastern Peninsular Ranges (Simpson, 1984), 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).

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 lower plate lithologies on a regional basis. For example, in the Rincon Mountains east of Tucson, nonmylonitic, generally 1625 Ma, granodioritic, Precambrian rocks in the upper plate of the Catalina fault and their probable analogs in the eastern Rincon Mountains and Johnny Lyon Hills cannot be matched with mylonitic, generally 1400 Ma, granitic, Precambrian rocks in the lower plate anywhere in the mountain range. Importantly, the nonmylonitic Precambrian rocks of the upper plate are commonly juxtaposed over deformed Paleozoic rocks in the lower plate beneath portions of the Catalina fault and its analogs in an older over younger, thrust sense. To remove the nonmylonitic upper plate from the generally mylonitic or deformed lower plate along a line parallel to the lineation requires cumulative transport of at least 35 km, which is the exposed outcrop width of lower plate rocks parallel to lineation.

In the Rawhide, Buckskin, and Northern Plomosa Mountains extensive lithologic mismatches occur between predominantly mylonitic lower plates (generally without 1400 Ma granitic protolith) and nonmylonitic upper plates (with widespread, 1400 Ma granitic, Precambrian protolith). As in the Rincon Mountain example, younger rocks may exist in the lower plate beneath the Precambrian upper plate. In the Buckskin Mountains and Rawhide Mountains Shackelford (1980) has mapped a 'middle plate' of tectonized Paleozoic and Mesozoic rocks above the Rawhide-Buckskin detachment fault. In an 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. If the Precambrian-bearing upper plate existed as a regional sheet from the Rawhide to the Plomosa Mountains, then a minimum overlap of 35 km 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, Sacramento, Dead, and Newberry Mountains of southeastern California and southernmost Nevada.

Ultimate amounts of transport could have been much greater than the minimum of 10 to 35 km deduced directly from the overlap of nonmatching lithologies. Overall transport may have been related to regional, southwest-directed transport on the Maricopa thrust system. The upper plates of the Maricopa thrust system throughout west-central Arizona mainly consist of nonmylonitic, Precambrian, crystalline rocks 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 south of the Colorado Plateau were stripped away by erosion during the Mesozoic through early Tertiary. The 'plate' of Tertiary deposited on nonmylonitic Precambrian, which is predominantly 1400 Ma granite, is the structurally highest plate in the Riverside, Whipple, Rawhide, Buckskin, Harquahala, Big Horn, Harquvar, and Plomosa Mountains. The lower plates in this region consist of tectonically imbricated, Precambrian, Paleozoic, and Mesozoic protoliths. The occurrence of Mesozoic protoliths in the mylonitic lower plate beneath well-documented nonmylonitic Precambrian rocks in the upper plate thus indicates a regional, older over younger, thrust-relationship. Seismic data indicate that the surface of lithologic mismatch may project beneath the Colorado Plateau in a geometry consistent with regional, southwest-directed thrusting.

If the Maricopa thrust is taken as the leading edge of the above mentioned, regional, thrust 'plate', then present lithologic overlap between the 'plate' bearing the Mogollon Highlands terrane and the lower plates 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. Ninety km is the distance between the Riverside Mountains in southeastern California (the southwesternmost exposures in the upper plate where middle Tertiary unconformably overlies Precambrian) and the northern Rawhide Mountains in western Arizona (the northernmost exposures where metamorphosed Paleozoic sections occur in the lower plate).

Regionally, intrusion of shallow level, metaluminous plutons of the Morenci assemblage by deep level, peraluminous plutons of the Wilderness assemblage suggests regional thrusting occurred after the Morenci assemblage intrusions in any given area. For example, in the Santa Catalina Mountains, Leatherwood suite plutons of the Morenci assemblage are associated with shallow level (less than 3 km), porphyry copper-skarn mineralization of early Paleocene age (Keith and others, 1980). They are intruded in the Eocene by the Wilderness granite, which probably crystallized at depths of 10 km or more (see discussion of Wilderness assemblage rocks). Thus, at least 7 km of crust was added to the Santa Catalina area after Morenci assemblage intrusion and prior to Wilderness assemblage intrusion. The only logical way to accomplish this is to thicken the crust by regional thrusting on a proto-Catalina fault during culminant Laramide orogeny in early Eocene time.

Six to eight km thicknesses of thrust plates above Wilderness assemblage plutons is consistent with field relationships in several areas that indicate upper plate thicknesses of 3 to 12 km. Examples include 5 to 8 km thickness for the upper plate of the Baboquivari thrust system on the Papago Reservation (Haxel and others, 1984); a 6 km thickness of upper plate in the Johnny Lyon Hills 40 km east of Tucson; a 3 km thickness of the rotated Precambrian plate above the imbricated Paleozoic section in the northern Rawhide Mountains (Davis and others, 1980); and as much as 12 km of tilted crystalline Precambrian rocks in the Mohave Mountains (Howard and others, 1982). In the Arizona State A-1 well (Reif and Robinson, 1981) the upper plate is at least 2.3 km thick and consists of 1400 Ma granite.

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 3^{o}, then about 150 km of thrust overlap is required using the sine function. This figure roughly agrees with lithological overlap evidence presented earlier.

Age of Wilderness Assemblage

In common with metaluminous magmatism of the earlier Laramide, 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 an approximately 80 Ma Rb-Sr isochron for the Sweetwater Wash pluton. To the east U-Pb data from the Pan Tak pluton in the Coyote Mountains is 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 (Keith and others, 1980). Peraluminous plutonism, mylonitization, and southwest-directed thrusting occur in southeast California between 85 and 75-70 Ma, between 70 to 60 Ma in western Arizona, and between 60 to 44 Ma in southeastern Arizona.

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). 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). Thus, Wilderness assemblage magmatism in any given area represents the culmination of Laramide orogeny.

Reduced Isotopic Ages. Wilderness assemblage plutonism, deformation, and metamorphism is accompanied by widespread resetting of relatively nonresistant K-Ar and fission-track, isotopic systems. The reduced isotopic ages are about the same age as or slightly younger than the emplacement of the peraluminous granites in the general vicinity. As with the peraluminous plutons of the Wilderness assemblage and the magmatism of Laramide strato-tectonic assemblages in general, Wilderness assemblage reduced ages become younger eastward. For example, in the Transverse Ranges of southeast California, Miller and Morton (1980) 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). In each area, the reduced K-Ar and fission track dates coincide with emplacement ages of peraluminous plutons of the Wilderness Assemblage.

Orocopia Assemblage

The name Orocopia assemblage was given by Keith (1984) to Laramide recrystallization phenomena in older schistose rocks that possibly were Jurassic or Cretaceous 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 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 in southeastern California.

Rocks 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). 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 underthrusting 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 metamorposed during the Paleocene (Ehlig, 1968). 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.

Structural Features of Orocopia Assemblage

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 inclined, 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. 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, with some suggesting northeast and some indicating southwest transport.

Magnitude of Thrusting. Lateral transport along Orocopia assemblage thrust faults probably was at least 150 km and may have been as much as 625 km or more. The metagraywackes, minor metapelites, cherts, and mafic metavolcanic rocks in the lower plates of Orocopia assemblage thrust faults have no lithologic analogs anywhere in the North American upper plate. 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 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.

Evidence for continent-scale underthrusting of Franciscan-like materials beneath North America was reported by Helmstaedt and Doig (1975). They obtained samples of blueschist ecologite 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 ecologite inclusions and the Franciscan-like rocks was affirmed by lawsonite cores within amphibole phenocrysts and jadeite cores within pyroxene phenocrysts from the ecologite inclusions. Helmstaedt and Doig (1975) suggested 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 ecologite inclusions are indeed underthrust Franciscan, then the amount of implied lithologic overlap would be at least 625 km.

Missing Crust. A remarkable structural feature of the Orocopia assemblage thrusting is that deep level schistose terranes or metagraywacke packages have been commonly juxtaposed under supercrustal 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 commonly missing. There are places, such as in the San Gabriel and Orocopia Mountains, 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 plate that is resting allochthonously on a probable schistose basement. Some of the deep crustal COCORP seismic lines recently shot across the western Mojave block 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 possibility exists that regional-scale tectonic erosion of the North American plate occurred during Orocopia assemblage metamorphism and thrusting.

Age of Orocopia Assemblage

Relative age relationships and geochronologic calibration along the various thrust faults suggest Orocopia assemblage thrusting occurred after 85 Ma and terminated about 60 Ma. In the San Gabriel Mountains hornblende-biotite quartz diorite in the upper plate that is in fault contact with the Vincent thrust yields K-Ar dates on hornblende of 67 Ma (Miller and Morton, 1980). One of the plutons in the San Gabriel Mountains has yielded a U-Pb date on zircon of 80 +/- 10 Ma (Carter and Silver, 1971). Thus, available evidence in the San Gabriel

Mountains indicates emplacement of the Vincent thrust after 80 Ma.

In the Randsburg area, Silver and others (1984) report a U-Pb date of $\sim$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 emplacement of the schist beneath the Rand thrust is younger than 85 Ma. 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 and Dillon, 1978).

In any given area, Orocopia assemblage tectonism appears to post-date Wilderness assemblage tectonism. In several areas of southern California, Wilderness assemblage, peraluminous alaskites are truncated by the Chocolate-Vincent thrust system of the Orocopia Assemblage.

Termination of Laramide Orogeny

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). 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). Along the Mogollon Rim segment of the Colorado Plateau in Arizona, 'Rim gravels', which contain clasts yielding early Eocene dates, could be middle Eocene in age and rest beneath the late Eocene-early Oligocene unconformity as they are locally overlain by late Oligocene-Miocene volcanics (28 Ma K-Ar date by Peirce and others, 1979). This regional unconformity of late Eocene to early Oligocene age described by Peirce and others (1979) separates the Laramide and Galiuro orogenies on the Colorado Plateau.

In supercrustal stratigraphic sections of southern Arizona, the Laramide-Galiuro boundary is contained in an unconformity between medial Galiuro orogeny volcanics and sediments and medial Laramide, Morenci assemblage, igneous rocks. In southern Arizona, the unconformity represents a gap of about 20-40 million years (Damon and Mauger, 1966). Thus, conventional use of unconformities yields poor control for the Laramide-Galiuro boundary.

Analysis of the strato-tectonic correlation chart (Fig. 1), however, reveals that little or no time separates Galiuro from Laramide orogeny, because active Laramide deformation, metamorphism, and plutonism was occurring at mid- to sub-crustal levels throughout Eocene time (Wilderness and Orocopia assemblages). In any given area, Orocopia assemblage tectonism post-dates Wilderness assemblage plutonism and is thus the youngest Laramide event, where its prescence can be established (southwestern Arizona and southeastern California). In southeast Arizona, however, Wilderness assemblage is the youngest proven Laramide event, although Orocopia assemblage may exist at depth. From the strato-tectonic chart, the termination of Laramide orogeny in southeastern Arizona and southwestern New Mexico is placed at about 43 Ma and in western Arizona and southeastern California at about 38 Ma.

GALIURO OROGENY

The Galiuro orogeny was originally named by Keith (1977) to differentiate two fundamentally different and independent orogenic events of the middle and late Tertiary: "The style of the Galiuro orogeny (35-15 m.y.) is characterized by: 1) Broad NW-trending elongate uplifts with intervening syntectonic basins containing continental clastic deposits; 2) Broad NW-trending, low-plunging folds; 3) NW-trending dike swarms; 4) Denudational faulting and megabreccia landslides directed away from uplifts; 5) Widespread calc-alkaline magmatism peaking 24-27 m.y. ago; 6) Emplacement of metamorphic core complexes accompanied by SW-NE-trending lineation" (Keith, 1977).

In Arizona these orogenic phenomena have previously been referred to the mid-Tertiary orogeny (Eberly and Stanley, 1978; Shafiqullah and others, 1980). The term 'mid-Tertiary orogeny' is a time term that does not precisely reflect the diachronous nature of orogenic phenomena. In the northwestern United States, Tertiary orogenic phenomena very similar to Galiuro orogeny in Arizona are Eocene or early Tertiary in age; in Baja California similar phenomena are 15 to 5 Ma or middle to late Tertiary in age. Similarly in New Mexico, Galiuro orogenic phenomena are 37 to 22 Ma or early to middle Tertiary in age.

Classically, orogenic nomenclature typically has evolved from some reference region that contained rocks and structures that are considered representative of the orogeny. Thus, geographic terminology, such as 'Sevier' and 'Laramide', is preferable to time terminology, in order to conform with terminology for other orogenies and to emphasize physically locatable phenomena. In southeastern Arizona, rocks, structures, and mineral deposits that are excellent examples of Galiuro orogeny phenomena are well exposed in the Galiuro Mountains and surrounding mountain ranges. Thus, the Galiuro Mountains and vicinity (especially exposures in the Santa Catalina and Tortilla mountains) is designated as the type area for the Galiuro orogeny.

The beginning of Galiuro orogeny in the Basin and Range Province of southern Arizona may be placed at the unconformity below the base of Galiuro assemblage volcanics or underlying Mineta continental clastics. In any given area, the Galiuro orogeny can generally be subdivided into three broad phases that sequentially overprint previous phases in a systematic manner. Galiuro orogeny is divided into initial, medial, and culminant phases that may consist of one or more strato-tectonic assemblages that exhibit lateral or vertical facies relationships with one another (Table 3). On a regional basis, Galiuro orogenic

OROGENIC PHASE	ASSEMBLAGE	SEDIMENTATION	MAGMATISM	STRUCTURAL FEATURES	MINERAL RESOURCES	AGE (Ma)
Culminant GALIURO	Whipple	coarse & fine clastics megabreccia blocks	alkalic hydrous volcanics & local epizonal stocks (metaluminous)	low-angle normal detachment faults SSE-NNW-trending folds NW-SE striking thrusts & reverse faults	Cu-Au-Ag in vns, replacement lenses & in detach. faults epithermal Au-Ag vns hotspring Mn & U	18-11 ? CA 34-13 AZ 28-18 ? NM
Medial GALIURO	Galiuro Datil Facies	local clastics interfinger with volcanics	alkali-calcic hydrous ignimbritic volcanics & epizonal plutons (metaluminous)	broad NW trend folds NW and NE-trending dikes	Pb-Zn-Ag +/- F vns & replacements epithermal Ag hotspring Mn	38-18 NM 28-18 AZ 22-18 CA
	South Mountain Facies	clastics interfinger with volcanics	calc-alkalic hydrous volcanics and epizonal plutons (metaluminous)	broad NW trend folds NW trend dikes minor NE trend dikes	Au +/- Cu-W veins & disseminated deposits	30-22 AZ 31-14 CA
Initial GALIURO	Mineta	coarse & fine clastics & evaporites in lacustrine environ.	rare volcanics mostly within 'volcanic gap'	local broad basins poss. WNW trend. reverse faults	uranium clay exotic copper	38-28

Table 3. Summary of assemblages of the Galiuro orogeny in Arizona.

phases are diachronous and, in a general way, become younger from east to west (Fig. 1).

Initial Galiuro Orogeny

Mineta Assemblage

Rocks deposited during the initial Galiuro orogeny are sporadically scattered throughout the Basin and Range Province of Arizona (Fig. 3) and are herein named the Mineta assemblage. The name Mineta is taken from the Mineta Formation of Chew (1952) and Clay (1970) along Mineta Ridge in the eastern Redington Pass area about 40 km northeast of Tucson, which is designated as the type area for Mineta assemblage. Other reference areas include the Teran Basin sequence of the southeastern Galiuro Mountains (Scarborough and Wilt, 1979) and the Gene Canyon Formation of the southeastern Whipple Mountains (Davis and others, 1980) where the Gene Canyon Formation is exposed. Mineta Assemblage is conceptually similar to the lower Unit I of Eberly and Stanley (1978) and the pre-ignimbrite sediments of Wilt and Scarborough (1981).

Rocks of the Mineta Assemblage

Mineta Assemblage rocks are predominantly continental sedimentary rocks that consist primarily of fine-grained lacustrine sediments and secondarily of coarse-grained, typically reddish, conglomerates in alluvial fan deposits; they typically range from 650 to 3400 m thick. Thinner accumulations are typically relatively thin, basal conglomerates that either conformably or unconformably underlie the volcanic-dominated medial Galiuro assemblages. Volcanics are only rarely present in Mineta assemblage rocks and consist of thin volcanic flows, such as Turkey Track andesite, or thin ash flow tuffs. Fine-grained facies of the Mineta assemblage commonly contain carbonates and gypsum in laterally widespread, lacustrine facies. Away from basin centers, braidplain deposits are common with fanglomerate facies locally occurring near basin edges.

Mineta assemblage sedimentary rocks contain fine-grained, low energy, lacustrine facies that occupied what may have been laterally continuous basins of considerable geographic extent. For example, some fine-grained strata that may have been deposited in a basin that pre-dated the present Rincon Mountains include: the claystone member of the Pantano Formation south of the Rincons, the fine-grained facies of Rillito I of Pashley (1966) northwest of the Rincons, fine-grained Mineta Formation, and gypsiferous mudstones of the Teran Basin sequence northeast of the Rincons. All of these formations contain a Turkey Track andesite dated at 27-28 Ma (Damon and Mauger, 1966; Shafiqullah and others, 1978; Scarborough and Wilt, 1979). Thus, it appears that the area now occupied by the Rincon Mountains was a broad depocenter for Mineta assemblage rocks in Oligocene time.

In southeasternmost California and west-central Arizona, lacustrine limestone and evaporite-bearing mudstones are important parts of the Gene Canyon Formation and lower Artillery Formation. The overall sedimentology of these rocks suggested to Davis and others (1980) that Gene Canyon Formation mantled a low topography that was developed on Proterozoic crystalline rocks. Tuffs interbedded with lacustrine deposits in the Gene Canyon Formation in the southern Whipple Mountains are as young as 24 Ma on the basis of radiometric dating (Davis and others, 1982). As in the exposures around the Rincon Mountains, the Gene Canyon basin pre-dated elevation of the Whipple Mountains.

Where stratigraphic relationships are well documented, initial sedimentation in Mineta assemblage basins is predominantly conglomeratic reflecting an initial interval of rapid sedimentation. The upper portions of these Mineta assemblage formations commonly consist of large amounts of lacustrine sediments such as carbonates and gypsiferous mudstones. In basins with a long history of sedimentation, the lacustrine units may be overlain by younger fanglomerate units that commonly contain megabreccia clasts and that probably reflect subsequent Galiuro orogenic events.

Structural Features of Mineta Assemblage

Structural data for Mineta assemblage is difficult to document; but, where structures are present or can be reasonably inferred from sedimentologic evidence, Mineta assemblage strata may have accumulated in a series of basins that are elongate in an east-west to west-northwest direction. These basins are bordered by steep, E-W to WNW-trending, elongate uplifts that were possibly bounded by reverse faults. A good example of Mineta assemblage structural features is the Babocomari Basin between the northern Huachuca Mountains and the southern Mustang Mountains. Here, a thick sequence of older deformed gravels is probably equivalent to the Mineta assemblage part of the Pantano Formation (Vice, 1974). The northern boundary of the Babocomari basin is marked by a east-west to WNW-trending fault zone along and just north of the Babocomari River in the area of the Babocomari Ranch. Hayes and Raup (1968) show this fault as a steep to intermediate, north-dipping reverse fault that juxtaposes Paleozoic of the southern Mustang Mountains over the older gravels of the Mineta assemblage. Volcanic rocks intercalated within these conglomerates yield a date of 38.9 Ma (Marvin and others, 1973) from south of the Babocomari River and dates of 27.2, 26.1, and 24.3 Ma from a thin volcanic unit intercalated in the gravels along the Babocomari River near the Babocomari Ranch (Vice, 1974; Shafiqullah and others, 1978). The southern boundary of the basin is marked by the Kino Springs fault zone, which is a near vertical fault that cuts the Mineta assemblage sediments for about 12 km (8 miles) along strike.

Another Mineta assemblage basin is the lower part of the Pantano Formation between the Rincon and Santa Rita Mountains (Finnell, 1970; Brennan, 1962) where outcrops of the lower fanglomerate member of the Pantano are restricted to an east-west trending zone that is partly bounded by WNW- to E-W striking, nearly vertical faults on the south (Scarborough and Wilt, 1979). However, on the eastern side of the outcrops, the claystone member seems to depositionally overlap the eastern projection of the structural boundary. The basin probably filled up rapidly with fanglomerates derived from the east and southeast (from clast data in Brennan, 1962, and paleocurrent data reported by Cooley and Davidson, 1963). By the time the middle Pantano was deposited, the claystone member overlapped the previous southern boundary of the basin. Other areas (Fig. 3) that possibly contained west-northwest-trending basins of Mineta assemblage sediments include the Comobabi Mountains, the northern Quijotoa Mountains, the Whipple Mountains (Davis and others, 1980), and the southern part of the Teapot Mountain quadrangle, where there are thick sequences of White Tail Conglomerate south of a west-northwest- trending fault zone.

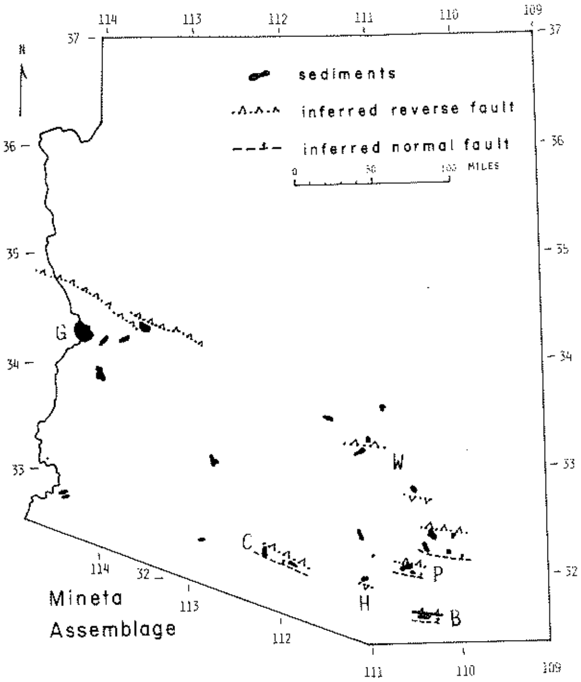


Figure 3. Map of Mineta assemblage of the initial Galiuro orogeny. Locations are Babocomari Basin (B), Pantano Fm. (P), Helmet Fanglom. (H), Whitetail Congl. (W), Gene Canyon Fm. (G), and Comobabi area (C).

Although data is limited, Mineta assemblage basins may have developed with a southwest-facing asymmetry, as the best documented basins of the Mineta assemblage occur south of E-W to N60W-striking structures. The southern boundaries of Mineta assemblage basins appear to be steep, near vertical faults that may also represent recurrent movement on elements of the Texas Zone; they are depositionally overlapped by lacustrine facies of Mineta assemblage, which suggests that the southern parts of the basin were not active throughout deposition of Mineta assemblage. The faults along the northern sides of the basins probably were active throughout Mineta assemblage deposition because, where mutual contacts occur, the faults cut the entire Mineta assemblage and are not depositionally overlapped by Mineta assemblage strata.

Age of Mineta Assemblage

Because volcanic units are rare within strata of Mineta assemblage, age dates are not abundant. In southeastern Arizona, volcanics within clastic units of Mineta assemblage in the Babocomari basin have yielded four radiometric dates that range between 38.9 Ma and 24.3 (Marvin and others, 1973; Vice, 1974; Shafiqullah and others, 1978). In the Pantano Formation southeast of Tucson, four K-Ar determinations on three samples range from 36.7 to

28 Ma (Damon and Mauger, 1966; Marvin and others, 1973; Shafiqullah and others, 1978). In the northern Tucson Mountains thin Mineta assemblage conglomerates occur beneath the Rillito Andesite, which has been dated at 38.5 Ma (K-Ar on biotite; Damon and Bikerman, 1964). A plagioclase K-Ar date of 31.4 Ma and 27.9 Ma (Damon and Bikerman, 1964) has been obtained from Turkey Track andesite porphyry in the Helmet Fanglomerate, a possible Mineta assemblage unit in the east central Sierrita Mountains south of Tucson. In the northern Galiuro Mountains 50 km north-northeast of Tucson, White Tail Conglomerate that is unconformably overlain by 28 Ma Galiuro Volcanics has yielded a date of 32 Ma (Krieger and others, 1979). Thus, in southeastern Arizona, numerous K-Ar dates on clastic formations assigned to the Mineta assemblage range in age from 39 to 28 Ma.

Mineta assemblage rocks appear to be younger in western Arizona and southeasternmost California. Four K-Ar dates on volcanics intercalated into the Gene Canyon Formation in the southeastern Whipple Mountains range in age from 31.8 to 25.7 Ma (Davis and others, 1982). Gene Canyon Formation or Artillery Formation strata in the Northern Plomosa Mountains have yielded an K-Ar age date of 25 Ma on biotite from a thin rhyolitic tuff unit (Eberly and Stanley, 1978). The lower Artillery Formation is unconformably overlain by the basalt member, which is probably 16-21 Ma based on two K-Ar whole rock dates on basalts from the basalt member (Shackelford, 1980; Eberly and Stanley, 1978). Thus the lower Artillery Formation is pre-21 Ma. In a similar fashion, redbeds at Adair Park in the southern Laguna Mountains north of Yuma are unconformably overlain by Kinter Formation clastics which contain a 23 Ma ash (Olmsted and others, 1973). Thus, dates within Mineta assemblage rocks range from 31 to 24 Ma in western Arizona and are younger than in eastern Arizona, where they range from 39 to 28 Ma.

Medial Galiuro Orogeny

Galiuro Assemblage

The name Galiuro assemblage is given to products of the medial Galiuro orogeny that post-date the Mineta assemblage, where they are both present, and that otherwise unconformably overlie Morenci assemblage of the Laramide orogeny or older rocks. Rocks, structures, and mineral deposits of the Galiuro assemblage are especially well developed in the Galiuro Mountains and surrounding mountain ranges. Thus the Galiuro Mountains and vicinity are designated as the type area for the Galiuro assemblage. Rocks of the Galiuro assemblage are especially well exposed in the Mogollon-Datil volcanic field of southwestern New Mexico and this area is designated as a reference area for volcanic rocks of the Galiuro assemblage.

The term Galiuro assemblage is broadly equivalent to the mid-Tertiary 'ignimbrite flareup' of Coney (1976), to the middle Unit I of Eberly and Stanley (1978), and to the ignimbrite package of Wilt and Scarborough (1981). In addition, Eberly and Stanley (1978) designated this unit (the ignimbrite-dominated middle Unit I) as the mid-Tertiary orogeny in their Figure 2. As used in this paper, Galiuro assemblage is also broadly equivalent to the 'mid-Tertiary orogeny' of Shafiqullah and others (1980) and of Damon and others (1984). Where in contact with Mineta assemblage rocks, Galiuro assemblage rocks are generally concordant to and locally conformable with the underlying Mineta strata. In general, Galiuro assemblage rocks are separated by angular unconformities from the overlying Whipple assemblage, where the assemblages are in mutual contact. Locally, basin-fill and basaltic volcanics of the Basin and Range assemblage of the San Andreas orogeny may unconformably overlie Galiuro assemblage rocks.

Rocks of the Galiuro Assemblage

Sedimentary Rocks. Sedimentary rocks of the Galiuro assemblage are generally subordinate in volume to Galiuro igneous rocks, but locally sedimentary sequences can be very thick (locally greater than 1.5 to 3.3 km). Where present, Galiuro assemblage sedimentary rocks consist of conglomeratic material, debris flows, and megabreccia units near uplifts and of braidplain sediments away from the uplifts. Because sedimentary rocks of the Galiuro assemblage commonly interfinger with volcanic facies, the sediments have a strong volcaniclastic component. In thick sedimentary sections where both Mineta and Galiuro assemblages are present without Galiuro volcanic rocks as a separating datum, the upper conglomerates which commonly contain megabreccia units are assigned to the Galiuro assemblage. For example, in the Pantano basin southeast of Tucson, the fine-grained, gypsiferous claystone member of the Pantano Formation is assigned to the Mineta assemblage; the overlying fanglomerate member, designated by Drewes (1977) as the upper Pantano, is assigned to the Galiuro assemblage.

Within the Hackberry Formation of Schmidt (1971) in the Ray and Hayden area is a spectacular horizon of megabreccia slide blocks described by Schmidt (1971) and Krieger (1977); some of these blocks are up to 3 km long and 1/2 km thick and consist of Paleozoic and Precambrian sediments that are highly crackled but maintain their internal stratigraphy. Krieger (1977) suggested that the megabreccia units were emplaced at high velocities into the depositional basin on top of an air cushion that kept deformation of the underlying soft sediments to a minimum. The Hackberry Formation interfingers locally with the Andesite of Depression Canyon, which is dated at about 25 Ma (Creasey and Krieger, 1978). Paleocurrent data and paleoclast data indicate that the source of much of the Hackberry sediments was from the Tortilla Mountains to the west. Thus, while the Tortilla Mountains was rising rapidly to the west, the Galiuro Volcanics were being deposited in a trough to the east. Other similar relationships are well-documented in the Cloudburst Formation in the southern Tortilla

Mountains (Weibel, 1981) and the basalt member of the Artillery Formation in western Arizona (Shackelford, 1980; Otton, 1982).

Igneous Rocks. The widespread magmatism expressed both as plutons and large volumes of locally thick, ignimbritic volcanics is the best known feature of the Galiuro assemblage (Fig. 4). Volcanics commonly occur in large volcanic fields which generally have andesitic basal units that interfinger upward into more silicic units, which commonly are regional ash flow sheets. Many of the ash flow sheets are associated with extensive caldera development, such as the Bursum caldera in the western part of the Mogollon-Datil field. Thicknesses of the volcanic piles vary from several hundred meters to several thousand meters. For example, the section of Galiuro Volcanics in the southern Galiuro Mountains is at least 3 km thick and thins to about 0.5 km in the northern Galiuros. Local accumulations of volcaniclastic sediments generally constitute less than 10 percent of the section, although some of the sedimentary sections that interfinger with volcanic piles may be as much as 3.5 km thick. Plutons of the Galiuro assemblage range from hypabyssal dike swarms to large, composite batholiths and range from intermediate to silicic compositions. An example of plutonism of the Galiuro assemblage is the Catalina Suite within the central part of the Tortolita-Catalina crystalline complex (Keith and others, 1980).

Chemically and metallogenically, magmatism of the Galiuro assemblage can be divided into two distinct facies that are herein named the South Mountain facies and the Datil facies. Geographically, South Mountain facies magmatism generally occurs west of a N30W trending line through Tempe, Arizona, whereas the Datil facies predominates northeast of the line. Datil facies volcanism locally occurs in significant amounts west of the N30W line within the region predominated by South Mountain facies.

South Mountain Facies. The South Mountain facies is named for the South Mountain Granodiorite and related microdiorite dikes and gold mineralization in the South Mountains south of Phoenix. Because the South Mountain igneous complex has been well described and dated by Reynolds (1982) and Reynolds and Rehrig (1980), the South Mountains are designated as the type area of the South Mountain facies. In western Arizona and southeastern California, magmatism of the South Mountain facies is expressed by hypabyssal dikes, small stocks, and extensive calc-alkalic volcanism. Because this magmatism is well documented in the Chocolate Mountains of Imperial County in southeastern California (Crowe and others, 1979), this area is designated as a reference area for South Mountain facies magmatism.

Magma series chemistry of South Mountain facies magmatism displays metaluminous aluminum contents, calc-alkalic alkalinity, and is hydrous, oxidized, and generally iron-poor. Strontium isotopic initial ratios range between 0.705 and 0.709 indicating that a small crustal component is present.

Datil Facies. The Datil facies is named for the extensive and thick volcanic sequences in the Mogollon-Datil volcanic field of western New Mexico. Because of the long history of documentation and abundant geochronological and geochemical data for the Mogollon-Datil volcanic field, this region is designated as the type area for the Datil facies. The Mogollon-Datil volcanic field is a composite of numerous interfingering volcanic centers and caldera complexes (Bornhorst, 1982). Almost the entire field is characterized by alkali-calcic magma chemistry.

Another reference area for Datil facies of the Galiuro assemblage is the Galiuro Mountains of southeastern Arizona where there is also abundant documentation (Creasey and Krieger, 1978; Creasey and others, 1981). This extensive volcanic field is present throughout the 75 km length of the mountain range, is dated at 28 to 22 Ma, and is of alkali-calcic alkalinity. Similar geochronologic and geochemical control now exist for extensive volcanic piles in the Superstition Mountains northeast of Phoenix (Stuckless and Sheridan, 1973), in the central Plomosa Mountains in west-central Arizona (Shafiqullah and others, 1980), and in the Turtle Mountains of southeastern California (R. Hazelett, pers. commun., 1985). Plutons of the Datil facies are widespread and locally constitute small to moderate-sized batholiths. The Catalina suite batholith has especially good geochronologic, map, and geochemical control (Keith and others, 1980) and is designated as a reference area for Datil facies plutonism.

Magma series chemistry of Datil facies magmatism displays metaluminous aluminum contents, alkali-calcic alkalinity, and is hydrous, oxidized, and generally iron-poor. Strontium isotopic initial ratios range between .705 and .710 and generally are between 0.7069 and 0.7096 indicating that a small crustal component is present.

Structural Features of the Galiuro Assemblage

Large-scale Folds. The most significant structural feature of the Galiuro orogeny is a set of regionally extensive, long wavelength, large amplitude, open, broadly folded, northwest-striking, warps or anticlines and synclines (Fig. 4). Culminations of the Galiuro assemblage anticlinal arches coincide with areas of widespread, reduced, K-Ar and fission-track, isotopic dates. Galiuro assemblage fold phenomena represent broader, crustal-scale warping that precedes the more obvious and more resolved, more northerly trending, en echelon folds of the Whipple Assemblage. Thus, the folds shown on Figure 4 are not defined by attitude data taken from lower plate, mylonitic foliation within the crystalline cores of lower plate windows through arched, Wilderness assemblage thrusts (metamorphic core complexes of recent literature). Rather, the folds are inferred from more regional data, such as distribution and thickness of Galiuro

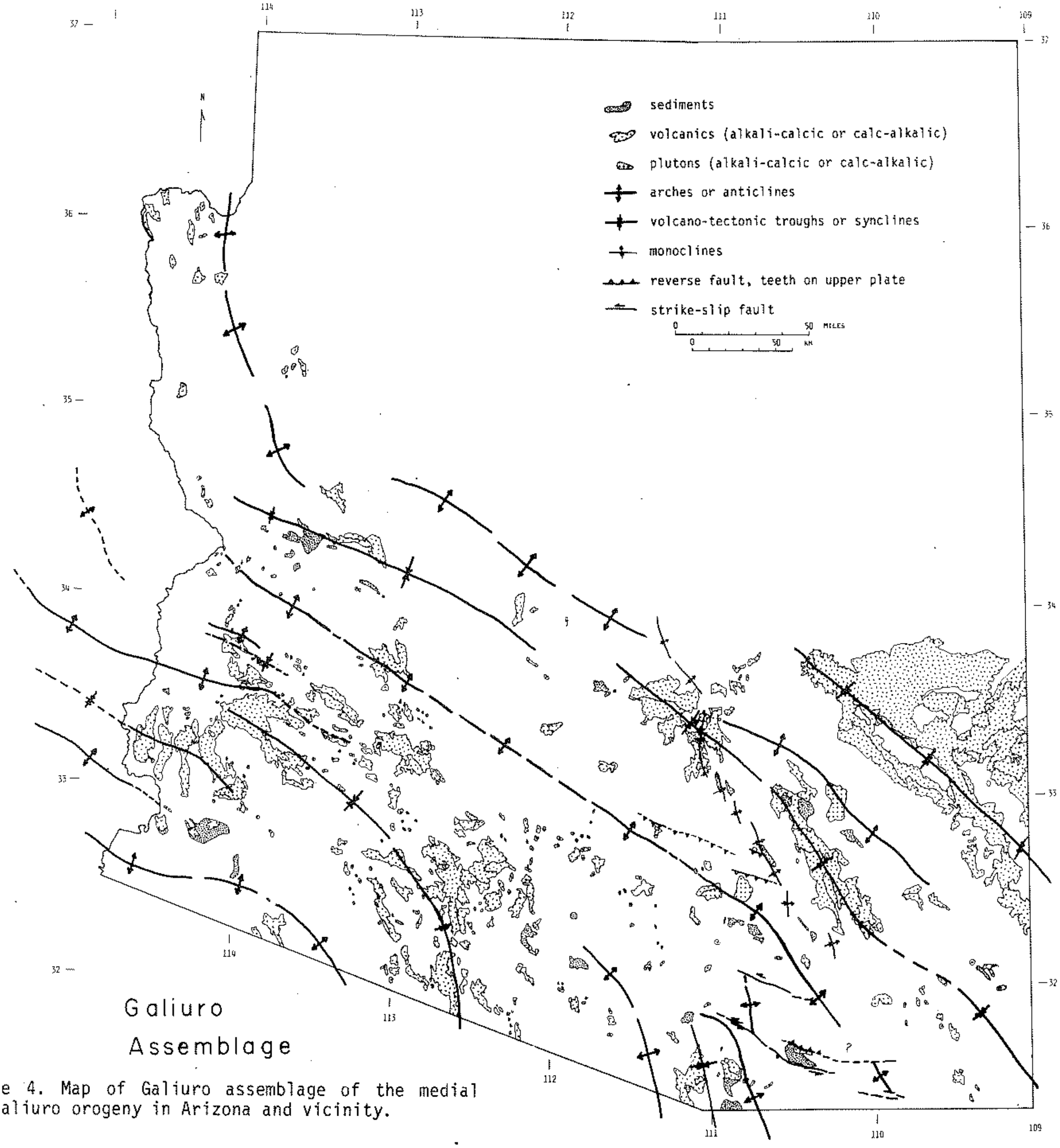


Figure 4. Map of Galiuro assemblage of the medial Galiuro orogeny in Arizona and vicinity.

assemblage volcanics and sediments; distribution and transport directions inferred from areas underlain by Whipple assemblage detachment faults (Fig. 5); distribution of reduced, mid-Tertiary, age dates; and presence of regional warp-like deformation of low-angle reflectors on regional seismic sections shot for the recent petroleum play (Keith, 1980).

Amplitudes of Galiuro assemblage warps are very large. From seismic data that was shot for the Arizona oil and gas play of 1979-1980, the amplitude or structural relief of some of the warps is as much as 6 km (20,000 feet) (Reif and Robinson, 1981). One unpublished seismic line that was shot in the Tucson region was from the southwestern Rincon Mountains across the Tucson Basin. The seismic section showed a dramatic zone of strongly continuous seismic reflectors that correlated well with surface outcrops of the Catalina fault. To the southwest the zone of strongly continuous, seismic reflectors dipped southwest and flattened at a depth of about 2 seismic seconds. This corresponds with a depth of about 6 km (20,000 feet) below sea level beneath Tucson. As the Catalina fault can reasonably be projected over the top of Mica Mountain to the northeast at an elevation of about 3 km (10,000 feet) above sea level, an amplitude of about 9 km (30,000 feet) is possible for anticlinal warping of the Catalina fault.

Another independent way of assessing the structural relief developed on Galiuro assemblage warps is petrologic in nature. Because of the extensive presence of volcanic components, it is clear that magmatism of the South Mountain facies is shallow level (typically within 3 km) compared to the deeper level of peraluminous plutons of the culminant Laramide orogeny. In the crystalline core of the northwestern Santa Catalina Mountains, alkali-calcic plutons locally contain miarolitic cavities which indicate shallow depth levels of probably less than 2 km. These shallow plutons intrude plutons of the Wilderness assemblage that were emplaced at deep levels of 8-10 km or more. Thus, at least 6 km of uplift and erosional removal occurred in the crystalline core of the Santa Catalinas between 44 and 24 Ma.

An even greater amount of structural relief can be inferred from reduced age dates obtained from older rocks in the crystalline cores of the anticline-like uplifts. In the Santa Catalina Mountains, K-Ar ages for hornblende or large muscovite grains from older rocks are either not reset or are only partially reset (Keith and others, 1980), indicating that temperatures in the lower plate prior to 30 Ma were not greater than 400° C. However, K-Ar determinations on biotite and fission track determinations on zircon and sphene consistently yield reduced ages between 28 and 24 Ma, suggesting cooling below 200° C. If the reduced ages are related to uplift refrigeration of K-Ar clocks, then between Eocene (44 Ma) and mid-Oligocene (24 Ma) the complexes cooled from 400° to 200° C., which represents uplift of 8 km assuming a normal crustal geotherm of 25° C/km. 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. Most, if not all, of the structural relief associated with the arches was probably generated after 28 Ma, because lacustrine strata of the Mineta assemblage once occupied basins that extended across the now uplifted arches. This uplift totaled about 8 km of uplift from 28 Ma to 24 Ma, with an additional 4 km of uplift between 22 and 18 Ma. With these kinds of uplift rates, it is not surprising that Galiuro assemblage sediments contain widespread megabreccia blocks of all sizes.

The fold warps are also characterized by long wavelengths. The distance between anticlinal crest and synclinal, volcano-tectonic troughs (one-half wavelength) is about 30 to 40 km as indicated by seismic data. Between the anticlinal crests are large synclinal troughs that represent major sags or synclinal basins in which substantial amounts of Galiuro assemblage volcanics and sediments accumulated.

One of the best examples of such a synclinal trough is the Galiuro Mountains where at least 4 km of Galiuro assemblage volcanics and sediments have accumulated in a trough between the Pinaleno and Santa Catalina mountains. The distance between the crests of the anticlines is about 80 km and the thickest parts of the Galiuro Volcanics occur in the trough along an axis approximately midway between the crests. Attitudes of bedding, foliation, and low angle joints in the Pinaleno Mountains show that the Pinaleno Mountains also occupy a broad, anticlinal arch (Thorman, 1980; Rehrig and Reynolds, 1980). Similarly, attitude data for volcanics in the Galiuro Mountains show that the Galiuro Volcanics (Creasey and others, 1981) are broadly warped into a broad synclinorium containing several smaller scale anticlines and synclines. The northwest-trending trough or depression may have continued to the southeast into the central Chiricahua Mountains where a thick volcanic section of the Rhyolite Canyon Formation is present.

Similar volcano-tectonic troughs are inferred to exist from the Ajo Range and Batamote Hills and Crater Mountains in the Ajo region to the Castle Dome Mountains in Yuma County, through the Chocolate Mountains of southeastern California, and from the Garlock fault southeast through Barstow to the Bristol and Bullion Mountains in southeastern California. Significantly, the amount of volcanic and sedimentary material deposited in the volcano-tectonic troughs is approximately the same as the amount of material erosionally removed from uplifts centered on the anticlinal axes shown on Figure 4.

An obvious kinematic interpretation of the fold phenomena is that they reflect crustal shortening. From inspection of Figures 4 and 5, the approximate axis of shortening relative to the Galiuro assemblage folds is along a N30E to N40E line. The amount of crustal shortening related to the warping may be calculated from the amplitude and wavelength data. For example, if amplitudes of 10 km and half wavelengths of 40 km are assumed for a typical fold, the shortening is 3 percent.

Smaller-Scale Monoclines and Folds. The best examples of north- to northwest-trending monoclinal structures of the Galiuro assemblage are the segmented monoclines along the Tortilla Mountains. Because the monocline system occurs for most of its strike length along the west side of and parallel to the San Pedro Valley, in this paper it is called the San Pedro monocline system. It extends from the Superior area for some 160 km to the eastern Rincon Mountains at its southeast end. The San Pedro monocline system is composed of a series of north-northwest-trending monoclines which locally display an en echelon pattern. The monocline system itself is defined by moderately to steeply dipping, to slightly overturned, east-dipping, middle limbs.

Reverse Faults. Intra-Galiuro assemblage reverse faulting is difficult to document, but where present, may be large scale. A probable example of a reverse fault of the Galiuro assemblage is the Black Canyon Ranch fault in the Black Hills segment of the southern Tortilla Mountains about 3 km southwest of San Manuel mapped by Weibel (1981). The Black Canyon fault is a WNW-striking fault that dips 35° to 75° South; it juxtaposes, with reverse separation, Precambrian granite (1400 Ma) and San Manuel granodiorite (Laramide) over a thick sequence of fanglomerate within the Cloudburst Formation. The amount of reverse slip could have been at least 2 km, which is the thickness of the Cloudburst Formation on the north side of the fault. More speculatively, at least 2 to 4 km of reverse separation with a northeast sense of vergence is indicated along the south-dipping Mogul fault in the northern Santa Catalina Mountains and the North Star fault in the Picacho Mountains. Here, analysis of the Phillips drilling results north of the North Star fault zone (Reif and Robinson, 1981) indicates possible Wilderness assemblage thrust plates may be offset during Galiuro assemblage uplift of the Santa Catalina Mountains south of the Mogul fault.

Dike Swarms. The numerous prominent dike swarms of both South Mountain and Datil facies of Galiuro assemblage commonly trend northwest (Rehrig and Heidrick, 1976). However, nearly as many dike swarms of Galiuro Assemblage strike northeast. Some of the northwest- striking dike swarms include the Aravaipa dike swarms in the western Santa Teresa Mountains (Simons, 1964), the central Dragoon Mountains dike swarm (Gilluly, 1956), the South Mountain dike swarm (Reynolds, 1982), the Harquahala dike swarms, the Castle Dome dike swarms, and the Chambers Well dike swarm in the Whipple Mountains (Davis and others, 1982). Some of the northeast- to east-striking dike swarms of Galiuro Assemblage are the Stockton Pass dike swarm (Thorman, 1980), the Eagle Pass dike swarm, the Apache Pass dike swarm, and the central Santa Rita and Box Canyon dike swarms (Drewes, 1972), and the Sacramento Mountains dike swarm in southeast California (Spencer and Turner, 1982).

Mylonitic shear zones. Although most (75-85 percent) of the mylonite development in the lower plates of the crystalline complexes probably developed during earlier Laramide and Sevier orogenies, mylonitic shear zones of middle Tertiary age were developed at least locally in several areas. Known areas of mid-Tertiary mylonitization include the deformed Tortolita Quartz Monzonite of the Catalina suite (Keith and others, 1980), the deformed South Mountain plutonic complex at South Mountain (Reynolds, 1982; and Reynolds and Rehrig, 1980), and a similar mylonitic pluton in the southeastern part of the Picacho Mountains 45 km northwest of Tucson (W. Rehrig and S. Keith, unpub. data). The present attitudes of the above-described shear zones, in combination with S-C fabric data, indicates that the shear zones have low-angle normal shear.

Age of Galiuro Assemblage

Age of Magmatism. Age patterns for Galiuro assemblage are well constrained because of abundant radiometric dates on the widespread igneous components. In general, the age patterns of Galiuro assemblage rocks are the mirror image to that of Laramide assemblages; that is, Galiuro Assemblage rocks become younger to the west (Coney and Reynolds, 1977; Wilt and Scarborough, 1981). This westward younging applies to both South Mountain and Datil facies magmatism and also to reduced dates by K-Ar, fission track, and Rb-Sr mineral isochron methods on older crystalline rocks now exposed in the central, uplifted cores of Galiuro and Whipple assemblage warps.

The ages of calc-alkalic magmatism of South Mountain facies of the Galiuro assemblage are oldest in eastern Arizona (30 to 28 Ma) and younger to the west from south-central Arizona (29 to 22 Ma) to western Arizona (28 to 24 Ma) to the southern Colorado River region (29 to 21 Ma) to southeastern California (23 to 19 Ma). In the eastern Chiricahua Mountains of eastern Arizona three dates on two samples of the metaluminous, calc-alkalic Faraway Ranch Formation yield dates between 29.6 and 28.0 Ma (Shafiqullah and others, 1978). To the west in the southern Santa Rita Mountains, the Grosvenor Hills volcanics, is a fairly widespread volcanic pile with calc-alkalic chemistry. Four K-Ar dates from three samples of Grosvenor Hills volcanics and a related subvolcanic laccolith range from 27 to 29 Ma (Drewes, 1972). To the northwest at the type locality of the South Mountain Facies at South Mountain south of Phoenix, the South Mountain intrusive complex is calc-alkalic (Keith and Reynolds, unpub. geochemical data) and is well dated between 26 and 22 Ma by K-Ar, Rb-Sr, and U-Pb techniques (Reynolds, 1982). To the west in the Harquahala Mountains 100 km west of Phoenix widespread, calc-alkalic, microdiorite dike swarms of the South Mountain Facies are dated at 28 to 25 Ma (Shafiqullah and others, 1980). To the south in the southeast Chocolate Mountains, the main volumes of volcanism are calc-alkalic and erupted between 30 and 22 Ma based on numerous K-Ar dates (Crowe and others, 1979). Farther to the west volcanism in the Diligencia Formation of the northeastern Orocopia Mountains is calc-alkalic and has yielded three K-Ar dates which range from 23.0 to 19.1 Ma (Spittler and Arthur, 1982).

The Datil facies of the Galiuro assemblage exhibits a broader geographic distribution than the South Mountain facies and thus exhibits a more obvious pattern of younging to the west. In southwest New Mexico the magmatism is mainly 38 to 24 Ma and becomes younger westward from southeasternmost Arizona (28 to 22 Ma) to south-central Arizona (28 to 22 Ma) to the Phoenix region (24 to 16 Ma) to west-central Arizona (22 to 18 Ma) and to southeastern California (22 to 18 Ma).

In the Mogollon-Datil volcanic field, alkali-calcic volcanics (Bornhorst, 1982) erupted in several volcanic cycles that range in age from 38 to 20 Ma (Elston and others, 1973). In the Peloncillo and Animas Mountains of southwesternmost New Mexico, an extensive field of caldera-related, alkali-calcic magmatism ranges from 37 to 24 Ma (Deal and others, 1978). In southeastern Arizona alkali-calcic magmatism, such as the Stronghold Granite of the central Dragoon Mountains yield K-Ar dates of 27 to 23 Ma (Damon and Bikerman, 1964; Marvin and others, 1973) and volcanics in the southern Pinaleno Mountains yielded five fission track dates that range from 26.8 to 22.8 (Thorman, 1980). To the northwest Galiuro Volcanics of the alkali-calcic Datil facies yield numerous K-Ar dates that range from 28 to 22 Ma (Creasey and Krieger, 1978; Scarborough and Wilt, 1979).

In the Catalina and Tortolita Mountains northwest of Tucson, the Catalina suite of plutons is well-dated by K-Ar, fission track, U-Pb, and Rb-Sr geochronology at 27 to 24 Ma (Creasey and others, 1976; Keith and others, 1980). To the west in the Tucson Mountains age data show that the mid-Cenozoic volcanics in the eastern Tucson Mountains are 28 to 23 Ma (Damon and Bikerman, 1964; Shafiqullah and others, 1978). Near Phoenix numerous K-Ar ages and geochemical data show that the majority of the Superstition Volcanics (below the Mesquite Flat breccia unit) have alkali-calcic alkalinity and are mostly 24 to 16 Ma (Stuckless and Sheridan, 1971). Northwest of Phoenix the Castle Creek volcanics are mainly alkali-calcic and are probably 22 to 18 Ma (C. Kortemier, pers. commun., 1985). Volcanism in the central Plomosa Mountains is shown by geochemical data (Gene Davis, pers. commun., 1985) to be alkali-calcic and has age dates of 20 to 18 (Shafiqullah and others, 1980). In southeastern California a large volcanic pile in the Turtle Mountains 40 km west of Parker, Arizona, has yielded numerous K-Ar dates between 22 and 18 Ma and is entirely alkali-calcic (Hazelett, pers. commun., 1985).

In any area where both facies are present, the South Mountain facies precedes the Datil facies. For example in the Phoenix region, the calc-alkalic South Mountain Granodiorite pluton and its associated microdiorite dikes and gold mineralization are 26 to 22 Ma in age (Reynolds, 1982). To the northeast in the Superstition Mountains, alkali-calcic Superstition Volcanics of the Datil facies are radiometrically younger and yield dates between 24 and 15 Ma (Stuckless and Sheridan, 1971). In the Chocolate Mountains of southeastern California, Crowe and others (1979) have documented an extensive volcanic pile. The lower part of the volcanic section (Unit A and Unit B) is chemically calc-alkalic and is assigned to the South Mountain facies. It is overlain by a younger sequence of more mafic lava flows (Unit C), which are alkali-calcic and are associated with manganese-silver deposits and are assigned to the Datil facies. Units A and B are calc-alkalic and yield numerous K-Ar dates that range from 35 to 24 Ma, whereas Unit C is commonly alkali-calcic and yields K-Ar dates that range from about 26 to 22 Ma (Crowe and others, 1979).

Age of Structural Development. Galiuro assemblage warping and magmatism appear to be virtually coincident. Uplift of the lower plate gneisses was not underway during deposition of Mineta assemblage rocks because lacustrine facies of Mineta assemblage occupied basins across the sites of later Galiuro assemblage uplifts in the axes of the anticlinal warps. Thus, warping was not active in southeast Arizona prior to 28 Ma or in west-central Arizona and southeastern California prior to 25 Ma. However, by middle or late Galiuro assemblage, the gneisses had been uplifted and at least locally exposed to erosion because clasts of lower plate mylonitic rocks from the crystalline cores of the uplifts are locally present in the Galiuro assemblage sediments. For example, in the Whipple Mountains, mylonitic clasts are locally present in the conglomerates in upper portions of the Gene Canyon Formation. One of these mylonite clasts yielded an age of 83 Ma by the fission track method on sphene (Davis and others, 1982). Thus, in early Gene Canyon time (32-28 Ma) the area of the Whipple Mountains was occupied by lacustrine sediments, but by late Gene Canyon time (26 to 22 Ma) the basin had been disrupted by anticlinal uplift of the lower plate crystalline rocks, which began to supply mylonitic clasts to the Gene Canyon Formation.

Similarly, in the Santa Catalina mountains near Tucson, the Rillito II unit of Pashley (1966) contains mylonitic clasts that are derived from the mylonitic Wilderness complex in the crystalline core of the lower plate. A rhyolitic clast from Rillito II yielded a 22 Ma K-Ar date (H. W. Peirce and M. Shafiqullah, pers. commun., 1982) suggesting that the Rillito II is younger than 22 Ma. However, it contains clasts of Eocene aged Wilderness suite plutonic rocks which have yielded a reduced age of 26 Ma by the K-Ar method on muscovite. The area of the Santa Catalina-Rincon Mountains was also a site of lacustrine sedimentation during Mineta assemblage and before 28 Ma. By 26 Ma, the complex had been uplifted about 6 to 8 km and cooled from 400° to 200° C to refrigerate the K-Ar clock; after 22 Ma, the area was supplying clasts to basins adjacent to the uplift.

Volcanics intercalated with sedimentary units that contain mylonitic clasts are the same age as the reduced dates or cooling ages on the mylonitic rocks in the lower plate. For example in the Whipple Mountains, K-Ar dates from the Gene Canyon Formation are 31-25 Ma, and cooling ages on mylonitic clasts range from 26 to 16 Ma (Davis and others, 1982). In the Catalina Mountains fission track and cooling ages on mylonites are 28 to 18 Ma, and Rillito II strata that contain the mylonite clasts are post-22 Ma and probably are 22 to 18 Ma. In the Artillery Mountains, the basalt member of the Artillery Formation, which contains large megabreccia units of mylonitic rocks, yields dates from 21 to 16 Ma (Shackelford, 1980), and overlaps reduced ages on mylonites in the lower plate in the nearby Harcuvar and Buckskin Mountains and more distant Whipple Mountains (26 to 16 Ma) (Reynolds and Rehrig, 1980; Davis and others, 1982). Thus, if the mylonites were predominantly formed during the middle Tertiary, as is widely advocated in the literature (Rehrig and Reynolds, 1980; Davis, 1980), then the mylonites would have had to be uplifted instantaneously from their deep formation depth in order to supply clasts for the syntectonic sedimentation associated with the uplift. It is more reasonable to support an older age (late Cretaceous to early Tertiary) for the formation of most of the mylonitic rocks in the lower plate throughout this region (Fig. 1).

Culminant Galiuro Orogeny

Whipple Assemblage

Because of the excellent exposures in the Whipple Mountains of southeastern California and the extensive work done there (Davis and others, 1980; Frost, 1981; Frost and Martin, 1982), the rocks, structures, and mineral deposits of the culminant Galiuro orogeny are named the Whipple assemblage and the Whipple Mountains are designated the type area for the Whipple assemblage.

Rocks of the Whipple assemblage are broadly similar to upper Unit I of Eberly and Stanley (1978) or to the post-ignimbrite sedimentary package of Wilt and Scarborough (1981). Whipple assemblage covers the interval of the 'Transition Phase or Stage' as used by Shafiqullah and others (1980) and Damon and others (1984). Whipple assemblage strata are commonly separated from older Galiuro assemblage and younger strata of the San Andreas orogeny by angular unconformities.

Rocks of the Whipple Assemblage

Sedimentary Rocks. Sedimentary rocks of the Whipple Assemblage consist of coarse clastic rocks and finer grained lacustrine facies (Fig. 5). In general, though, the frequency of megabreccia units, debris flows, and coarse clastic sedimentation appears to be less than that in the preceding Galiuro assemblage. Facies changes in Whipple assemblage sediments appear to be much more rapid and the size of basins seems to be smaller on an overall basis. In areas of known detachment faulting much of the sedimentation accumulated in small, half-graben basins between antithetically rotated blocks in the upper plate and were up to 15 km long and 2-3 km wide. Whipple assemblage sedimentation also appears to have a higher percentage of lacustrine facies than the Galiuro assemblage. Mylonitic clasts are widespread and much more common in Whipple assemblage strata than they are in Galiuro assemblage strata. Thicknesses of Whipple assemblage typically range from 200 m to 1500 m and are generally thinner than those of the underlying Galiuro assemblage.

A sedimentological feature of conglomeratic units of the Whipple assemblage is the tuffoni weathering which leaves conspicuous water pockets or pock marks on more resistant exposures. Good examples of this tuffoni weathering are the tilted red conglomerate sections in the upper plate of the Plomosa fault in the northern Plomosa Mountains, the Camelback Formation on Camelback Mountain in north Phoenix, the Big Dome Formation south of Ray in Pinal County, the Apsey and Hell Hole Conglomerates in the Galiuro Mountains (Simons, 1964), and the Gila Conglomerate near the Gila Cliff Dwellings in southwestern New Mexico.

One of the best examples of Whipple assemblage sedimentation is the Copper Basin Formation in the Whipple Mountains. Here, the Copper Basin Formation angularly overlies the Gene Canyon Formation and consists of red sandstones, conglomerates, and siltstones with interbedded trachyandesites and trachitic volcanics (Teel and Frost, 1982). Primary sedimentary features such as mudcracks, ripple marks, and cross-bedding are abundant within the formation and suggest a fluvial or fanglomerate deposition environment for much of the unit.

Other examples of Whipple assemblage strata occur in the Plomosa, Rawhide, and Buckskin Mountains. Here, the Whipple assemblage includes the Chapin Wash Formation, which is a manganiferous, fine-grained siltstone and mudstone facies of probable lacustrine origin, and the unconformably overlying Cobweb basalt. A characteristic feature of the Chapin Wash and Copper Basin formations is the pervasive brick red color.

Farther to the southeast Whipple assemblage strata include the Big Dome Formation, the San Manuel Formation of Heindl (1962), the Rillito II beds of Pashley (1966), which are predominantly reddish conglomerates with about 5-10 percent gneiss clasts, and the Rillito III beds, which are tilted, lighter gray colored sediments containing about 70-80 percent gneiss clasts.

Igneous Rocks. In general, igneous rocks of the Whipple assemblage are not as widespread as sedimentary rocks; however, they can locally reach considerable thicknesses (greater than 2000 m). Volcanic rocks are more common, but small to moderate size stocks of Whipple assemblage are locally present. Volcanism and epizonal plutons of Whipple assemblage affinity are especially well developed and have been well documented (Ransome, 1923; Thorson, 1971) in the Oatman district of the southern Black Mountains of northwestern Arizona. Thus, this area is designated as a reference area for Whipple Assemblage magmatism. Another reference area is the Socorro region of south central New Mexico, where extensive geochemical data and map control exist for the La Jara Peak Andesite and its intercalated ash flow tuffs (Osburn and Chapin, 1983).

Mineralogically, Whipple assemblage magmatism commonly lacks quartz but does not contain nepheline, so that rock types such as latite, trachyandesite, or shoshonite are common volcanic

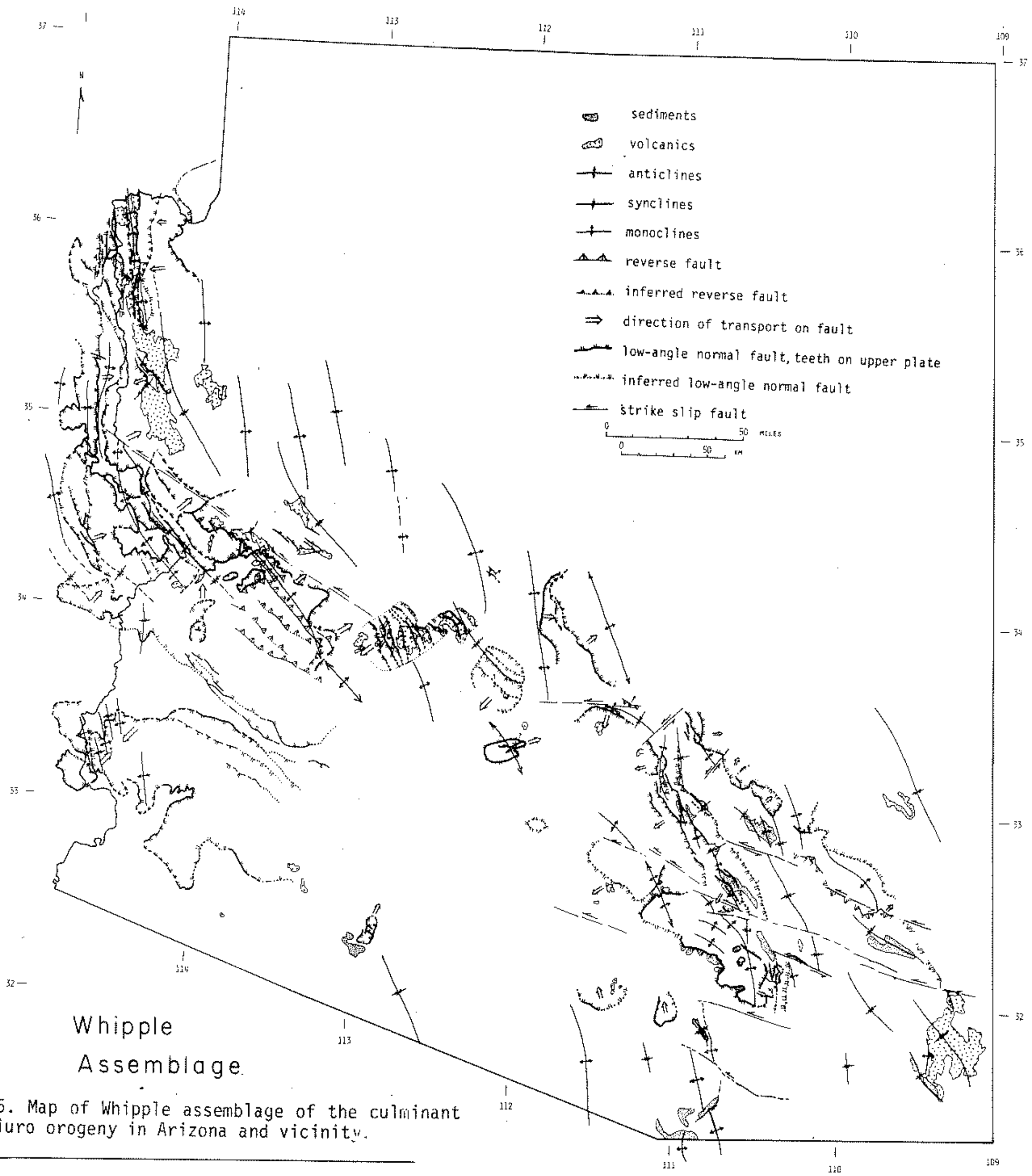


Figure 5. Map of Whipple assemblage of the culminant Galiuro orogeny in Arizona and vicinity.

phases and monzonite or quartz syenite are common intrusive phases. Biotite is the principal mafic accessory followed by hornblende and locally important augite, especially in augite monzonite stocks, such as those in the White Oaks and the Rialto stock of Lincoln County, New Mexico, and the Times Porphyry and Moss Porphyry monzonitic stocks northwest of Oatman, Arizona (Thorson, 1971).

Magma series chemistry of Whipple assemblage magmatism displays metaluminous aluminum contents, alkali-calcic to mostly quartz alkalic alkalinity, and is hydrous, oxidized, and generally iron-poor. The strontium initial ratios range between 0.705 and 0.710 indicating that a small crustal component is present.

Ultra-potassic chemistry (where K_2O/Na_2O ratios exceed 3:1) is another feature of Whipple assemblage volcanism. Within these areas, ultra-potassic chemistry seems to be restricted to areas of high K_2O, quartz-alkalic volcanism (especially trachytic and high K-rhyolite phases). For example, Shafiqullah and others (1976) and Rehrig and others (1980) have reported ultrapotassic chemistry from trachytes at Picacho Peak 45 km northwest of Tucson and from rhyolites in the Vulture Mountains 45 km northwest of Phoenix. Ultra-potassic trachytes are found in the Copper Basin Formation of the western Whipple Mountains (L. Anderson, unpub. data) and ultra-potassic rocks are widespread in the Socorro area (Osburn and Chapin, 1983). Ultra-potassic chemical data has not been reported from older Galiuro assemblages.

Structural Features of Whipple Assemblage

Detachment Faults. The most well-studied structural elements of the Galiuro orogeny are the spectacular detachment faults. In previous literature the terms denudational fault (Armstrong, 1972), dislocation fault or dislocation surface (Rehrig and Reynolds, 1980), or decollement (Coney, 1980; Davis, 1980) have been synonomously employed when referring to these structures. The terms 'detachment fault' or 'low-angle normal fault' have been used in more recent literature (Frost and Martin, 1982; Davis, 1983) and are continued here.

Low-angle normal faults or detachment faults of the Whipple assemblage have been well described in the Whipple, Rawhide, Buckskin, and Harquahala region and in the Santa Catalina, Rincon, and Tortolita region. In both locations low-angle normal faults appear to have reutilized pre-existing, low-angle, thrust zones (Drewes, 1981). Haxel and Grubensky (1984) have recorded similar reutilizations for detachment-related faulting in the Comobabi Mountains on the Papago Indian Reservation and in the Kofa Mountains of Yuma County.

Many of the detachment fault zones occur in areas that are underlain by mylonitic rocks of the lower plate, and some observers have interpreted the spatial association as causative (Davis, 1983; Reynolds, 1982; Rehrig, 1982). However, areas affected by low-angle detachment faulting are commonly not geographically restricted to areas of mylonitic rocks in the lower plate (Davis and others, 1980). This is documented in the central Whipple Mountains where nonmylonitic gneisses and plutonic rocks underlie the detachment fault at Savahia Peak (Gross and Hillemeyer, 1982). Detachment faulting in the Trigo Mountains occurs above nonmylonitic crystalline rocks (Garner and others, 1982), as it does in the Baker Peaks area of Yuma County (Pridmore and Craig, 1982). Similarly, detachment faulting in the Owlshead Mountains in southern Death Valley places antithetically tilted, middle Tertiary rocks of the upper plate against nonmylonitic, probably mid-Cretaceous, granitoids (Davis and Fleck, 1977). In some of these areas, such as the Owlshead Mountains and most of the Trigo Mountains, there is no evidence of any former thrusting. Thus, tectonics responsible for mylonitic phenomena and detachment phenomena are not mutually coincident, and are, therefore, probably not causally related.

The structural style of detachment fault zones consists of a basal chloritic breccia zone, a microbreccia zone, and a microbreccia ledge with a planar surface, above which are unmetamorphosed and nonmylonitic rocks of the upper plate. The crystalline rocks of the upper plate commonly are depositionally overlain by Mineta, Galiuro, and Whipple assemblage volcanics and sediments. These strata are tilted from a few degrees to near vertical but generally dip between 30 and 60 degrees. Areas characterized by the same dip directions are geographically distinct, so that it is possible to define domains of dip direction (Stewart, 1980; Rehrig and Heidrick, 1976) that inferentially overlie a single, common, basal detachment zone. In some places the dip domains can be inferred to represent antithetic tilting of middle Tertiary strata in the upper plate as a response to detachment faulting at depth. Not all of the tilt directions or dip domains can be interpreted as a result of detachment faulting; for example the tilted Galiuro Volcanics within the synclinorium of the southern Galiuro Mountains. In most places the tilt domains outline areas on the same flank of regional warps of Galiuro assemblage and dip away from the volcano-tectonic troughs. Areas of thick Galiuro sedimentation coincide geographically with axes that separate regions of inward dips on tilt domain maps.

On a subregional scale, tilt directions of the larger-scale blocks appear to be fairly consistent, but in detail, the geometries can be considerably more complex. A good example of the complexity has been documented by Gross and Hillemeyer (1982) for small-scale, detachment-related structures in the western Whipple Mountains and the Buckskin Mountains. The overall movement as indicated within a given domain of tilted blocks may be counterbalanced by small scale, less noticeable, antithetic faults. Gross and Hillemeyer (1982) demonstrate that simple, upper plate, synthetic, normal-fault models that are widely used in the literature cannot be structurally balanced, and leave gaping voids that somehow must be accounted for by more complex, keystone-like, fault relationships. Also, the obvious antithetic tilting of upper plate blocks may be, to some extent, counterbalanced by more subtle, synthetic tilting. Figure 10 in Gross and Hillemeyer (1982) is especially spectacular.

Direction of Transport on Detachment Faults. In general, the strike of the tilted mid-Tertiary strata is perpendicular to the direction of tectonic transport on the underlying 'basal' detachment fault. Slickensides on the detachment surfaces are generally parallel to the dip direction of the overlying, tilted strata of mid-Tertiary age. Although the direction of dip of the tilted strata is commonly parallel to that of the lineation in the mylonitic rocks of the lower plate, it is not always parallel. For example, lineation in the southern forerange of the Santa Catalina Mountains trends east-northeast to east-west, whereas the inferred transport direction during Whipple assemblage movement on the Catalina fault is thought to be S50W (Davis, 1983), a difference of about 30°. An even more discordant relationship is apparent in Redington Pass between the Santa Catalina and Rincon mountains where lineation in the lower plate of the Catalina fault analog trends N20-50W and is clearly discordant to the inferred, southwest-directed, normal transport along the Catalina fault system in mid-Tertiary time (Davis, 1983). As the lineation in the lower plate mylonites is not rigorously parallel to the tectonic transport of the overlying plate, a causal kinematic relationship between the lineation in the lower plate and the transport of the upper plate is not likely.

The strikes of the tilted blocks in the upper plate commonly strike between N20W and N50W. This implies that tectonic transport during detachment faulting is more or less parallel to a northeast-southwest direction. This has commonly been interpreted as an axis of regional, crustal extension (Davis, 1983; Frost and Martin, 1982). However, exceptions to the northeast or southwest transport are fairly frequent and include north transport on the Plomosa detachment fault in the Plomosa Mountains, implied north-northeast transport of Locomotive fanglomerate strata in the Ajo area, north to northwest transport on the Ajo Road fault (Gardulski, 1980), northwest transport on Helmet fanglomerate strata in the Sierrita Mountains, and west-northwest transport of the Helvetia klippe in the northern Santa Rita Mountains. These exceptions suggest that the transport direction above the low-angle normal faults may be a function of the geometry of the underlying, northwest-trending warps rather than a phenomena of regional crustal extension. In this model the detachment faults are smaller scale, near surface, denudational reactions to whatever process created the warps. For example, the previously mentioned anomalous directions could be transports directed down the noses of the folds; whereas the more common northwest-southeast transport directions could be directed down the more statistically prevalent flanks of the folds.

Magnitude of Transport on Detachment Faults. The best constrained data for the amount of tectonic transport that can be ascribed to the detachment fault process is derived from offsets along synthetic normal faults in the upper plate. Offsets across upper plate synthetic faults in the Whipple Mountains are fairly well known and range from 0.3 to 1.5 km across the major synthetic faults (Gross and Hillemeyer, 1982). In the Tortilla Mountains displacements along the Superstition-Tortilla detachment system range from 1 to 2.5 km (Lowell, 1968). If the reconstruction of Cooper (1960) of the San Xavier fault in the Pima mining district, and the beheaded porphyry copper deposit at Twin Buttes was moved to Mission-Pima, then the tectonic transport with respect to a basal detachment fault may have been about 10 km to the north-northwest along the San Xavier detachment fault. In the northern Santa Rita Mountains, displacement of the Helvetia skarn in the Helvetia klippe relative to a presumed correlative skarn associated with the Broadwater plug north of Gunsight Knob is about 2 to 2.5 km to the west-northwest. In summary, known displacements across upper plate detachment fault structures are typically 1 to 3 km of normal slip. Thus, where displacements are firmly known, no large displacements on any single fault feature have been proven to exist.

Large amounts of displacement have been speculated to exist based on the regional dimensions of the detachment structures themselves or from tenuous matches of lithologies between the upper and lower plates. For example, Davis and others (1982) have speculated that northwest-trending dike swarms in the Mohave Mountains are offsets of a single dike swarm 22 km to the northeast of the Chambers Well dike swarm in the Whipple Mountains. However, they may simply be two different dike swarms of similar chemical composition, rather than the same dike swarm, as the wall rock geology differs in each case.

Other kinematic models of detachment faulting require little net slip on the basal detachment fault. For example, much of the antithetic tilting and accompanying synthetic faulting in the upper plate could be accompanied by antithetic faulting and synthetic tilting that would compensate for the offset on the more obvious synthetic faults (Gross and Hillemeyer, 1982). At Savahia Peak in the Whipple Mountains, no more than 6 km of northeastward slip on the Whipple detachment fault would be required to produce the observed upper plate offsets (Gross and Hillemeyer, 1982). In their model and ours, the upper plate is more or less, directionally distended, in situ, above the basal detachment structure in domino-like fashion.

Northwest-trending Folds and Arches. The broad, northwest-trending folds of the Galiuro assemblage continued to develop during Whipple assemblage time. However, newer, smaller-scale, more northerly trending folds were also developed at this time (Fig. 5). For example, the Whipple detachment fault which reutilized older Laramide thrust faults could have initiated between 22 and 18 Ma as a response to a broad, Galiuro assemblage, north-northwest-trending warp with its axis in the western Turtle Mountains. The principle detachment activity on the Whipple detachment fault would have occurred between 18 and 15 Ma (Davis and others, 1982). Between 15 and 13 Ma the smaller-scale warps, such as the Whipple-Chemehuevi anticline, developed on the shallow, northeast-dipping flank of the Turtle Mountains warp and deformed the Whipple low-angle fault complex. Similar north-northwest-trending anticlinal axes are present in Galiuro assemblage plutons and volcanics in the Santa Catalina and Tortolita Mountains.

The Spine syncline documented by Wilson (1962) southwest of Ray is a fairly sharp, northwest-trending syncline that deforms the 20 Ma

Apache Leap Tuff and 18-15 Ma rhyolitic volcanics. Immediately north-northeast of Ray, a similar north-trending syncline deforms 18 to 15 Ma volcanics and Whipple assemblage conglomerates east of the School reverse fault zone (Cornwall and others, 1971; Keith, 1983b). Broader folds deform the Mesquite Flat Breccia, a Whipple assemblage quartz alkalic latitic volcanic rock, in the central Superstition Mountains (Scarborough, 1981). Also, the Apsey Conglomerate is folded by a west-northwest- to northwest-trending syncline in the Apsey Creek area of the northwestern Galiuro Mountains (Keith, 1983b). To the southeast in the Klondyke area of the northeast Galiuro Mountains, the Hell Hole Conglomerate (Simons, 1964) is more strongly folded around north-northwest-trending anticlinal and synclinal fold axes. In the Orocopia Mountains of southeastern California, the Diligencia Formation (23 to 19 Ma and assigned here to the Galiuro Assemblage) has been folded by three major folds that trend N70W (Spittler and Arthur, 1982).

Northwest-trending Reverse Faults. Folds of Whipple Assemblage are commonly associated with reverse faults. Where in mutual contact, the reverse faults cut the detachment faults. In western Arizona a broad northwest-trending zone of reverse faults extends from the Dead Mountains in California on the northwest for some 120 km to the Harquahala Mountains on the southeast. Reverse faults in this western belt generally trend northwest and exhibit southwest-directed tectonic transport of the upper plate hanging wall. The best example of these reverse faults is the Lincoln Ranch fault pictured in Wilson (1962) in the south-central Rawhide and Buckskin Mountains. Exposures of the Lincoln Ranch fault in the Rawhide Mountains were mapped in more detail by Shackelford (1980). At least 600 m of structural throw are present where lower plate metasedimentary and mylonitic gneisses in the hanging wall are juxtaposed over Lincoln Ranch redbeds of the Whipple assemblage, in the footwall. The Lincoln Ranch fault clearly offsets the Rawhide-Buckskin detachment fault. To the northeast in the Alamo Dam area another southwest-directed, northwest-striking reverse fault offsets the Rawhide-Buckskin fault system with at least 90 m of reverse separation.

In central to southeastern Arizona another zone of diffuse reverse faulting directly cuts sedimentary rocks of the Whipple assemblage with movements of hanging wall to the northeast. On the west side of Camelback Mountain in the Phoenix region, megabreccia units and coarse arkosic units in the Camelback Formation are cut by a reverse fault dipping 30 degrees west that has about 60 m of reverse slip. In the Superstition Mountains a west-northwest-trending zone of folds and northeast-directed reverse faults cuts the youngest units of the Superstition volcanics dated at about 16-15 Ma (Scarborough, 1981; Stuckless and Sheridan, 1971). Near Ray, the School reverse fault zone cuts the 20 Ma Apache Leap Tuff and the overlying Big Dome Conglomerate and rhyolitic tuff (probably 18-15 Ma) and indicates up to 600 m of reverse slip (Cornwall and others, 1971; Keith, 1983b). Farther to the southeast in the Galiruo Mountains Krieger (1968) mapped a number of WNW-striking, southwest-dipping reverse faults that cut the Holy Joe Peak member (26 Ma, Creasey and Krieger, 1978) of the Galiuro Volcanics.

An example of northeast-directed reverse faults in southern Arizona includes the Apache Pass fault in the northern Chiricahua Mountains shown by Sabins (1957) to deform middle Tertiary volcanics. Other examples of possible Whipple assemblage reverse faults are present in California. In the Orocopia Mountains, more tightly folded upper units of the Diligencia Formation are locally broken into northeast-directed reverse faults (Spittler and Arthur, 1982). In the Barstow region of the central Mojave, the middle Miocene Barstow Formation north of Barstow is cut by a major, northeast-dipping, southwest-directed, reverse fault that juxtaposes 18 Ma Pickhandle volcanics (Miller and Morton, 1980) over younger lacustrine units of the Barstow Formation, which is locally spectacularly folded.

Dike Swarms. Dike swarms that are cogenetic with quartz alkalic magmatism of the Whipple assemblage are locally present, but are not as extensive as the dike swarms of the Galiuro assemblage. Where present, the dike swarms generally strike northwest. In the western Whipple Mountains, late quartz alkalic dikes that strike north-northwest cut the calc-alkalic, Galiuro assemblage dikes of the Chambers Well dike swarm (Davis and others, 1982; L. Anderson, pers. commun., 1985). In the Vulture Mountains of west-central Arizona, an extensive swarm of latitic and high-K rhyolitic dikes of quartz alkalic chemistry strike northwest and have yielded several K-Ar whole rock dates that range from 18 to 16 Ma (Rehrig and others, 1980). Some of these Whipple assemblage dikes are cut by low-angle normal faults, whereas other dikes appear to intrude the low-angle detachment faults.

Age of Whipple Assemblage

Age of Volcanism. Age dates on volcanics in the Whipple assemblage range from 28 to 13 Ma or from late Oligocene to mid-Miocene. As with the earlier assemblages of the Galiuro orogeny, the rocks are older to the east and younger to the west. To the east in New Mexico Whipple assemblage rocks such as the La Jara Peak Andesite and interfingering Hell's Mesa tuffs in the Socorro region are about 27 to 24 Ma (Osburn and Chapin, 1982). In eastern Arizona in the central Chiricahua Mountains, the Rhyolite Canyon Formation and associated underlying monzonite stock are probably part of the Whipple assemblage and have been dated at about 25 to 23 Ma. Whipple assemblage alkaline volcanics at Picacho Peak and the Samaniego Hills are 22 to 15 Ma (Shafiqullah and others, 1976; Eastwood, 1970). Still farther west in the classic area of the Whipple Mountains of southeast California and in the Rawhide Mountains of western Arizona, quartz alkalic volcanics within the Copper Basin Formation and Chapin Wash Formation have yielded numerous age dates between 18 and 15 Ma (Martin and others, 1982). In northwestern Arizona in the northern Black Range and El Dorado Mountains of southern Nevada, radiometric dates on the Patsy Mine Volcanics range from about 18 to 14 Ma (Anderson and others, 1972). Thus, from southwestern New Mexico to western Arizona and southeasternmost California, there appears to be a clear younging of Whipple assemblage volcanism that ranges from 27 to 23 Ma in New Mexico and from 18 to 15 Ma in the Colorado River region between Arizona and California.

Age of Faulting. Many of the detachment faults can be stratigraphically bracketed within the Whipple assemblage volcanism and sedimentation. Detachment faulting of the Whipple assemblage is slightly younger from southeast (18 to 15 Ma in central Arizona) to northwest (14 to 11 Ma in northwestern Arizona.

In the Whipple Mountains of southeastern California, Davis and others (1980; 1982) and Teel and Frost (1982) have shown that the Copper Basin Formation, which has yielded 6 K-Ar dates between 18.7 and 17.1 Ma, is a syntectonic deposit with respect to the detachment movement on the Whipple fault. A minimum age for the detachment fault is provided by numerous dates on the Osborn Wash Formation, which ranges in age from about 9 to 15.9 Ma (Davis and others, 1982); the Osburn Wash Formation is virtually flat lying and angularly truncates the Copper Basin Formation. Thus, detachment faulting in the Whipple Mountains occurred mainly between 18.7 and 15.9 Ma.

In the El Dorado and northern Black Mountains of southern Nevada and northwestern Arizona, detachment-related tectonics mainly occurred between 14 and 11 Ma. A pre-detachment volcanic unit named the Patsy Mine Volcanics has yielded several K-Ar dates between about 18 and 14 Ma. The Patsy Mine Volcanics is rotated and is angularly overlain by the Davis Mountain Volcanics which rest above the Bridge Spring Tuff datum. The Davis Mountain Volcanics have yielded several K-Ar dates between 13 and 11 Ma (Anderson and others, 1972) and are cut in many places by low-angle normal faults that are probably detachment related. The Davis Mountain Volcanics, which are commonly steeply tilted, are in turn overlain by nearly flat lying Muddy Creek Formation which has yielded K-Ar dates as old as 11 Ma (Anderson and others, 1972).

Detachment-related tectonics in west-central Arizona occurred approximately between 18 and 16 Ma. In the Vulture Mountains, steeply tilted, rhyolitic volcanics are cut by detachment-related, low-angle normal faults and have yielded K-Ar dates between 16 and 17 Ma (Rehrig and others, 1980). The low-angle normal faults are, in places, intruded by ultra-potassic, rhyolite porphyry dikes that are undeformed. One of these dikes has yielded a K-Ar age on biotite of 18 Ma. Further confirmation of the 18 to 15 Ma age of faulting is provided by K-Ar whole rock dates of 13.5 Ma on essentially untilted, post-detachment, probable Basin and Range basalts that angularly truncate the tilted rhyolitic volcanics in the Vulture Mountains.

In the Superior region in the Teapot Mountain quadrangle, detachment related low-angle faults may be tightly bracketed between about 18 and 15 Ma. Here, low-angle normal faults cut rhyolitic volcanics as young as 18 to 16 Ma and are overlain depositionally by rhyolitic tuffs (Keith, 1983b) that correlate with rhyolitic tuffs in the adjacent Mineral Mountain quadrangle that are dated at 16 to 15 Ma (Theodore and others, 1978). Farther to the southeast in the northern Tortilla Mountains, rhyolitic tuffs in the Ripsey Wash sequence of Schmidt (1971) have been dated at about 18 Ma. The Ripsey Wash sequence occurs in the upper plate of the Ripsey Wash detachment fault and, because it is cut by the Ripsey Wash detachment fault, the detachment fault must be younger than 18 Ma.

Termination of Galiuro Orogeny

Termination of Galiuro orogeny in the Basin and Range Province of Arizona is represented in general by a regional unconformity that is commonly angular and is of late mid-Miocene (15-11 Ma). Above the unconformity are basin-fill sediments in the sense of Scarborough and Peirce (1978) and Wilt and Scarborough (1981) or sediments of Unit II of Eberly and Stanley (1978). Below the unconformity are the sediments and volcanics of culminant Galiuro orogeny, which include Unit I of Eberly and Stanley (1978) or post-ignimbrite sediments of Wilt and Scarborough (1981). The unconformity at the end of the Galiuro orogeny is generally better displayed in horst blocks and is less obvious in the basin blocks.

One of the best indications of the termination of Galiuro orogeny is the dramatic change in the chemical nature of the magmatism from the culminant Galiuro orogeny to that of the succeeding San Andreas orogeny. The chemistry of the overlying San Andreas magmatism is of similar alkalinities to the Galiuro orogeny, but is distinctly more metaluminous. Also, magmatism of the San Andreas orogeny is distinctly more iron-rich, dramatically more anhydrous, less oxidized, and noticeably less siliceous than earlier Cretaceous-Cenozoic magmatism. The anhydrous nature of San Andreas magmatism is dramatically illustrated by the general lack of hydrous minerals such as amphibole or mica, whereas Galiuro orogenic magmatism generally contains noticeable hydrous minerals (greater than 1.5 volume percent). Strontium initial ratios for culminant Galiuro magmatism range from 0.706 to 0.7010, whereas strontium initial ratios for San Andreas basaltic magmatism are generally less than 0.705 and may be as low as 0.7022 (Keith and Dickinson, 1979). Galiuro orogeny magmatism features large volumes of siliceous ignimbrites having silica contents greater than 65 weight percent, whereas San Andreas magmatism features large volumes of basalt with silica contents between 42 to 50-52 weight percent.

The chemical and mineralogical switchover from Galiuro to San Andreas magmatism occurred between about 13 to 12 Ma in the Basin and Range Province south of Kingman and from about 11 to 9 Ma in northwestern Arizona between Kingman and Las Vegas. Thus, magma chemistry indicates the switchover from Galiuro to San Andreas orogeny in Arizona and vicinity occupied a very narrow time interval of about 2 million years. The changeover is not represented by a broad transitional interval, such as the 'mid-Tertiary transition' of Shafiqullah and others (1980) or the Stage 2 transition of Damon and others (1984).

SAN ANDREAS OROGENY

The present physiography of the Basin and Range Province and of the Transverse Ranges was produced by the most recent orogenic event in the region. The event is herein named the San Andreas orogeny for very similar, modern day tectonics related to the San Andreas transform system in California, southwesternmost Arizona, and the Gulf of California region. As used in this paper, the term San Andreas orogeny is similar to the Basin and Range nomenclature widely used in the literature, for example, the Basin and Range disturbance of Scarborough and Peirce (1978). However, the term Basin and Range is not broad enough to include transverse physiographic components that probably developed at the same time as most of the Basin and Range physiography, for example, the spectacular Transverse Ranges of southern California and similar, transverse, physiographic mountain ranges in west-central Arizona. The term San Andreas orogeny is herein coined to include both physiographic elements. Consequently, San Andreas orogeny can be subdivided into two orogenic phases, which are also assemblages: the Transverse assemblage and the Basin and Range assemblage (Table 4).

Transverse Assemblage

The Transverse Assemblage is physiographically marked by mountain ranges that trend east-west to east-northeast--west-southwest. These trends are perpendicular to the trend of most of the ranges in the Basin and Range Province. The anomalous physiographic trend coincides with east-northeast-trending folds in Arizona and folds and thrusts in California.

Sedimentary rocks of the Transverse assemblage consist of coarse clastics near the mountain fronts that grade to braidplains and coastal plains away from the range fronts and towards the center of the valleys. The facies changes are less abrupt than in the Basin and Range assemblage. Igneous rocks are generally absent, but when present consist mainly of basalt with local rhyolites. In Arizona one of the best candidates for Transverse assemblage strata is the Osborne Wash Formation northeast of Parker, which rests in a northeast-trending synclinal trough and thins away from the axis of the trough. Predominantly clastic sedimentary rocks in the Butler and McMullen valleys southeast of Parker are also assigned to the Transverse Assemblage.

In Arizona structures of the Transverse assemblage consist mainly of northeast-trending, broad to open anticlines and synclines, commonly arranged in en echelon patterns (Fig. 6). Where exposed, the folds typically have wavelengths of 4 to 12 km and amplitudes of 100 to 600 m (Spencer, 1982). These sharply contrast to earlier Galiuro orogeny folds, which have wavelengths of 50 to 100 km and amplitudes of 6 to 10 km. Structures assigned to the Transverse assemblage include the zone of en echelon folds from the Harquahala to Parker region in west-central Arizona, South Mountain south of Phoenix, and west-southwest-plunging folds in the Rincon Mountains southwest of Tucson. Another transverse structural element is northwest-trending faults with right slip movement in areas of northeast-southwest- trending folding. Examples of such faults are widespread in the Harquahala to Parker region, where some of these faults cut the 15 to 9 Ma Osborne Wash Formation. Also, throughout this region, the northeast-southwest-trending folds conspicuously deform the 18 to 15 Ma detachment faults and thus are at least as young as 15 Ma.

Basin and Range Assemblage

The Basin and Range assemblage is physiographically marked by mountain ranges that trend north-south to north-northwest. In non-pedimented areas, the mountain ranges are bounded by steep, northwest- to north-trending normal faults.

Sedimentary rocks of the Basin and Range assemblage include coarse clastics at the edges of the steep mountain fronts with local megabreccias near the range front faults. The coarse clastics undergo rapid facies changes to fine-grained and

ASSEMBLAGE	SEDIMENTATION	MAGMATISM	STRUCTURAL FEATURES	MINERAL RESOURCES	AGE (Ma)
Basin & Range	clastics & evaporites in grabens	alkaline anhydrous metaluminous basaltic volcanism	N-S trend horsts & grabens bounded by generally steep normal faults	sand and gravel salt, zeolites cinders, gypsum	0-13
Transverse	clastics	none or rare	NE-SW-trending folds, NW-striking, right-slip faults	petroleum, gas	0-13

Table 4. Summary of assemblages of the San Andreas orogeny in Arizona.

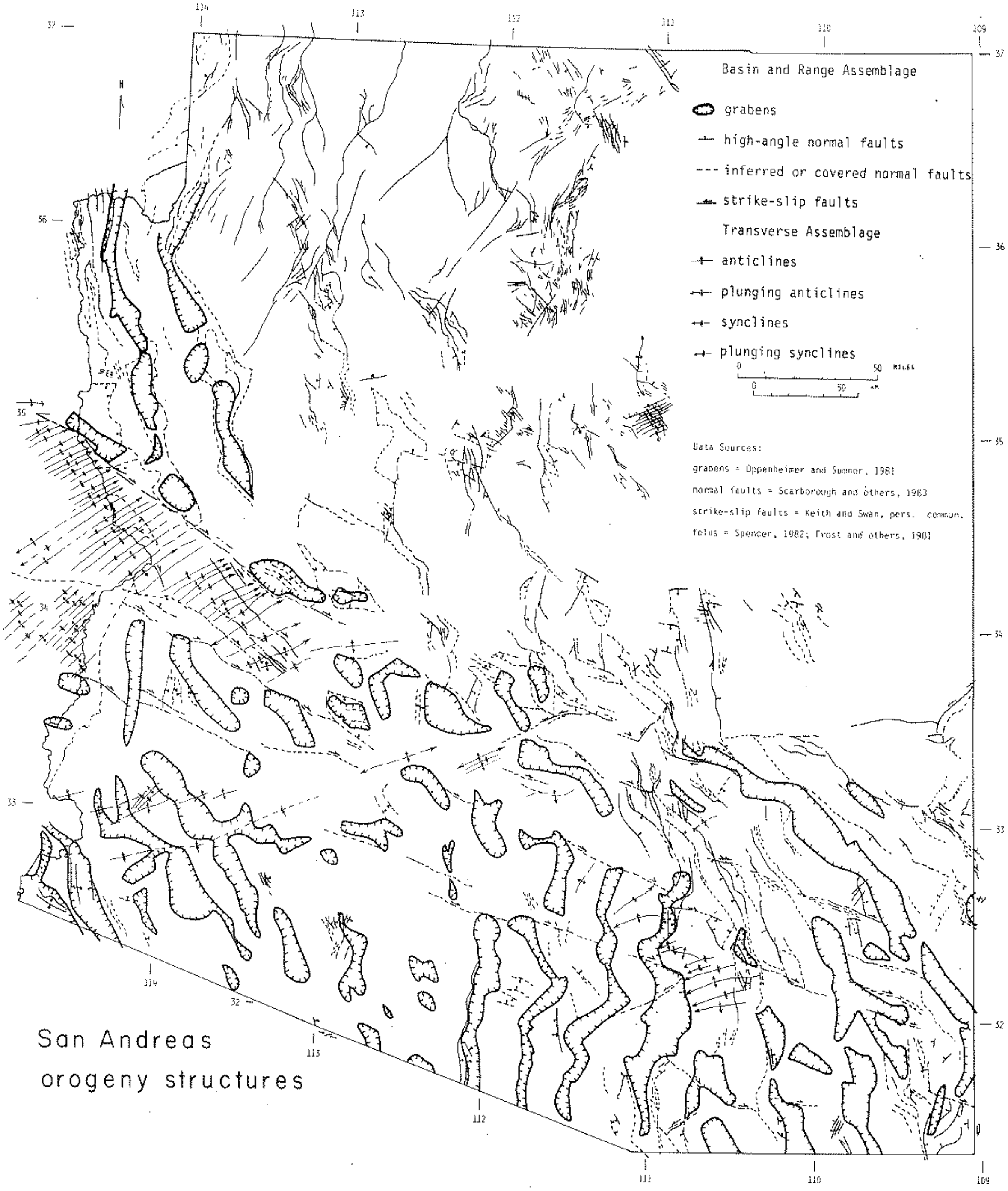


Figure 6. Map of structural features of the San Andreas orogeny in Arizona and vicinity.

evaporitic facies in the basin centers. Numerous sedimentary accumulations in Arizona have been documented by Peirce (1976), Eberly and Stanley (1978), Scarborough and Peirce (1978), Wilt and Scarborough (1981), Nations and others (1982), and Peirce (1984). Present basins include the Picacho Basin in Pinal County, the Red Lake Basin in Mohave County, the Safford Basin in Greenlee County, the Wilcox playa of Cochise County, and the Tucson Basin. Sedimentary formations assigned to the Basin and Range assemblage include the St. David and Quiburis formation in the upper and lower San Pedro

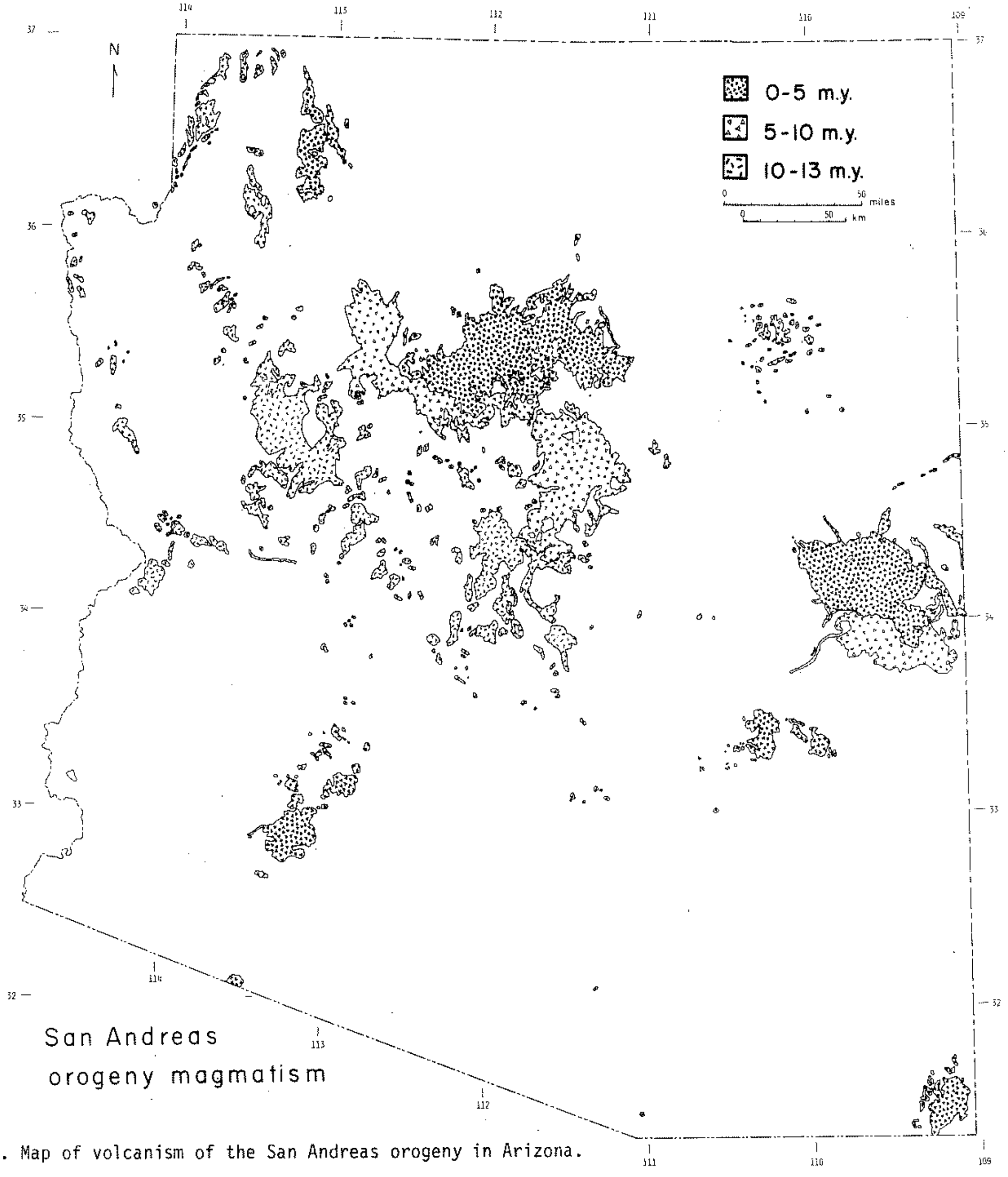


Figure 7. Map of volcanism of the San Andreas orogeny in Arizona.

valley of southeast Arizona, the Verde Formation in the Verde Valley of central Arizona, Bouse Formation, and the Muddy Creek Formation in northwestern Arizona.

In contrast to the Transverse assemblage, basaltic volcanism is widespread in the Basin and Range assemblage. Examples of the main volcanic fields include the San Francisco Peaks near Flagstaff, the White Mountains volcanic field in eastern Arizona, the San Bernardino Volcanic field in southeasternmost Arizona, the Pinacate volcanic field of southern Yuma and Pima Counties, the Sentinel volcanic field south and west of Gila Bend, the Hickey basalts of northwestern Arizona and the Hopi Buttes volcanic field of northeastern Arizona (Fig. 7). Basaltic volcanism consistently migrated toward the Colorado Plateau from 13 to 0 Ma (Best and Brimhall, 1974; Luedke and Smith, 1978; Wilt and Scarborough, 1981). The earliest volcanics in the Basin and Range assemblage are the Hickey basalts in the central part of the state; they date from 13 to 9 Ma (Shafiqullah and others, 1980). Volcanism from 9 to 4 Ma occurred in the southern parts of the White Mountain field (Ratte and others, 1969), the San Francisco field (Damon and others, 1974), and the Cottonwood Basalt; volcanism during this time straddled the boundary between the Colorado Plateau and Basin and Range provinces. Volcanism from 3 to 0 Ma occurred in the northern parts of the White Mountain field and San Francisco field north of the Colorado Plateau boundary; volcanism also occurred in the San Bernardino valley in southeasternmost Arizona (Lynch, 1978), the Sentinel volcanic field of south central Arizona, and the Pinacate volcanic field (Gutmann and Sheridan, 1978) in southwestern Arizona. Chemistry of igneous rocks of the Basin and Range assemblage are markedly different from preceding Cretaceous-Cenozoic magmatism, as previously discussed.

Structures of the Basin and Range assemblage are shown in Figure 6. These structures generally consist of north-south to north-northwest trending grabens that are either symmetric or asymmetric. Many of the grabens exhibit pull-apart geometries with steep normal faults on their west and east margins and northwest- to west-northwest- trending faults with probable right slip motion on their north and south margins reminiscent of Death Valley. Structural relief developed in Basin and Range basins was locally impressive. For example, Scarborough and Peirce (1978) estimated as much as 2.5 to 3.7 km estimated stratigraphic separation for eight basins with drill hole control. The duration of Basin and Range faulting in any given area is less than 5 million years. In the Desert province of Arizona, Basin and Range faulting probably initiated about 13 Ma and terminated about 8 Ma; whereas in the mountain province, it probably initiated about 5 to 6 Ma and dramatically slowed about 2 Ma and continues at a much slower rate to the present.

CONCLUSION

Application of the strato-tectonic approach to late Cretaceous and Cenozoic orogenic development in Arizona has resulted in two fundamental, new insights. Firstly, a major, new, late Laramide, stratigraphic and tectonic event, previously unrecognized in Arizona was established. That is, the presence of intracrustal, peraluminous magmatism is accompanied by significant and possibly world class, gold mineralization (Mesquite, California) that developed in the presence of major, southwest-directed thrusting and crustal shortening of unprecedented magnitude. Secondly, structural development during Galiuro orogeny may well have been related to regional, crustal-scale warping that was accomplished by 2 to 4 percent crustal shortening rather than crustal extension, in contrast to interpretations widely advocated in the literature.

Thirdly, it is impossible to overemphasize the importance of the strato-tectonic approach in understanding resource development and potential. In particular, Arizona may have much better gold potential than previously thought, if the peraluminous magmatism and its related gold metallogeny is fully explored. Also, because thrusting is of late Laramide age and is directed southwesterly rather than northeasterly as previously advocated in the literature, petroleum plays based on northeast-directed thrust models should be reevaluated.

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