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LARAMIDE STRUCTURES OF ARIZONA

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ABSTRACT

The Laramide structures of Arizona make up a diverse and controversial array. Four tectonic provinces mirror present physiographic provinces: Colorado Plateau, Transition Zone, southeastern Arizona, and southwestern Arizona. The Colorado Plateau province is characterized by monocline-bound basement uplifts and basins. The Transition Zone also contains monoclines and basement uplifts but with important differences. Studies in southeastern Arizona have fostered two major conflicting interpretations: basement-cored uplift flanked by reverse fault zones with opposite vergence or regional overthrust with consistent vergence. The southwestern Arizona province contains a variety of structures that are still being discovered and documented, including stacked thrust faults and regional metamorphism. Statewide characteristics include Laramide reactivation of preexisting structures, which may have produced major Laramide features oblique to regional principal strains, and consistent northeast-southwest compressional dynamics.

INTRODUCTION

Structures attributed to the Laramide orogeny of Arizona make up a diverse and somewhat controversial array. Four regional structural domains or provinces, which closely parallel present physiographic provinces, can be distinguished based on deformational style. The three provinces which make up eastern and central Arizona display similar structures which differ mainly in intensity of deformation, but the less studied province encompassing the western portion of the state stands structurally distinct.

Purpose and Scope

The main object of this paper is to provide a comprehensive yet concise review of Laramide structures in Arizona. This review is intended to provide a useful introduction to the structural aspects of the Arizona Laramide orogeny for those not already familiar with the state, as well as a geographically and topically organized text. Those readers desiring more detailed information can find it by investigating the references cited in the appropriate section.

Brevity necessitates a survey approach that relies heavily on regional and subregional studies already published. This paper does not offer complete geographic coverages; rather a presentation of representative structures for each province has been the goal. A reference map (fig. 1) displays the coverage of the various regional studies cited in the text.

The Laramide Orogeny

The Laramide orogeny has long been recognized in the northern Cordillera of Wyoming and Colorado as a period of basement uplift and thrust-fault deformation spanning parts of the Cretaceous and early Tertiary (Eardley, 1962; Berg, 1962). Damon and others (1964) and Damon and Mauger (1966), focusing on the southern Cordillera, cited a period of intense calcalkaline magmatism in southern Arizona and New Mexico that spanned 75 Ma to 50 Ma ago. Coney (1971, 1976) related the timing of Laramide deformation throughout the Cordillera deformation to changes in plate tectonic motions and suggested an orogenic time span of 80 to 40 Ma.

Classically, the Laramide orogeny of the Rocky Mountain foreland and the Sevier orogeny, expressed in the fold-and-thrust belt, have been kept distinct and analyzed separately. However, as work progresses, modern interpretations increasingly reveal the similarities in timing and dynamics of the two orogenies (Smithson and others, 1978; Jordan, 1981; Dickinson, 1981). The Laramide and Sevier orogenies occurred side by side, too close to be unrelated. Ultimately, the difference in structural styles between the two orogenies may be found in their tectonic settings: within the miogeocline for the Sevier and inboard of the miogeocline for the Laramide. If the geologic setting is the only difference, the "Sevier-Laramide" orogeny will represent one period of deformation expressed by distinct structural styles in different areas, with perhaps a regional west-to-east sweep of deformation (Coney, 1978).

In Arizona, the use of the term "Laramide" to describe structures derives both from geometric and dynamic similarities to the northern Cordillera as well as similarities in the timing of deformation.

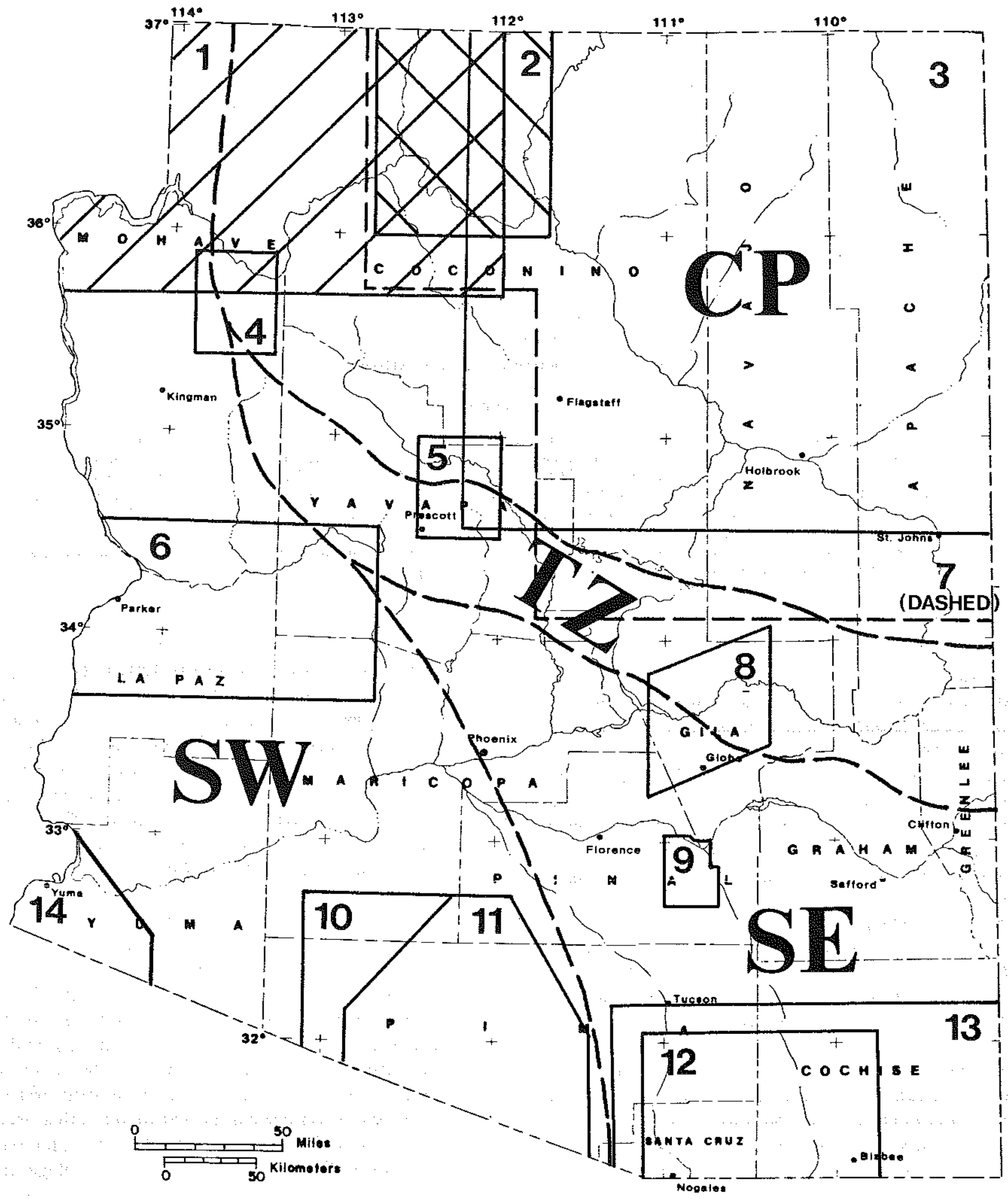

Figure 1. Structural provinces and coverage of various published regional studies within Arizona. Provinces: CP, Colorado Plateau; TZ, Transition Zone; SW, Southwestern Arizona; SE, Southeastern Arizona. Regional studies: 1, Lucchitta (1974); 2, Huntoon (1974); 3, Kelley (1955b); 4, Young (1979); 5, Krieger (1965); 6, Reynolds (1980); 7, Davis (1978); 8, Davis and others (1981); 9, Krieger (1974); 10, Haxel and others (1984); 11, Haxel and others (1980); 12, Davis (1979); 13, Drewes (1980,1981); 14, Olmsted and others (1973).

Arizona Provinces

The differences between the major regional structures of Arizona define structural provinces that underlie and ultimately influence the present physiographic provinces (fig. 2). In the order presented, these are the Colorado Plateau of northern and eastern Arizona; the Transition Zone, which lies along the southern edge of the Plateau; southeastern Arizona; and southwestern Arizona. Each of these provinces has experienced different histories before, during, and after Laramide time.

The Colorado Plateau and Transition Zone provinces are characterized by basement uplifts bound by reverse faults and monoclines (Kelley, 1955a, 1955b; Davis and others, 1981). A portion of southeastern Arizona has also been interpreted as a major basement uplift (Davis, 1979), which, if correct, means that the eastern two-thirds of the state would be characterized by basement uplifts, although with contrasting magnitudes and styles of deformation. Alternatively, southeastern Arizona has been interpreted as an overthrust terrane with major low-angle faults (Drewes, 1973, 1981). At least some of this controversy stems from the complexities of both pre- and post-Laramide tectonics of the region (Titley, 1976; Davis 1980).

No matter what the interpretations for the other provinces may be, southwestern Arizona remains distinct. Characteristic structures include regional metamorphism with associated tectonic fabrics and enticing remnants of imbricate, low-angle thrust that provide hints of regional-scale faults (Reynolds, 1980; Haxel and others, 1984). Kinematic analyses also yield orientations in southwestern Arizona different from those across the central and eastern portions of the state. Timing of deformation has yet to be ascertained over much of the area, and some deformation may even be pre-Laramide.

Despite differences, the provinces do exhibit some statewide patterns and characteristics. These include Laramide reactivation of pre-Laramide structures and consistently oriented northeast-southwest compressional dynamics. These similarities, and others, provide the basis for a statewide synthesis and Laramide structural scenario.

COLORADO PLATEAU

The Colorado Plateau in Arizona is often described as an anomalously stable region capped by flat-lying Paleozoic and Mesozoic rocks. However, the Colorado Plateau also displays a collection of diverse structures that reveal a complex tectonic history (Kelley, 1955a, 1955b). The most obvious structures in the Colorado Plateau domain are the monoclines, which are commonly associated with preexisting reactivated faults. Many monoclines occur along the boundaries of broad uplifts and basins. Smaller Laramide structures in the province include gentle to moderate upright folds that may more directly reveal the orientations of regional Laramide strain and stress in the Colorado Plateau.

The Colorado Plateau uplifts and monoclines have been related to the classic uplifts and thrust faults of the Rocky Mountain foreland (Coney, 1978). Although very different in magnitude, uplift structures from both provinces share many similarities, including interpretations of dynamics. Debate about the formation of Laramide uplifts centers about the relative roles of forced folding and buckling. Recent work offers information to help quell the controversy (Smithson and others, 1978; Reches and Johnson, 1978).

Structures

Uplifts and Basins. Although strata on the Colorado Plateau seem to extend laterally without interruption, northeastern Arizona actually contains several broad, flat uplifts and basins (fig. 3). Much of the spectacular scenery of cliffs and plateaus is due to the structural relief between uplifts and basins, which, in Arizona, ranges up to 2,500 m between the Kaibab uplift and the Black Mesa basin. Most of the Arizona uplifts trend north-south, with average horizontal dimensions of 80 by 30 km. The roughly circular Black Mesa basin measures about 100 km across.

Structural relief between adjacent basins and uplifts is accomplished by the bounding monoclines and faults. Regional warps and gentle broad folds account for minor intrabasin and intrauplift structural relief.

Monoclines. Monoclines are the most dramatic structural features of the Colorado Plateau, which is their type area (Powell, 1873; Gilbert, 1876). A monocline has been defined as a local steepening of uniformly gently dipping strata (Kelley, 1955b), a one-limbed flexure or steplike bend (Bates and Jackson, 1980), or a flexure above a fault (Reches, 1978). In this paper, monocline will refer to a steplike flexure without any genetic implications.

Plateau monoclines exhibit various geometries (Kelley, 1955b) (fig. 4). Middle-limb dips may be as steep as vertical or slightly overturned, and middle-limb widths, measured perpendicular to the monocline trend may be as much as 5 km (Davis, 1978). The thickness of the Phanerozoic strata originally involved in the folding may have been as much as 3 km.

Major monoclines of Arizona are shown on figure 2. Aggregate length of monocline trace over the entire Colorado Plateau totals 4,000 km, with map patterns ranging from the relatively straight Echo Cliffs monocline to the highly sinuous East Defiance monocline (Kelley, 1955a). Monoclines may also branch into two monoclines as displayed by the East Kaibab monocline. Most Arizona monoclines face east, as is common for the rest of the western Colorado Plateau monoclines. Kelley (1955b) suggested that monoclines commonly face in the same direction as the regional dip.

Structural relief, measured as the elevational difference of corresponding stratigraphic units on either side of the monocline, also varies. Maximum structural relief in Arizona reaches 1,800 m at the East Defiance monocline. The Colorado Plateau maximum relief of over 2,400 m is

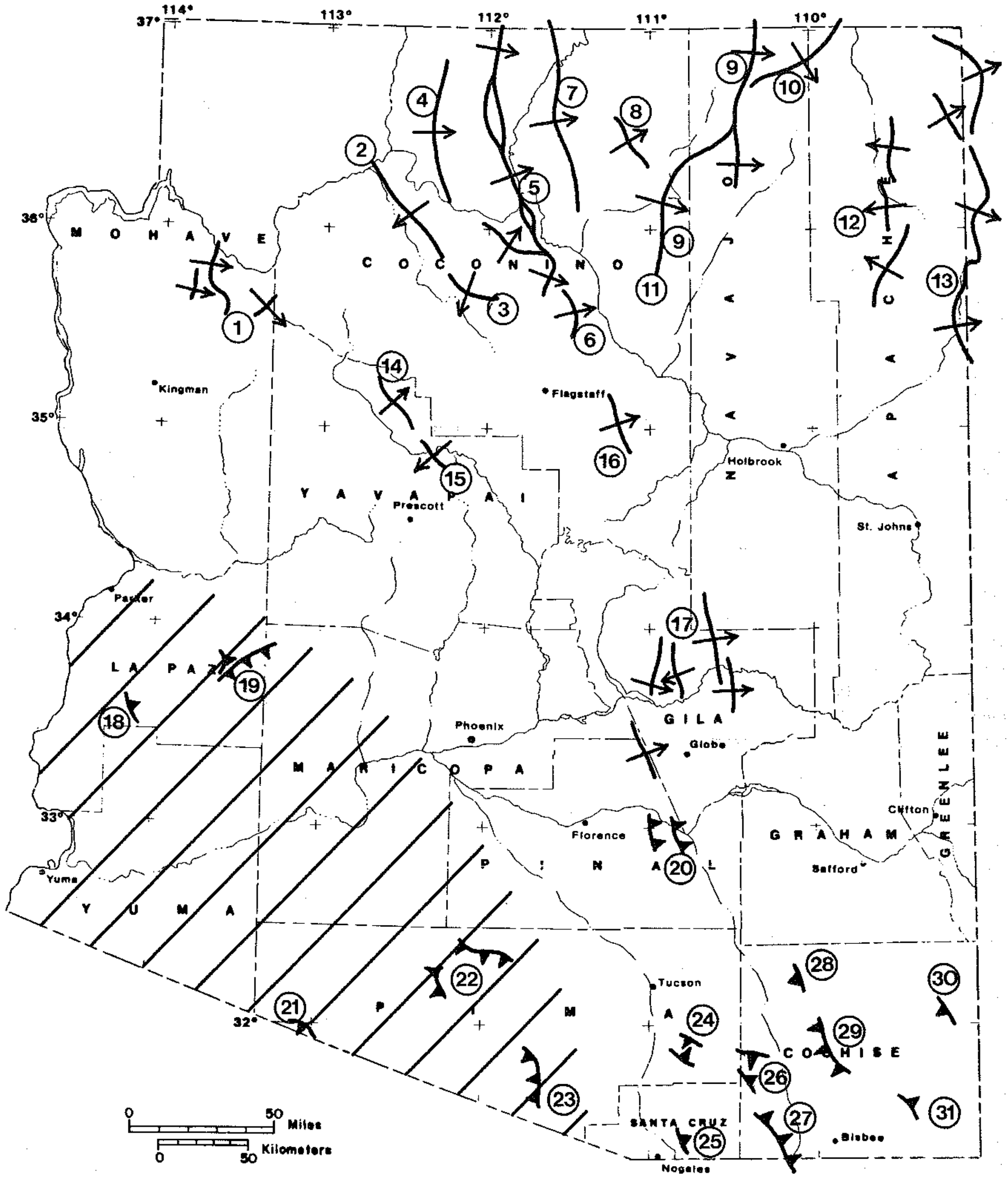

Figure 2. Major Arizona Laramide structures: monoclines with arrows showing middle-limb dip directions; reverse and thrust faults with teeth on hanging wall. Ruled area shows regional metamorphism. Structures: 1, Hualapai Plateau monoclines; 2, Supai monocline; 3, Heater monocline; 4, Sevier monocline; 5, East Kaibab monocline system; 6, Coconino Point monocline; 7, Comb Ridge monocline; 8, Red Lake monocline; 9, Kayenta monocline; 10, Comb Ridge monocline; 11, Cow Springs monocline; 12, West Defiance monocline system; 13, East Defiance monocline system; 14, Limestone Canyon monocline; 15, Coyote monocline; 16, Two Guns monocline; 17, Salt River Canyon monoclines; 18, Plomosa thrust faults; 19, Harquahala thrust system; 20, Winkelman thrust faults; 21. Quitobaquito thrust; 22, Window Mountain Well thrusts; 23, Baboquivari thrust; 24, Empire–Santa Rita thrust faults; 25, Harshaw Creek fault; 26, Whetstone–Mustang thrust faults; 27, Huachuca thrust system; 28, Little Dragoon–Johnny Lyon Hills thrust faults; 29, Dragoon thrust system; 30, North Chiricahua–Apache Pass thrust system; 31, Swisshelm thrust faults.

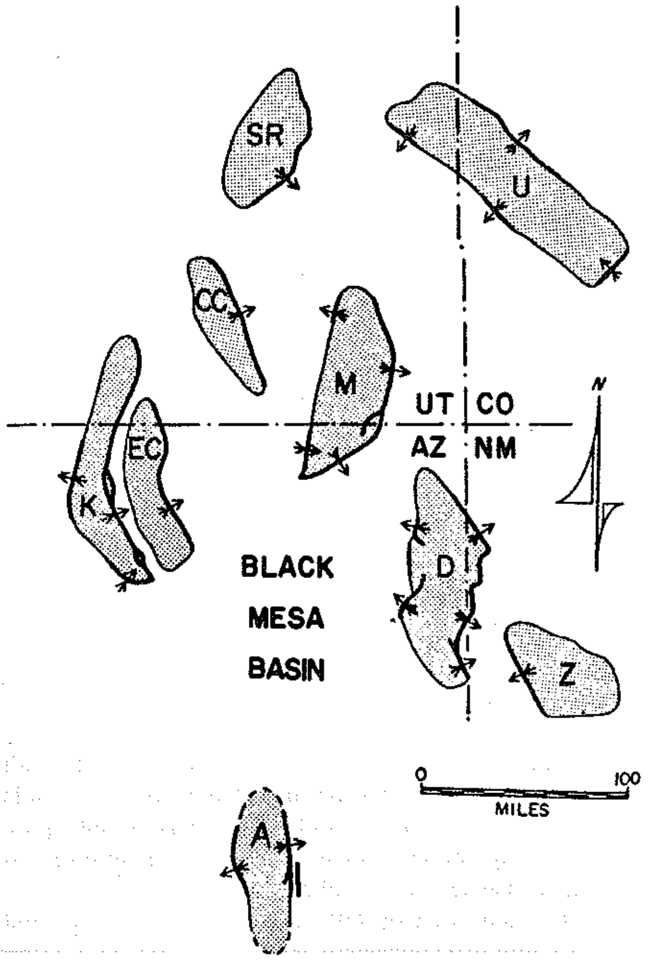

Figure 3. Colorado Plateau uplifts in the Four Corners region. Uplifts: SR, San Rafael; U, Uncompaghre; CC, Circle Cliffs; M, Monument; EC, Echo Cliffs; K, Kaibab; D, Defiance; Z, Zuni; A Apache. (After Davis and others, 1981. Permission granted by the authors.

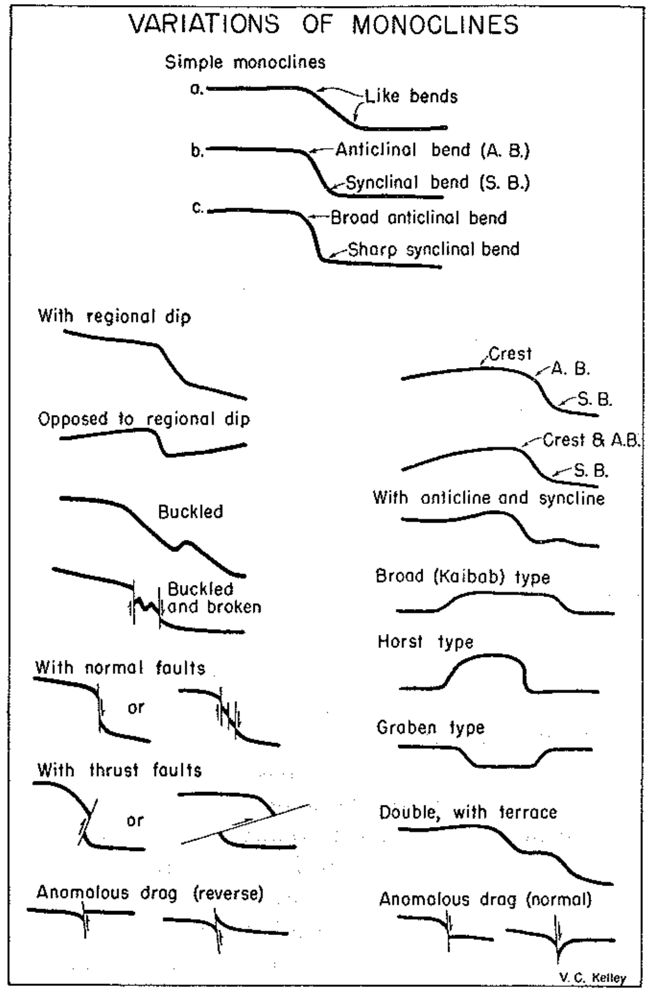

Figure 4. Diagrammatic variations of monoclines in profile. (From Kelley, 1955b. Permission granted by the University of New Mexico Press; Vincent C. Kelley, Regional Tectonics of the Colorado Plateau and Relationship to the Origin and Distribution of Uranium, copyright 1955.)

found at the Hogback monocline in New Mexico (Kelley, 1955a).

Monoclines have been related to underlying basement faults both directly (Huntoon, 1974; Reches, 1978) and indirectly (Baker, 1935; Lucchitta, 1974; Davis, 1978). These faults are commonly high angle with the present sense of separation commonly, but not always, sympathetic to that of the overlying monocline. A direct relationships between a monocline and a basement fault was reported by Reches (1978) for the Palisades monocline, a branch of the East Kaibab monocline (fig. 5). The Palisades monocline faces east and is directly above the Palisades fault, a high-angle fault with east-blockdown separation. The main East Kaibab monocline displays similar relationships with the underlying Butte fault.

Most of these faults are older structures that experienced faulting before and after the monoclinal folding episode (Walcott, 1890; Huntoon, 1974; Huntoon and Sears, 1975; Reches, 1978). Huntoon and Sears (1975) listed eight phases of faulting, including reversals of slip sense and changes in separation magnitude. They reported a Precambrian separation of 400 m for the Bright Angel fault, which was reactivated during Laramide time for 76 m of separation with opposite sense.

The geometry of these faults at depth is not known; faults exposed near the surface are commonly high angle and reverse slip. The pattern of monoclinal trends and alignment of monocline ends are attributed by Davis (1978) to a mimicry of the basement fault pattern, which is essentially a Precambrian mosaic. Davis also suggested that some faults may continue along strike in the basement without surficial monoclinal expression.

Colorado Plateau monoclines are dated on the basis of only a few age relationships. Gilbert (1880) reported Upper Cretaceous strata folded in the Waterpocket monocline of Utah and truncated by flat-lying Eocene units. The East Kaibab monocline displays essentially the same relationships (Gregory and Moore, 1931). The age of the Defiance monocline is less tightly constrained between Late Cretaceous and Miocene (Kelley, 1955a).

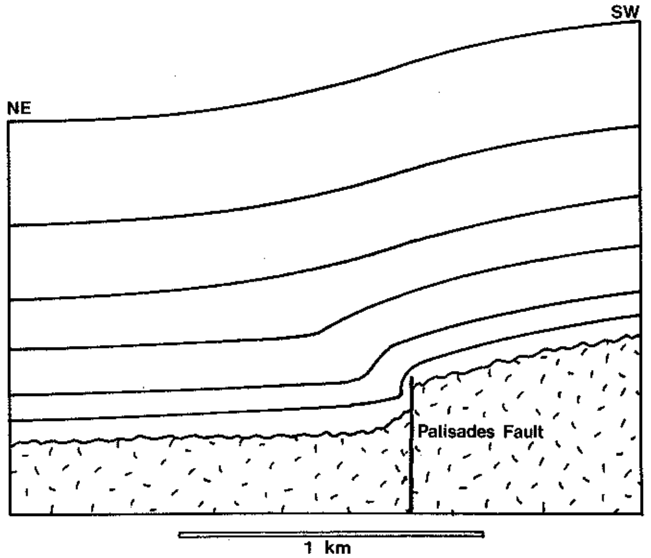

Figure 5. Geometrically constructed profile of the Palisades monocline. Stippled rocks are Precambrian. (After Reches, 1978. Permission granted by the author.)

Small Folds. Kelley (1955b) emphasized the existence and importance of what he called small folds. These folds are at least an order of magnitude smaller than the monoclines and regional warps but may be continuous for 100 to 200 km. Small folds of various sizes are superimposed on the larger structures; locally, small folds cross monoclines at both high and low angles. Kelley also emphasized the dominant northwest trend of these small folds, which becomes obvious if both the monoclines and regional warps are removed from the structural map (fig. 6). The boundaries of the Paradox fold belt of southeastern Utah parallel the many northwest-trending folds it contains. The high density of parallel folds may relate to the distinct stratigraphy of the Paradox basin.

Interpretation

Kinematic Considerations. Although many workers have described the monoclines of the Colorado Plateau as folds and as such attributed an elements of horizontal shortening across the fold trend, few detailed analyses of internal strain have been conducted. Reches and Johnson (1978) analyzed the formation of monoclinal flexures in the context of three distinct modes: buckling, drape folding, and kinking. The effect of each mode on a multilayered sequence was investigated both in theoretical models and in the field, especially at the Palisades monocline (Reches, 1978).

The three modes can be easily distinguished (fig. 7). Kinking, a product of layer-parallel shortening plus shear (or shortening oblique to layering) produces a characteristic angular fold style. Drape folding of plastic layers over a rigid, faulted basement produces a simple monoclinal profile with both layer-parallel shortening and extension in the middle limb. Buckling can operate only where layer-parallel shortening can amplify an existing flexure or discontinuity. Buckling produces a monoclinal fold with exaggerated anticlinal and synclinal bends, with the middle limb showing only layer-parallel shortening. Ideally, pure drape folding should display middle-limb extension and thinning, whereas pure buckling should not.

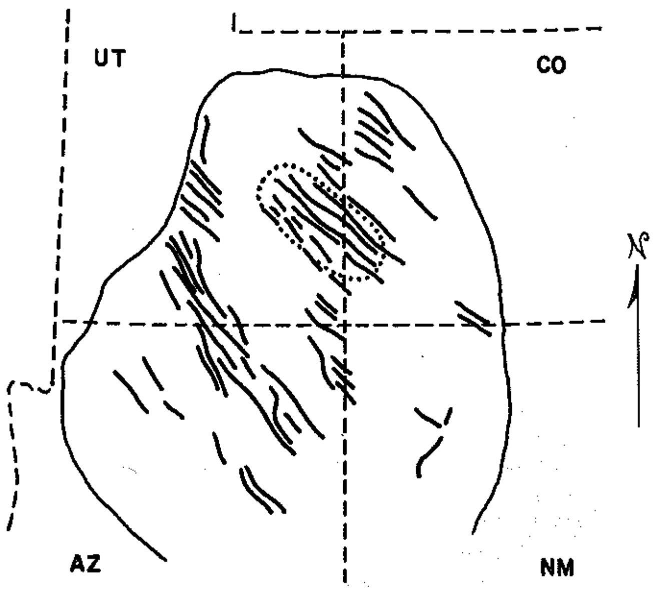

Figure 6. Traces of small folds within the outline of the Colorado Plateau. Paradox fold belt shown in dotted outline. (After Kelley, 1955b. Permission granted by the University of New Mexico Press; Vincent C. Kelley, Regional Tectonics of the Colorado Plateau and Relationship to the Origin and Distribution of Uranium, copyright 1955.)

Reches and Johnson (1978) concluded that a general model of monocline development appropriate for Colorado Plateau structures would be a combination of the three modes. Although the Palisades monocline displays a drape foldlike profile, middle-limb kinematics reveal only layer-parallel shortening indicative of buckling. Kinking plays a role in the formation of some monoclines, such as the Yampa monocline in northeastern Utah. In the general model, drape folding above a fault may initiate the flexure, which is enhanced by buckling. If the initiating fault is assumed to be a reverse fault, horizontal shortening across the monoclinal trend is accomplished in both the basement and the layered cover.

Because of the variability of structural trends on the Colorado Plateau, assigning a single direction of principal shortening is not a straightforward process. Kelley (1955b) compiled a map showing structures and inferred orientations of "forces" for the entire Colorado Plateau. His inferred directions of compressive force, usually perpendicular to structural grains, are dominantly northeast-southwest but also trend east-west, north-south, and even northwest-southeast.

The orientations of some structures, such as monoclines, may reflect the configuration of preexisting faults rather than the orientation of regional Laramide strain. Davis (1978) concluded that the trends and positions of monoclines were inherited from a Precambrian basement fracture system, which was, at least in part, oblique to Laramide principal strains. Figure 6 shows the Colorado Plateau folds excluding monoclines and related folds. Hence, what have been called small folds (Kelley, 1955b) may more accurately reflect Laramide strains. The formation of small folds discordant to regional basement kinematics implies disharmonic deformation. Disharmonic deformation is probably responsible for the consistent northwest trends of small folds in the Paradox fold belt, where an underlying layer of salt would have permitted easy detachment of the overlying strata. Such a consistent northwest trend for these folds and for small folds across the Colorado Plateau suggests a principal Laramide horizontal shortening oriented northeast-southwest.

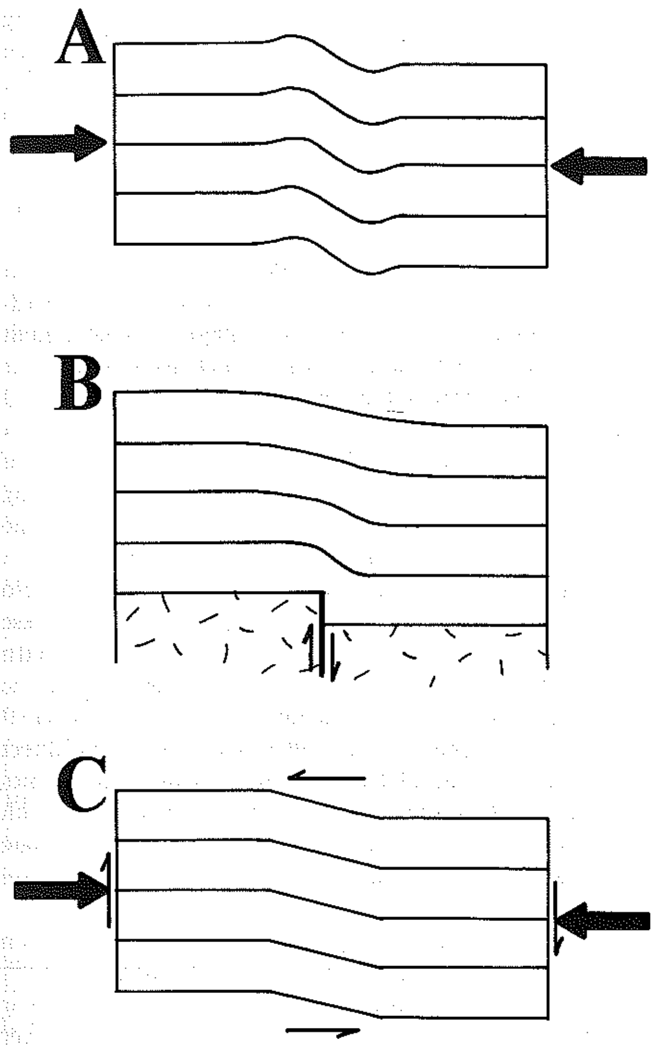

Figure 7. Diagrammatic cross sections of a layered sequence subjected to (A) buckling, (B) drape folding, and (C) kinking.

Dynamics. The central question in deciphering basement dynamics is assessing the nature of the basement faults associated with the monoclines. More specifically, what was the shape, orientation, and slip character of faults at depth during the Laramide deformation?

Because there are no data on Colorado Plateau faults at depth, one can look to analogous structures of the classic Rocky Mountain uplifts of Colorado and Wyoming (Berg, 1962; Coney, 1978; Brewer and others, 1980). These features are characterized by a drapelike fold over a reverse-slip basement fault, but on a scale larger than that of the monoclines on the Colorado Plateau. Rocky Mountain uplifts have the same tectonic setting, similar variation of orientation, and, of course, the same Laramide age.

A number of workers have long postulated a style of Rocky Mountain basement dynamics dominated by vertical motions along steep faults (Warner, 1956; Prucha and others, 1965; Stearns, 1971; Stearns and Weinberg, 1975; Couples and Stearns, 1978; Stearns, 1978). However, the Consortium for Continental Reflection Profiling (COCORP) data for the Wind River uplift reveal a 30-degree-dipping thrust fault, which apparently cuts the entire crust (Smithson and others, 1978; Brewer and others, 1980). This fault geometry fits the interpretations of Berg (1962). Clearly, horizontal tectonics dominate.

Major crustal discontinuities, such as the Wind River thrust, may or may not be analogous to the faults observed below the Colorado Plateau monoclines. Arguments concerning Colorado Plateau dynamics can only be based directly on monoclines and other fold kinematics. Baker (1935) argued for dominantly horizontal east-west compression in southeastern Utah on the basis of geometric and kinematic evidence. Kelley (1955a, 1955b) concurred with horizontal compression, enhancing the dynamic model to include initial vertical motions to produce flexures in the Phanerozoic strata. Horizontal compression followed the initial vertical motions. This hypothesis presaged the work of Reches and Johnson (1978), whose general model included an initial vertical drape enhanced by horizontal compression. In view of the kinematics of all the Colorado Plateau structures, horizontal northeast-southwest compression does seem the most plausible dynamic solution for the Arizona Colorado Plateau domain.

The contrast between the relative structural integrity of the Colorado Plateau block and the surrounding, more intensely deformed regions suggests that the Colorado Plateau acted as a coherent block during Laramide time. Kelley (1955b) postulated discontinuities between the western Colorado Plateau and the fold-and-thrust belt to the west, with regional left-slip. He also proposed right-slip between the eastern Colorado Plateau and the Rocky Mountains. Such offsets would have resulted from a northward-shifting Colorado Plateau.

The same general idea was proposed by Chapin and Cather (1981) when they suggested that the Colorado Plateau translated northward 60 to 120 km. Right-slip along the eastern Colorado Plateau margin resulted in en echelon folds, faults, and basins. They attributed the intense telescoping at the northern Colorado Plateau margin under the Uintah Mountains to the northward translation.

Similar ideas include a northward translation model of Woodward and Callender (1978) and a northeastward clockwise rotation of the Colorado Plateau about an Euler pole in Texas suggested by Hamilton (1978, 1981).

TRANSITION ZONE

The Transition Zone is distinguished by present topographical and structural contrasts with the Colorado Plateau to the north and the Basin and Range to the south. Plateaulike uplifts and monoclines are developed in Precambrian basement rocks, which are exposed at much higher elevations than in the Colorado Plateau province. The Transition Zone also contains major Late Cenozoic normal faults similar to those found in the Basin and Range. However, these modern contrasts are largely the result of middle to late Cenozoic tectonics (Heindl and Lance, 1960).

During Laramide time, the Transition Zone probably functioned in accordance with its name. Although Laramide structures in northeastern and southeastern Arizona may appear similar in style, they differ in magnitude. And the truly distinct Laramide tectonics of western Arizona may have extended eastward to the Transition Zone in the form of regional tilting and sedimentation patterns.

Structures and Interpretations

Within the Transition Zone are monoclines and basement uplifts similar to structures of the Colorado Plateau and perhaps southeastern Arizona. Superimposed on these structures is a regional northeastward Laramide tilt and related stratigraphic record.

Monoclines and Uplifts. The monoclines and uplifts of the Transition Zone are associated with reactivated faults, as in the Colorado Plateau province. However, because of the depth of exposure in the Transition Zone and the higher structural elevations of basement, most of the Laramide structures include upper Precambrian units.

The Salt River Canyon region contains well-exposed Laramide structures, including north-trending monoclines and related fault structures (Davis and others, 1981). All but one of six monoclines in the region face east, with trends ranging from north to northwest (Grange and Raup, 1969). Maximum structural relief of 100 m is found on the Rock Canyon monocline. Davis and others (1981) described substantial thinning of stratigraphic units in the middle limb, as well as a drape foldlike profile (Reches and Johnson, 1978). Although Davis and others (1981) attributed the Salt River Canyon monoclines to regional compression, the features described for the Rock Canyon monocline are more diagnostic of a drape fold. Other northwest-trending folds, however, do imply northeast-southwest shortening.

The faults associated with the Salt River Canyon monoclines have a complex reactivation history, including a phase involving conspicuous diabase sills intruded along preexisting faults 1,100 ± 15 Ma ago (Silver, 1978). Shride (1967) described these as syn-intrusion inflation faults that permitted differential uplift between adjacent blocks with contrasting thicknesses of sill inflation. To the two episodes of Precambrian faulting must be added both the Laramide episode and a middle to late Tertiary episode (Peirce and others, 1979).

Davis and others (1981) have identified the Apache uplift (fig. 3), a north-south elongate feature defined by outward-facing monoclines and associated major basement fault zones. Laramide structural relief is postulated at 1,700 m or more but has been greatly reduced by younger superposed faulting. They attributed the uplift to northeast-southwest shortening accommodated by reverse-sense reactivation of preexisting faults in the basement and monoclinal folding in the upper Precambrian cover, essentially the same mechanism proposed for the Colorado Plateau uplifts.

Monoclines in the Hualapai Plateau region are also attributed to Laramide compression (Young, 1979). These monoclines face eastward and are associated with polyphase faults. Post-Laramide faulting has reversed the sense of offset, in a manner similar to the faults associated with the monoclines of the Salt River Canyon. No direct evidence for the age of deformation is available; monoclines in both areas are dated as Laramide by association with Colorado Plateau structures. A minimum age of pre-late Oligocene for the Hualapai monoclines is based on drainage reversals.

Regional Tilting. The regional tectonics of the Transition Zone is best summarized by Peirce and others (1979). A regional northeast tilting is expressed as a pair of angular unconformities. The first lies below Turonian (Upper Cretaceous) strata, which in turn are overlain by an uncomformity between Cretaceous and older units and the Eocene-Oligocene Rim Gravels. The Rim Gravels contain clast of 54-Ma-old rock and are capped by 28-Ma-old volcanics (Peirce and others, 1979). The Rim Gravels display consistent northeast paleocurrent indicators and are believed to have been shed off a Laramide highland to the southwest. Precambrian clasts in the gravels imply considerable tectonic and erosional relief. Regional tilting may have been accomplished by a combination of basement uplifts as well as the effects of a rising Laramide highland immediately to the southwest (the Mogollon highland of Coney, 1976). Somewhere to the south and west of the tilted region, the Transition Zone would have passed into the distinctive Laramide geology of western Arizona.

SOUTHEASTERN ARIZONA PROVINCE

The southeastern quarter of Arizona is a region of impressive Laramide structures. These Laramide structures, however, are presented in dissected, somewhat isolated form because of subsequent Basin and Range faulting. Adjacent ranges commonly display quite different structural styles and degrees of deformation, and regional synthesis is difficult.

Structures attributed to the Laramide orogeny include reverse and thrust faults, strike-slip faults, fold of various scales, regional homoclines, local penetrative tectonic fabrics, and systematic joints. These structures are superimposed on older ones and have themselves been overprinted by younger deformation.

The complexity of southeastern Arizona may be responsible for the many conflicting regional and local interpretations. Kinematic models have included regional overthrusting, both northeast (Drewes, 1981) and southwest directed (Keith, 1983), basement uplift thrusting (Davis, 1979), and differential vertical displacements (Jones, 1963; Rehrig and Heidrick, 1976). Both compressional and extensional dynamics of various orientations have also been proposed. The problem is not merely academic; oil and gas potential of a possible overthrust terrane has whetted the appetite of numerous corporations (Keith, 1979, 1980).

Structures

Reverse and Thrust Faults. Thrust faults have been mapped in nearly every mountain range in southeastern Arizona (fig. 8). In many of these ranges, the reverse faulting is superimposed on older structures (Drewes, 1972, 1981; Titley, 1976) and in at least the Huachuca and Dragoon Mountains has been reactivated during younger post-Laramide deformation (Keith and Barrett, 1976; Crespi and others, 1982).

The geometries and complexities of Laramide reverse faulting are exemplified in the cross sections by Hayes and Raup (1968) for the Huachuca Mountains (fig. 9). The faults there define a northwest-striking zone and dip shallowly to steeply northeastward. The geometries of the faults and the style of faulting at depth are not documented. Sense of offset is northeast over southwest (Hayes and Raup, 1968; Davis, 1979).

A somewhat more complex and controversial fault system is exposed in the Dragoon Mountains. Gilluly (1956) reported a series of moderately to steeply southwest-dipping reverse faults that placed Precambrian and Paleozoic rocks northeastward over Cretaceous rocks. Drewes (1976) incorporated the reverse faults into his regional synthesis, proposing very large thrust displacements. Keith and Barrett (1976), however, reexamined the central Dragoon Mountains and concluded that the major fault mapped by Gilluly (1956) and Drewes (1976) is actually an overturned unconformity with little if any fault slip. Keith and Barrett (1976) also suggested that the other southwest-dipping faults are related to local folding and that some of these faults experienced postcompressional normal slip. Drewes (1981) again visited the central Dragoon Mountains and reasserted the existence of a major northeast-vergent fault. He suggested that some of the disagreement may stem from the subtleties of bedding-plane faults and polyphase deformation.

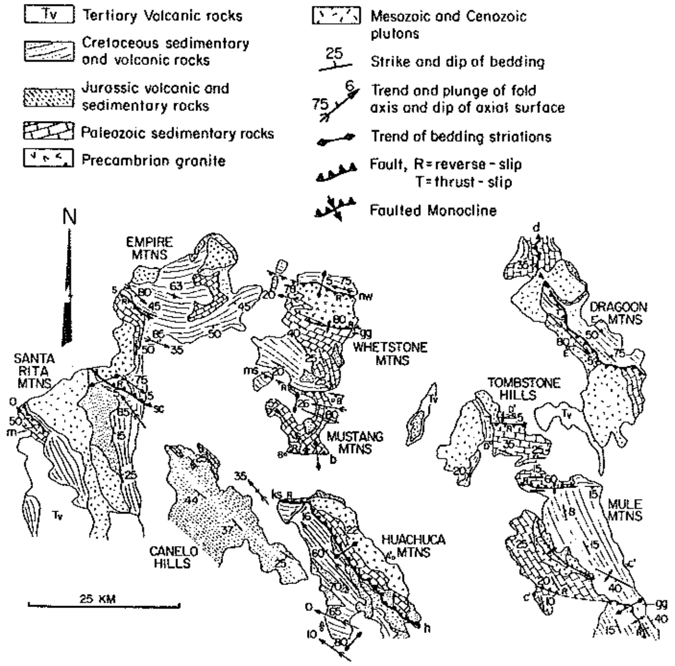

Figure 8. Map of generalized geology and structures in southeastern Arizona. (From Davis, 1970. Permission granted by the American Journal of Science.)

Another controversial site is on the eastern flanks of the central Santa Rita Mountains where Drewes (1972) has mapped a major thrust fault system, including a fault contact between the basal Cambrian quartzite and the underlying Precambrian granite. Both Hennessy (1976) and Davis (1979) reinterpreted this contact as a nonconformity below the basal Cambrian strata, and neither recognized significant fault slip.

Controversy also surrounds interpretations of the Lime Peak "thrust" of the Johnny Lyon Hills and Little Dragoon Mountains. First mapped by Cooper and Silver (1964), the Lime Peak thrust and other nearby thrusts were incorporated by Drewes (1980, 1981) as part of the regional Laramide overthrust system. Recently, Dickinson (1984) suggested a

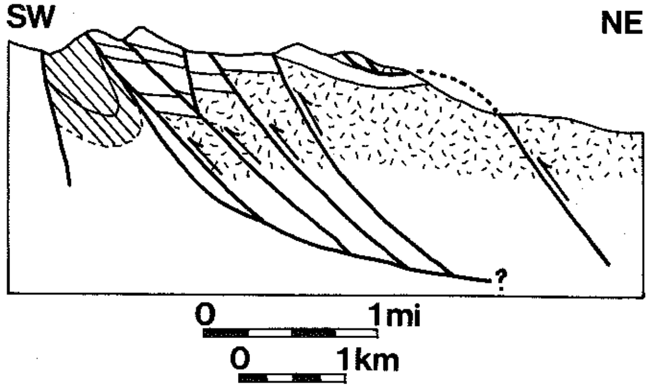

Figure 9. Simplified cross section of reverse faults in the eastern Huachuca Mountains. Stippled rocks are Precambrian granite; diagonally ruled rocks are Cretaceous sediments folded in syncline. (After Hayes and Raup, 1968. Permission granted by the authors.)

distinctly different tectonic interpretation for the Lime Peak fault: southwest-vergent normal slip during middle Tertiary time.

Yet another controversy concerns the Catalina fault, a gently southwest-dipping fault along the flanks of the Santa Catalina and Rincon Mountains. Drewes (1973, 1977, 1981), following the lead of Darton (1925), Moore and others (1941), and Pashley (1966), interpreted the Catalina fault as a major thrust that accommodated tens of kilometers of northeast tectonic transport. He attributed both the thrust fault and the underlying mylonitic fabrics to Laramide compressional tectonics. He also recognized a post-Laramide episode of normal sense, reactivated slip on the Catalina fault. Thorman and Drewes (1981) described low-angle faults in the Rincon Mountains, including the Catalina fault or its equivalent, as Laramide thrusts. They related time and sense of movement on the faults to the underlying mylonitic rocks and based their interpretation on regional relationships, including Oligocene intrusive and volcanic rocks that truncate some faults.

However, both Arnold (1971) and Davis (1975) concluded on the basis of hanging-wall kinematics that the Catalina fault displayed normal slip. Davis and Coney (1979) included the Santa Catalina and Rincon Mountains in their compilation of metamorphic core complexes and related both the fabrics to normal sense simple shear along a broad zone during Middle Tertiary time. Since then, a number of microfabric investigations have been carried out on the rocks within and below the Catalina fault zone, which have been described as "spectacular" mylonites (Lister and Snoke, 1984). To date, all of the studies have found southwest-vergent kinematics and support a normal sense of shear for both the mylonites and the overlying Catalina fault (DiTullio, 1983; Martins, 1984; Gordon Lister, 1984, personal commun.; Naruk, 1986a).

However, even if the major low-angle faults and adjacent mylonites are the result of middle Tertiary extensional tectonics, the presence of Laramide structures cannot be ruled out. Krantz (1983) documented southwest-vergent normal slip on the Catalina and other major low-angle faults in the Rincon Mountains but also reported northeast-vergent, low-angle faults exposed in dissected form in fault-bound blocks above the Catalina fault. He suggested that Laramide structures were incorporated and dissected by middle Tertiary extension.

In general, reverse faults in other mountain ranges in southeastern Arizona strike northwest to west. Subsurface geometries are not well documented, and dip magnitudes vary as much by author as by area. Although reverse faults are common in southeastern Arizona, Davis (1979) pointed out that the fault density is not evenly distributed among the various lithologies. Cumulative fault-length densities in the Paleozoic rocks are three to five times greater than those measured in Cretaceous strata. He further suggested that this contrast reflects distinct differences in basic mechanical behavior of Paleozoic and Cretaceous rocks.

Strike-slip Faults. Fault patterns are especially complicated in areas where high-angle, strike-slip faults bound or separate the major reverse fault domains. One such system, the northeast-striking Kino Springs fault zone in the northern Huachuca Mountains (Alexis, 1949; Hayes and Raup, 1968; Davis, 1979), displays 1 km of right-lateral separation. Other northeast-striking tear faults interrupt the main, southwest-vergent Huachuca reverse fault zone further to the southeast (Hayes and Raup, 1968).

Drewes (1981) has interpreted the northern Mule Mountains as containing an east-west-striking, high-angle fault zone with possible left-lateral movement. The fault system isolates lower and middle Paleozoic rocks between upper Paleozoic and Mesozoic units. Within the east-striking fault zone are west-northwest-trending folds, sympathetic to left-lateral shear.

On a more detailed scale, mapping in the west-central Tucson Mountains has revealed a series of high-angle, northeast- to east-striking faults with complex offset patterns (fig. 10) (Showalter, 1982). For the most part, these high-angle faults separate compartments (Brown, 1975) of north-northwest-trending folds and local reverse faults. Apparent offset on any one high-angle fault can vary from left lateral to right lateral to vertical.

Folds. Davis's (1979) synthesis of Laramide structures of southeastern Arizona includes a comprehensive survey of folds, including gentle upright folds, tight anticlines and synclines, monoclines, and overturned folds associated with local fault structures. Major folded terranes include the northern and central Santa Rita Mountains, western Huachuca Mountains, northern Whetstone Mountains, Dragoon Mountains, and western Tucson Mountains. Fold axes are typically horizontal to gently plunging and vary in trend from west-northwest to north-northwest, although trends are more consistent within specific domains (Davis, 1979). In the central Santa Rita Mountains, fold axes trend dominantly north-northwest, whereas those of the Whetstone Mountains are strongly west-northwest. Fold-axis orientations within each domain are in agreement with pi axes derived from bedding orientation data.

Certain domains also display consistent directions of fold overturning. In the western Huachuca Mountains and just to the south across the U.S.-Mexico border, folds are consistently overturned to the southwest and are locally disrupted by minor southwest-vergent reverse faults (Hayes and Raup, 1968; Davis, 1979). The southwest-vergent reverse fault system exposed in the eastern Huachuca Mountains overrides a large syncline of Cretaceous strata in the core of the range. The syncline is also overturned to the southwest. Conversely, fold structures in the Dragoon Mountains are consistently overturned to the northeast (Gilluly, 1956; Keith and Barrett, 1976).

The folded domains contrast sharply with large homoclinal domains (Davis, 1979). Homoclinal bedding is exposed in the eastern Santa Rita Mountains, the central Whetstone Mountains, the Tombstone Hills, and the Mule Mountains. These homoclinal domains are characterized by moderate to gentle dips, local small faults, and gentle upright folds.

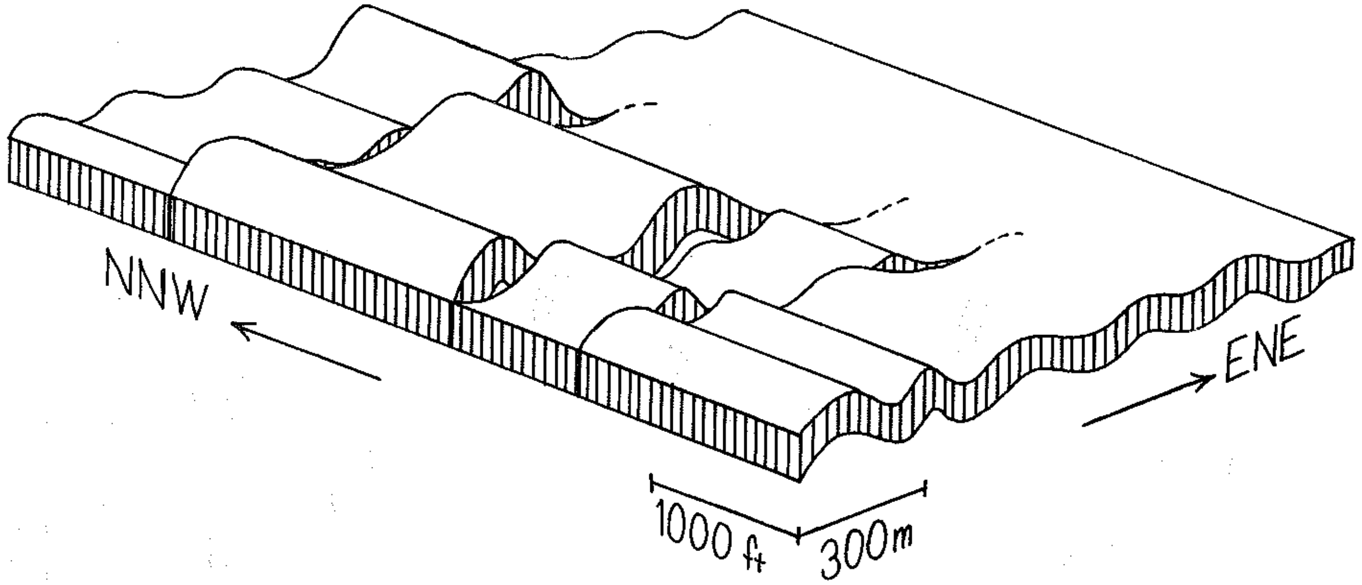

Figure 10. Schematic view of compartmental faults and folds in the western Tucson Mountains.

Tectonic Fabrics. Tectonically produced lineations and foliations younger than Precambrian, with the exception of large mylonite terranes, are uncommon in southeastern Arizona. What few unequivocal Laramide tectonic fabrics are found consist of axial-plane foliations developed in folded argillic units and tectonically flattened and stretched rocks in and near major fault zones. Locally abundant, conspicuous mylonitic terranes are at least in part the result of middle Tertiary extensional tectonics; the role of Laramide deformation in forming these mylonites is controversial.

Fault-related fabrics, although not ubiquitous, are more common. Foliated strata can be found along many major fault zones, especially in Cretaceous units. The Lower Cretaceous Glance Conglomerate forms a fantastic tectonite of flattened and stretched limestone cobbles. Foliated fault-zone rocks have been reported from the northern and central Santa Rita Mountains (Drewes, 1972; Davis, 1979), the Huachuca Mountains (Hayes and Raup, 1968; Davis, 1979; Crespi and others, 1982), and the central Dragoon Mountains (Sousa, 1980). Tectonites in the first two ranges are present in both high-angle fault zones (Sawmill Canyon fault zone in the Santa Rita Mountains and Kino Springs fault zone in the Huachuca Mountains) and along moderate- to low-angle reverse faults. With the exception of some foliated Cambrian Abrigo Formation in the central Santa Rita Mountains, the tectonites are all derived from Cretaceous units.

Vast terranes of mylonitic crystalline rocks are exposed in the Tortolita, Santa Catalina, Rincon, Pinaleno, Picacho, and South Mountains. The mylonitic rocks are commonly found in the footwall of major low-angle faults. These relationships led early workers to interpret the faults as thrusts and to relate the mylonitic fabrics to Laramide tectonics (Darton, 1925; Moore and others, 1941; Pashley, 1966). The Laramide thrust interpretation has been reiterated for the Rincon Mountains by Thorman and Drewes (1981), for the Santa Catalina Mountains by Drewes (1976, 1981), and for the Pinaleno Mountains by Thorman (1981).

In the last decade, these mylonitic terranes and their associated low-angle faults have been reinterpreted in the context of middle Tertiary extensional tectonics and have been collectively termed "metamorphic core complexes" (Coney, 1980; Davis, 1977, 1980, 1983; Davis and Coney, 1979; Rehrig and Reynolds, 1980). The southeastern Arizona complexes are part of a belt of core complexes that extends along the North American Cordillera from Mexico to Canada. Recent work has demonstrated that some mylonitic fabrics are as young as 25 Ma (Reynolds and Rehrig, 1980; Reynolds, 1985). Kinematic indicators in the mylonitic rocks are overwhelmingly down the regional dip of the foliation and the overlying faults (Martins, 1984; Lister and Snoke, 1984; Reynolds, 1985; Naruk, 1986b). This translates into a normal sense of shear, southwest vergent in the Santa Catalina, Rincon and Tortolita Mountains, and northeast vergent in the South and Pinaleno Mountains.

Although some of the details are still unclear, it is now apparent that middle Tertiary extensional tectonics have played a major role in the development of these metamorphic core complexes. There is some suggestion (Drewes, 1978, 1980, 1981; Krantz, 1983; Bykerk-Kauffman, 1983) that preexisting Laramide structures may have been incorporated or reactivated by middle Tertiary tectonics.

Joints. The orientation and nature of Laramide stresses have been carefully documented through structural analysis

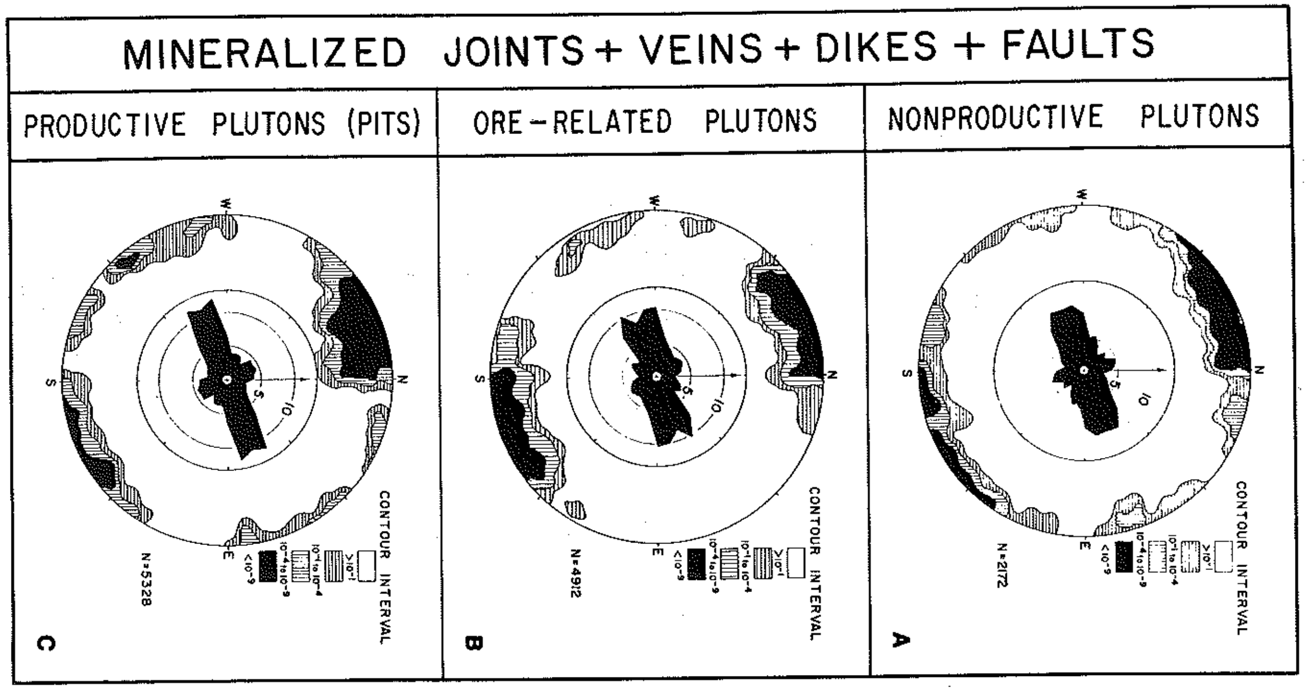

Figure 11. Synoptic, lower-hemisphere equal-area nets of N-poles and strike histograms of all mineralized joint sets, veins, dikes, and faults measured in nonproductive, ore-related, and productive Laramide plutons in the American Southwest. (From Heidrick and Titley, (1982. Permission granted by the University of Arizona Press, copyright 1982.)

of joints, veins, dikes, and related features in and near Laramide intrusive bodies (Rehrig and Heidrick, 1971, 1976; Heidrick, 1974; Heidrick and Titley, 1981). To date, this work has encompassed 18 Laramide plutons across the whole of central and southern Arizona and more than 50,000 measured mesoscopic structures. Ages of the plutons studied range from 74 Ma to 50 Ma (Heidrick and Titley, 1982).

In brief, Laramide dikes, veins, and fault-veins in both Arizona and New Mexico strike east-northeast to east (fig. 11). A second, smaller set strikes north-northwest to northwest. This pattern is essentially mirrored by joint orientations. Unmineralized joints are strongly grouped about the north-northwest direction, with an orthogonal subgroup striking east-northeast. Mineralized joints display the opposite pattern, with most striking east-northeast. Geometric relationships suggest that the joint sets are truly orthogonal and not part of a conjugate set. Some features, especially those with northwest trends, are post-Laramide.

Interpretation

The diverse array of structures just discussed has fostered a variety of interpretations and regional models. Some of the disagreement stems from different interpretations of field relationships, and the rest largely from contrasting investigative philosophies. Because of this, many of the present-day hypotheses are in apparent conflict.

Much of the controversy centers about the role of low-angle thrusting during Laramide time in southeastern Arizona. Although previously proposed by others, the chief advocate of the Arizona overthrust has been Drewes (1976, 1981). The overthrust model contrasts sharply with proposals that consider reverse and thrust faulting as local phenomena directly related to significant vertical tectonics as advocated by Jones (1963), Mayo (1966), and Rehrig and Heidrick (1976). Davis (1979) interpreted southeastern Arizona in the context of a basement-cored uplift flanked by two zones of reverse faults. Davis's model does include significant horizontal shortening produced by compressional dynamics but still considers reverse faults to be local features. A lesser controversy concerns the dynamics of regional and local Laramide stresses. Essentially both northeast-southwest compression and tension have been proposed, although the modern data base makes the latter interpretation rather untenable.

This paper will not attempt to resolve the conflicts between the major camps. Although I have inherited a good dose of bias, firsthand field experience so far supports that bias. Ultimately, the interpretation is up to the reader.

Arizona Overthrust Model. Local thrusting and regional overthrusting have been popular with workers in southeastern Arizona for some time (Ransome, 1904; Darton, 1925; Brown, 1939; Gilluly, 1956; Copper and Silver, 1964). This concept has been explored and most recently advocated by Drewes for more than a decade (1973, 1976, 1978, 1980), culminating in his (1981) U.S. Geological Survey Professional Paper entitled, "Tectonics of Southeastern Arizona." More than anyone else, Drewes has applied firsthand field experience to the concept of regional overthrusting.

In brief, Drewes's model includes two large, northeast-vergent thrust lobes separated by a northeast-striking tear fault complex (fig. 12). Each lobe contains an imbricate stack of two or more major allochthonous plates. Total thrust slip is interpreted by Drewes to be possibly 100 km or more. In this model, the overthrust terrane of southeastern Arizona links the fold-and-thrust belts of Utah-Nevada and northern Chihuahua to provide a continuous Cordilleran thrust orogen.

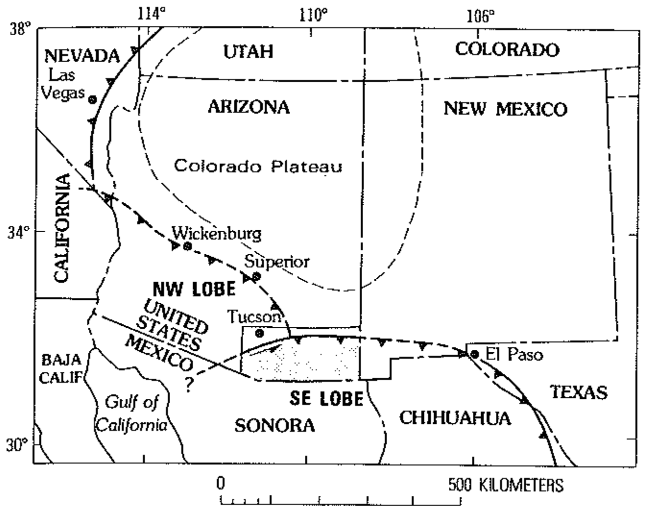

Figure 12. Projected regional distribution of major thrust plates. (From Drewes, 1981. Permission granted by the author.)

Drewes (1981) separated Laramide orogenic activity into two phases and proposed that the plates were emplaced under northeast-southwest regional compression during the early phase. After a period of quiescence, the late phase was expressed by local northwest-vergent thrusting and strike-slip faulting.

Although the overthrust model entails regional structures, the dissected nature of post-Laramide southeastern Arizona forced Drewes to locate most of his major fault traces below younger alluvium or volcanics, both of which cover vast areas. He based correlations of thrust plates on the similarities of structural style in adjacent ranges and an intimate knowledge of regional relationships.

There has been much controversy about both exposed and covered fault traces. Several contacts proposed as major thrusts by Drewes have been alternatively interpreted as nonconformities or other contacts without significant fault displacement. In addition, some fault systems clearly have a contradictory sense of vergence, as in the southwest-vergent Huachuca fault zone and the Lime Peak fault. Finally, the role, if any, of Laramide overthrusting in the development of the metamorphic core complexes may never be known. Present consensus attributes exposed fault relationships and metamorphic fabrics in the complexes to middle Tertiary extensional deformation (Davis, 1980, 1983; Rehrig and Reynolds, 1980; Coney, 1980; Reynolds, 1985; Naruk, 1985).

Davis (1979) has raised a conceptual mechanical argument against the overthrust hypothesis. Arizona is underlain by a relatively thin Phanerozoic section atop a rigid crystalline basement, unlike the thick miogeoclinal wedge that hosted thrust-belt deformation in Utah and Wyoming. A further impedance to low-angle tectonic transport would be pre-Laramide high-angle faults that disrupted both basement and cover (Titley, 1976); no continuous horizontal surfaces existed to initiate regional thrust faults, and thin-skinned tectonics would not have been a favored mode (Davis, 1979).

Basement Uplift Model. Although the lineage of uplift tectonic models in Arizona cannot be traced back as far as that of the overthrust model, there have been numerous uplift supporters. Jones (1963, 1966) proposed that vertical uplift of Precambrian, Jurassic, and Laramide-age granitic bodies has not only been the cause of most Laramide deformation but also delineated major mountain ranges that have persisted through Basin and Range tectonics. He proposed gravity-slide origins for reverse faults and other compressional features along the margins of vertical uplifts. Jones (1966) even went so far as to postulate regional tension during the Laramide. Others (Mayo, 1966; Mayo and Davis, 1976) have also advocated vertical uplift with concomitant localized compression and broad tension. The summary of Laramide tectonics of southeastern Arizona by Davis (1979) encompassed many of the above ideas in the context of a northwest-trending base-cored uplift. However, he suggested that the uplift occurred in response to regional northeast-southwest compression. The two major zones of reverse faulting flanking the uplift display outward vergence of Laramide features superimposed on older (Triassic-Jurassic) high-angle faults. Phanerozoic strata atop the uplift core are much less deformed and display gentle folds and regional homoclines. Northeast-southwest horizontal shortening is estimated at 30 percent.

In his cross section (fig. 13), Davis suggested that the uplift-bounding reverse faults steepen to near-vertical orientations at depth. Workers using COCORP data from the Wind River thrust in Wyoming (Smithson and others, 1978; Brewer and others, 1980) have emphasized the low-angle nature of the uplift-bounding fault at depth and the major role played by horizontal tectonics (see discussion in the Colorado Plateau section of this paper). If the basement uplift proposed by Davis (1979) for southeastern Arizona is an analogous structure, perhaps the major bounding faults might be less steep at depth than shown on his cross section (fig. 14).

The conclusions of Rehrig and Heidrick (1976) and Heidrick and Titley (1982) strongly support the basement uplift model in the context of regional northeast-southwest compressive stress. Rehrig and Heidrick (1976) proposed north-northwest-trending crustal arching during the Laramide as a result of deep crustal compression. Joints and other features were influenced by north-northwest to south-southeast dilation. Orthogonal joints were a result of middle Tertiary extension oriented at 90 degrees to Laramide dilation.

Another Hypothesis. At least one other hypothesis has been offered that presents variations on the two models

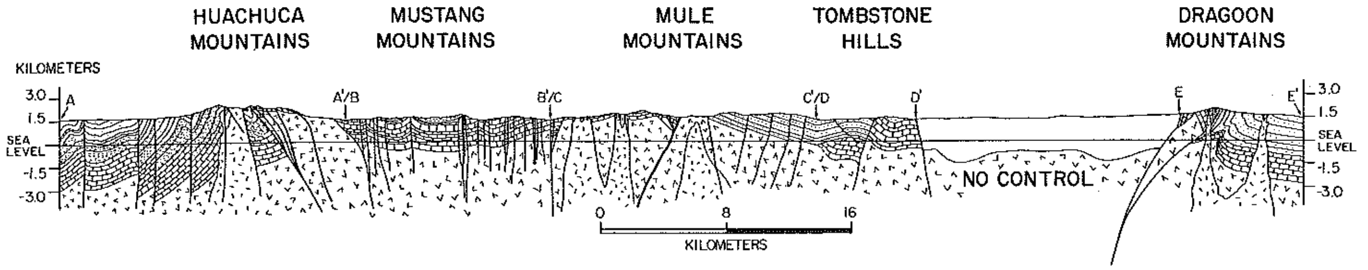

Figure 13. Cross section across southeastern Arizona. See figure 8 for key and location of section. (From Davis, 1979. Permission granted by the American Journal of Science.)

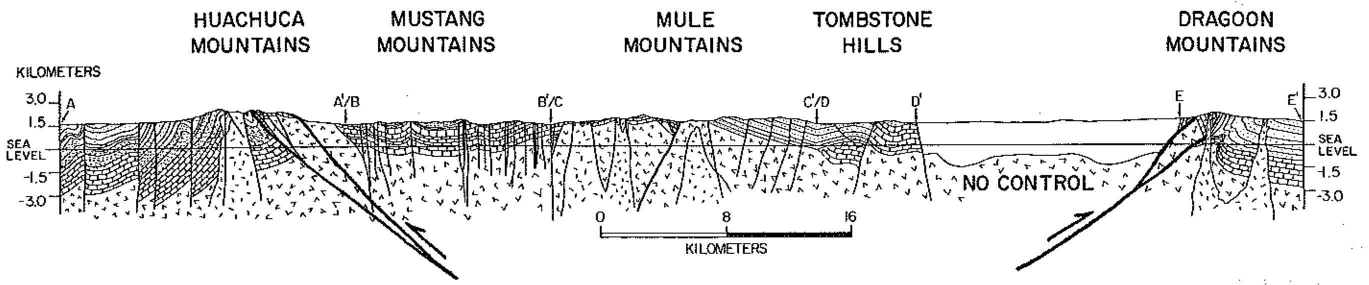

Figure 14. Cross section across southeastern Arizona with gently dipping basement block-bounding faults. (After Davis, 1979. Permission granted by the American Journal of Science.)

already discussed. Keith (1983) advocated southwest-vergent overthrusting, or more exactly, regional underthrusting of southern Arizona beneath the Colorado Plateau. This hypothesis is based on a new interpretation of age relationships among intrusive and metamorphic rocks of the Santa Catalina-Rincon metamorphic core complex. Keith proposed that southern Arizona was underthrust up to 200 km below the Colorado Plateau.

A Final Comment. The controversy concerning the Laramide orogeny of southeastern Arizona continues. Although the uninitiated might expect the two major hypotheses (overthrust and basement-uplift) to be easily evaluated in the field, complex, post-Laramide tectonics have muddied the waters sufficiently that clear-cut answers are obscured. To me, it is most unfortunate that the major interpretations are now entrenched in adversary camps.

A similar controversy is surfacing in adjacent New Mexico, where a proposed regional Laramide overthrust system (Corbitt and Woodward, 1973; Woodward and DuChene, 1981) is being reevaluated by some as part of a basement-cored uplift (Brown and Clemens, 1983; Seager, 1983). Time and further work may resolve these controversies.

SOUTHWESTERN ARIZONA PROVINCE

The southwestern Arizona province includes both a broad geographic range and a diverse array of structural styles. The areas and styles have been grouped together as much because none fit neatly into the domains already discussed as for their similarities. Workers are just beginning to comprehend the Mesozoic structures of this part of Arizona, especially the timing of deformation. This summary is based largely on the few papers and abstracts published since 1980, supplemented with informal discussions with those presently working in southwestern Arizona.

Three subprovinces will be discussed separately. These are the (1) south-central Arizona, referred to as the southern Papago terrane, (2) west-central Arizona, and (3) extreme southwestern Arizona.

Southern Papago Terrane Subprovince

The term "southern Papago terrane" derives from the former name of the Tohono O'odham Indian Reservation, which extends over much of south-central Arizona. Workers from the U.S. Geological Survey (Haxel and others, 1978, 1980, 1981, 1984) have been conducting an investigation of the Mesozoic and Cenozoic history of the area, including detailed geochronology. Most of what follows is derived from Haxel and others (1984).

Haxel and others (1980) subdivided the Tohono O'odham Indian Reservation area into northern and southern terranes (fig. 15). The northern terrane resembles much of central and southeastern Arizona, with Precambrian metamorphic and crystalline basement, upper Precambrian and Paleozoic sedimentary sequences, and Late Cretaceous-early Tertiary ("Laramide") intrusive rocks (Blacet and others, 1978; Briskey and others, 1978). The southern terrane, which includes most of the reservation, is distinct from "mainland" Arizona in a number of ways. Precambrian and Paleozoic rocks are relatively uncommon, and those exposures present are generally isolated tectonic or intrusive remnants. Also, the Mesozoic section includes

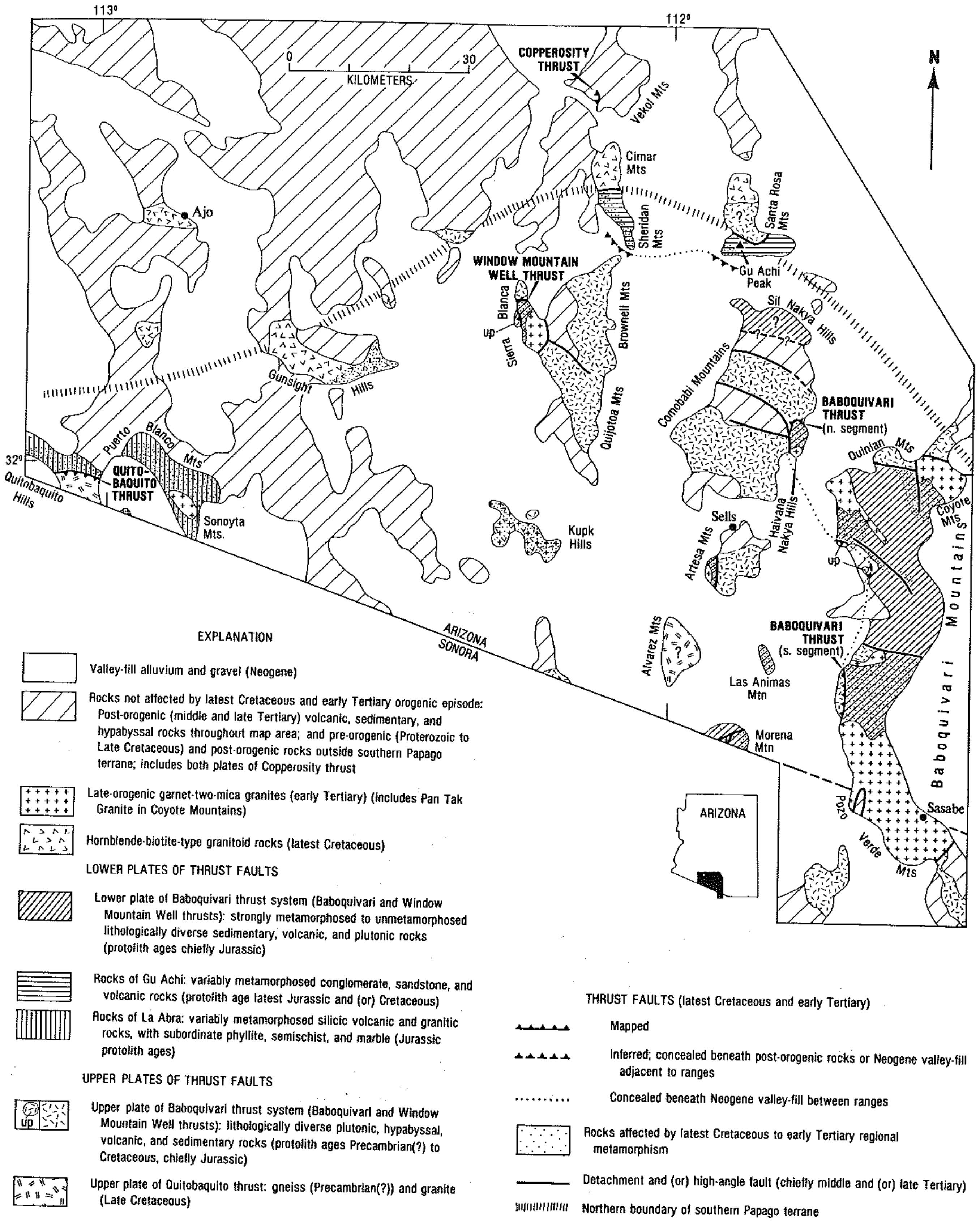

Figure 15. Tectonic map of south-central Arizona (Papago terrane). (From Haxel and others, 1984. Permission granted by the authors, copyright 1984.)

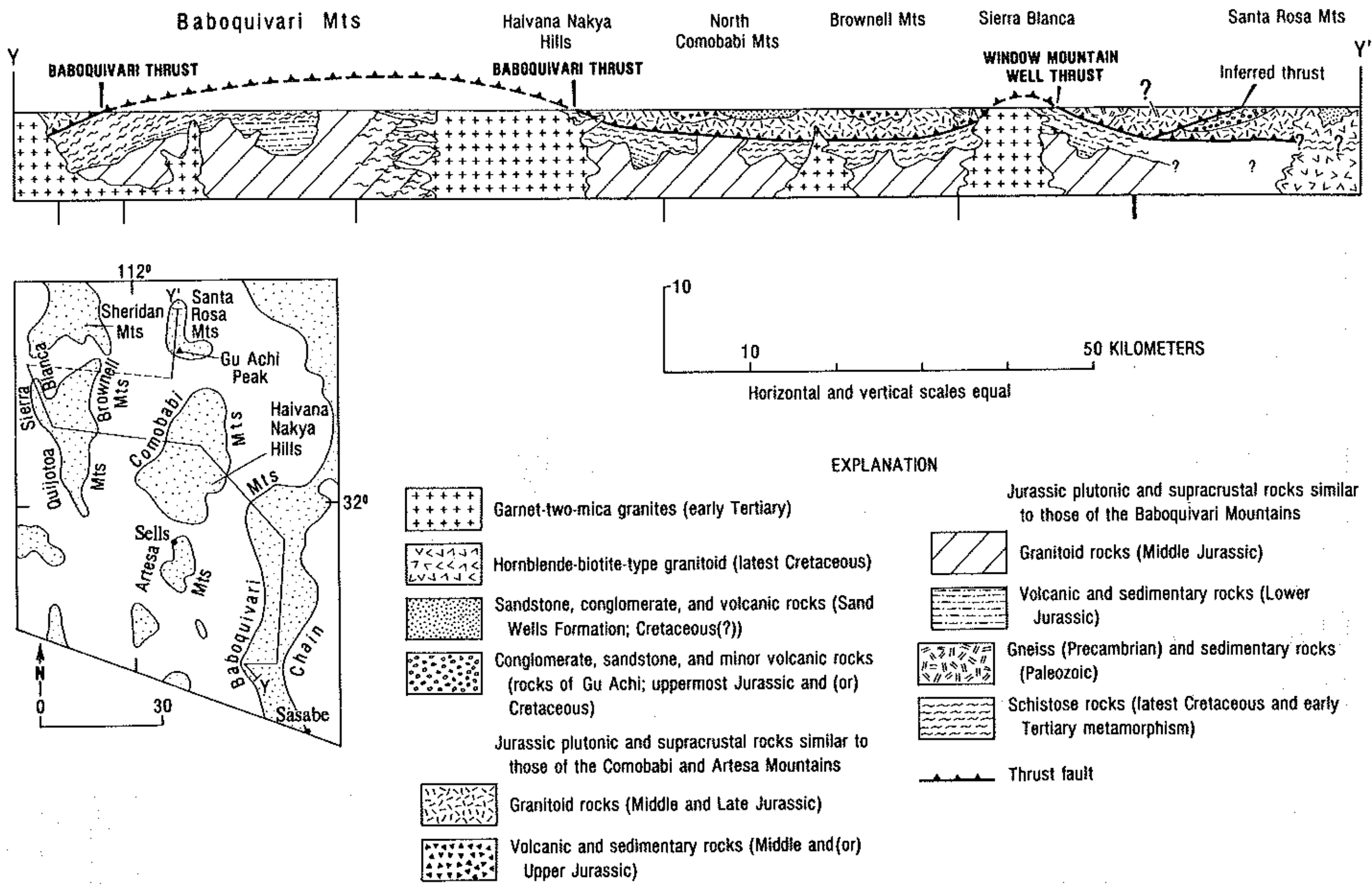

Figure 16. Interpretive cross section through south-central Arizona (see inset map) illustrating the extent of the Baboquivari thrust system, that is, the Baboquivari thrust plus the Window Mountain Well thrust. Cross section shows the inferred structural configuration of south-central Arizona after latest Cretaceous and early Tertiary orogenesis and prior to middle and late Tertiary deformation and magmatism. The relation depicted between the thrust south of the Santa Rosa Mountains and the Baboquivari thrust system is only one of several possibilities. The hypothetical zone of schistose rocks shown within the hornblende-biotite-type granitoid rocks in the Santa Rosa Mountains is analogous to the mapped shear zone in the eastern Gunsight Hills. Light vertical lines along bottom of cross section mark bends in section. Heavier vertical line toward right end of section marks break in section between Sierra Blanca and Santa Rosa Mountains; break is represented on inset map by dashed line. (From Haxel and others, 1984. Permission granted by the authors, copyright 1984.)

considerably more volcanic and volcanoclastic rocks than are found to the north and east. Finally, of prime interest here, the Mesozoic rocks have been affected by a Late Cretaceous regional metamorphic event with associated thrust faults and related structures. At least some of the terrane was later affected by younger middle Tertiary metamorphism related to metamorphic core complex deformation (Davis, 1980; Davis, Gardulski, and Anderson, 1981).

Based on field relationships and isotopic age data, Haxel and other, 1984, p. 631) concluded that "thrust faulting, metamorphism, and granitic plutonism were closely related aspects of a latest Cretaceous and early Tertiary orogenic episode." A variety of Jurassic and Cretaceous rocks were metamorphosed and are overlain by crystalline rocks along low-angle thrust faults (fig. 16). The crystalline rocks include Precambrian gneisses and Jurassic and Upper Cretaceous plutonic rocks. Field relationships suggest that a thrust system of regional extent and that a large part of the southern Papago terrane, including most of the Baboquivari Mountains, is a large fenster. Haxel and others (1984) have suggested several tens of kilometers of displacement on this thrust system in either a southwest or northeast direction. Field data do not yet permit an absolute direction assignment and ultimately may support both. Regionally metamorphosed rocks yield K-Ar age dates of 71-58 Ma. Thrust faults involve rocks as young as Late Cretaceous. Haxel and others thus conclude that the Laramide orogeny affected south-central Arizona in the form of regional metamorphism and associated thrust faulting, starting about 80-70 Ma ago and culminating about 60-58 Ma ago.

West-central Arizona Subprovince

West-central Arizona is a geologically complex, poorly understood region. As in south-central Arizona, the western margin of the state experienced Mesozoic-Cenozoic regional metamorphism and deformation (Reynolds, 1980, 1982; Harding, 1982; Tosdal and Haxel, 1982). Mesozoic volcanic and clastic rocks, anomalously thick, have been metamorphosed to greenschist facies and display tectonic fabrics with north-dipping foliations.

The age of this deformation is constrained between Middle Jurassic and early Tertiary. Upper Mesozoic rocks are metamorphosed in several ranges, including the Granite Wash Mountains, where the metamorphic rocks are truncated by Late Cretaceous plutons (Reynolds, 1980). However, some of the regional metamorphism and deformation seen throughout the region may be Jurassic (Harding, 1980, 1982; Harding and others, 1983) or Tertiary (Varga, 1977).

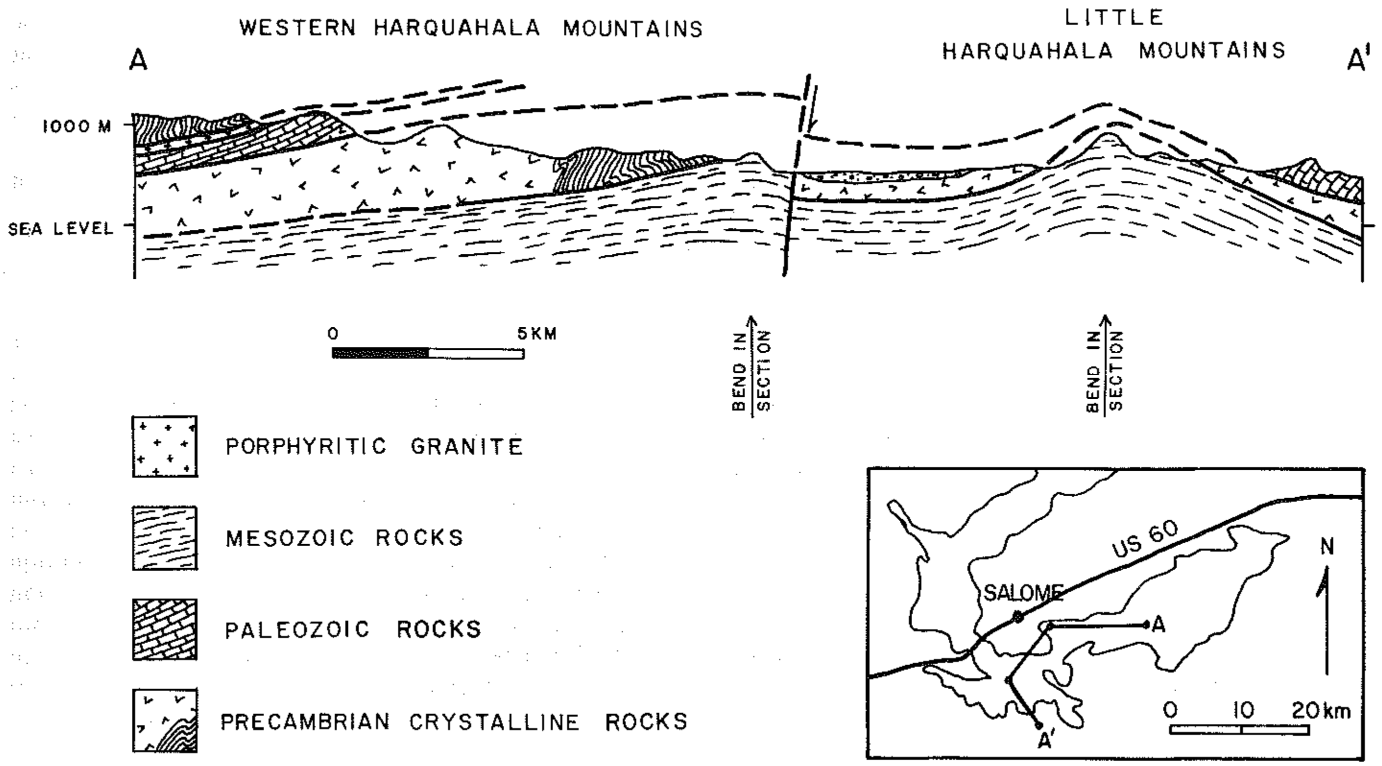

Figure 17. Schematic cross section through the western Harquahala and Little Harquahala Mountains. Vertical exaggeration x 2.5. (After Reynolds and others, 1980. Permission granted by the authors.)

A number of ranges display low-angle faults that cut late Mesozoic clastics but predate middle Tertiary volcanics (Miller and McKee, 1971). Some of the best examples of Laramide or older imbricate thrust faults occur in the Harquahala Mountains (fig. 17) (Reynolds and others, 1980; Reynolds, 1982). The thrust faults may be of several ages, but age of the structurally highest Harquahala thrust is poorly constrained between Middle Cretaceous and early Tertiary. Reynolds and others (1980) interpreted the vergence as north to north-northeast on the basis of overturned folds and suggested a displacement of tens of kilometers or more. However, recent analysis of small-scale structures in mylonitic rocks along the thrusts is supportive of south or southwest vergence (Reynolds, 1984, personal commun.). This apparent contradiction in vergence is unresolved and may be due to the presence of large pre-Laramide southeast-overturned folds that are discordantly truncated by the thrusts (Reynolds and others, 1980).

Richard (1983) also found thrust faults in the Little Harquahala Mountains that placed Precambrian and Paleozoic rocks above Mesozoic strata. The thrusts, which may be north vergent, also truncate older southeast-vergent compressional structures. Richard did not provide age constraints for the thrusting beyond Jurassic through early Tertiary.

Additional major thrust faults have been discovered farther west in the Granite Wash Mountains (Reynolds and others, 1983) and in the Plomosa Mountains (Miller and McKee, 1971; Harding, 1980; Harding, Butler, and Coney, 1983; Scarborough and Meader, 1983). Thrusts in these areas have been variably interpreted as west, southwest, and northeast vergent. The ages of the thrusts are not well-known.

Extreme Southwest Arizona Subprovince

Little is known in detail about the Mesozoic evolution of the southwest corner of the state. Adverse climate and terrain have inhibited workers and military firing and bombing ranges have kept certain areas completely closed to access.

Abundant Cretaceous- and Laramide-age plutons (Shafiqullah and others, 1980) have led to tectonic models that place the corner of the state inside a northwest-trending magmatic arc (Coney, 1976, 1978). As in adjacent regions, this area also experienced a regional metamorphism expressed in Mesozoic rocks. Wilson (1933) attributed the metamorphism to orogenic compression but could not find related major folds or faults. Olmsted and others (1973) suggested that some of the metamorphism may date from Laramide time.

STATEWIDE SYNTHESIS

The structures and tectonic evolution of the different provinces can be compared in terms of both deformation style and magnitude. One major theme of Arizona Laramide history is the reactivation and influence of older structures. Whatever the interpretation chosen for each province, statewide dynamics include consistent northeast-southwest compression. Although the complete story is not yet known for western Arizona and the last word in the controversy in southeastern Arizona has yet to be heard, a statewide structure scenario for the Arizona Laramide can be proposed.

Structural Styles and Behavior

Both the Colorado Plateau and the Transition Zone are characterized by fold- and fault-bound uplifts that involve basement. A favored interpretation for southeastern Arizona also includes fault-bound basement uplifts. In all three domains, uplifts rose along preexisting fault zones in response to northeast-southwest horizontal compression. Differences between the three provinces include the structural behavior at uplift margins (that is, monoclinal folding versus reverse faulting) and the magnitude of uplift and horizontal shortening.

Basement uplifts are all similar in scale and average 30 to 40 km across. This similarity may reflect a uniform spacing of preexisting fault zones, which in turn may be related to Precambrian crustal thicknesses. The variation in trend of the uplift margins was more likely controlled by the orientations of pre-Laramide faults than by local changes in the stress field, as minor structures display consistent orientations throughout the eastern half of the state. The overwhelming dominance of northwest-trending folds and reverse faults suggests regional northeast-southwest compression; this concept is further supported by the orientations of dikes and veins.

The smaller magnitude of strain on the Colorado Plateau resulted in uplifts bound by monoclines. Faults, where seen, are restricted to the basement or lowest units of the Phanerozoic cover. In contrast, the boundaries of the southeastern Arizona uplift are reverse fault zones with considerable stratigraphic separation. Thus, although 30 percent horizontal shortening has been calculated for southeastern Arizona (Davis, 1981), the Colorado Plateau province probably enjoyed no more than several percent shortening. Any northward or northeastward translation of the Colorado Plateau as a whole must also be taken into account. Anomalously high strains around the margins of the Colorado Plateau might have accommodated the relatively rigid behavior of its interior.

Southwestern Arizona stands in apparent discord to the other provinces. The Laramide geology of the southwest province is characterized by penetrative, regional tectonic fabrics. Isolated exposures of complex thrust faults hint at regional structures with significant offset. Again, pre-Laramide structures probably influenced the structural response to Laramide stresses. Although not yet clear, north-south or northeast-southwest Laramide compression was probably at least a major factor.

History of Arizona Laramide Structures

Large-scale Laramide deformation probably began in Middle Cretaceous time. Although uplift and igneous activity swept eastward through the state (Coney and Reynolds, 1977; Coney, 1978), a similar sweep of folding and faulting cannot yet be documented. The southern Papago terrane and probably the rest of southwestern Arizona began to experience penetrative metamorphism and thrust faulting about the same time that a belt of reverse fault-bound uplifts began rising across the eastern portion of the state. Increased northeast-southwest compression enhanced deformation everywhere and continued into Tertiary time. The Colorado Plateau may have been translated northward or northeastward as Laramide uplifts in Wyoming and Colorado also rose. The intrusive sweep from southwest to northeast signaled the end of intense deformation (Coney, 1978), leaving a broad, slightly uplifted, but complexly deformed terrane stretching diagonally across Arizona. This terrane set the stage for middle Tertiary and Basin and Range extensional tectonics that have put the most recent touches to the structural and physiographic patterns visible today.

ACKNOWLEDGMENTS

This paper would not have been possible without the support of Stephen Reynolds of the Arizona Geological Survey (formerly, Arizona Bureau of Geology and Mineral Technology). Further benefit was provided by discussions with Peter Coney, George Davis, Kenneth Yeats (now at Chevron), and Steve Naruk, all at the University of Arizona, and reviews by Chuck Thorman and Harald Drewes of the U.S. Geological Survey. Of course, a great debt is owed to the authors of the papers cited in the references for their contributions to Arizona geology. Finally, I wish to thank Shirlee Krantz for her support and patience during the time this paper was in the works.

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Revised manuscript accepted 1985.