Styles and timing of Early Proterozoic deformation in Arizona: Constraints on tectonic models

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ABSTRACT

A compilation of data on timing and style of Early Proterozoic deformation in Arizona reveals different ages and styles of orogenic deformation. The oldest recognized deformation, 1.74-1.735 Ga, affected rocks in central to northwestern Arizona and is characterized by northwest-striking, steeply dipping foliation and steeply west-plunging stretching lineation. In central Arizona, 1.72-1.70 Ga deformation is characterized by subcumbent folds and shallowly dipping foliation with evidence for west-directed shortening. The 1.70-1.69 Ga Yavapai orogeny is characterized by northeast-striking subvertical foliation and subvertical stretching lineation that variably overprint and reorient earlier fabrics. This is the dominant fabric of central to northwestern Arizona and it records partitioned crustal shortening. Intensity of 1.70-1.69 Ga deformation and grade of metamorphism (granulite to greenschist) decreases towards the southwest. The ca 1.65 Ga Mazatzal orogeny affected southeastern Arizona and is characterized by northeast-striking fabric that becomes more east in character to the northwest, towards central Arizona, accompanied by a decrease in grade of metamorphism from upper to lower greenschist facies.

Published tectonic models involving single orogenical events do not adequately explain observed structural complexities. Tectonic models involving complex progressive deformation are possible but require significant reorientations of shortening direction between 1.735 and 1.70 Ga. Structural data seem best explained by tectonic models involving separate subduction-related convergent systems and associated magmatic arc development. The relative importance of crustal addition by arc magmatism versus by collisions of tectonic mosaics remains unclear.

1.74-1.735 Ga deformation is interpreted as the development and subsequent shortening of a northwest-trending magmatic arc. Isotopic data suggest that magmatism involved unradiogenic, oceanic mantle-like sources in central Arizona. In contrast, magmatism in the Mojave incorporated older crustal materials or involved continental lithospheric mantle. There is a transitional zone in the Hualapai block of northwestern Arizona which shows characteristics of both central Arizona and the Mojave. The major shortening event at 1.70-1.69 Ga is interpreted as the product of amalgamation of terranes to North America. This deformation is manifested as a series of north- and northeast-striking shear zones that define the block architecture of the orogen. 1.71-1.69 Ga magmatic complexes in northwestern Arizona and in the Mazatzal block appear to be separate magmatic systems, as suggested by differences in composition and a gap in 1.70 Ga magmatism in the intervening Ash Creek block. They may represent separate subduction-related batholiths or collision-related melting of different lower crustal compositions. The angular unconformity at the base of the Red Rock-Mazatzal Groups records synorogenic 1.70 Ga uplift in northwestern Arizona related to regional shortening. The 1.65 Ga Mazatzal orogeny may represent the development of a continental margin arc in southeastern Arizona and subsequent deformation of the arc and continent by collisions to the south. By 1.65-1.60 Ga, the newly formed crust was apparently insulated from further plate margin magmatism and deformation.

INTRODUCTION

Early Proterozoic (1.8-1.6 Ga) orogeny in the southwestern United States resulted in the addition of large volumes of continental lithosphere to North America (e.g. Karlstrom and others, 1987; Hoffman, 1988,1989). Understanding this
period of continental growth, and processes of continental growth in general, involve understanding the interactions of two related processes: 1) magmatic additions to the crust, often in the form of subduction-related batholithic belts, and 2) collision of exotic terranes at convergent plate boundaries. Most models for development of juvenile continental lithosphere (eg. Hamilton, 1988) rely on the mutual interaction of both processes.

Continental lithosphere in Arizona is part of a 1300-km-wide orogenic zone that was accreted and stabilized within 150 m.y. (eg. Bowring and Karlstrom, 1990), and almost certainly records both types of accretionary processes. The orogenic belt contains 50-60% granitoids at present levels of exposure, indicating the presence of major batholithic belts. The dominant fabric of the orogen strikes northeast and is characterized by a series of shear zones that segment the orogenic belt into tectonic blocks (Fig. 1; Karlstrom and Bowring, 1988). In view of the rapid development and great width of this orogen, the block architecture suggests the possibility that some of the shear zones may record collision of exotic terranes. However, across many of the shear zones, it is still not known if adjacent blocks were or were not originally adjacent paleogeographic elements. Thus, there is continued uncertainty regarding the relative importance of accretion by successive development of magmatic arcs (eg. Condie, 1982; P. Anderson, 1986,1989a, 1989b) versus crustal growth by collision of tectonic fragments (Karlstrom and Bowring, 1988).

The goal of this paper is to summarize the character and timing of development of deformatonal fabrics in Arizona. This is one data base from which to consider the history of growth of southwestern North America. This paper emphasizes the presence of multiple deformatonal fabrics, and the spatial and temporal distribution of deformatonal and magmatic features in Arizona. These are important constraints for plate tectonic models of the Proterozoic of Arizona.

BACKGROUND

Earlier studies of deformatonal history in Arizona generally postulated a single deformational episode (eg. Wilson, 1939; Anderson, 1951, Anderson and Creasey 1958; DeWitt, 1979, 1980; Creasey, 1980; Anderson, 1989b). Most of these studies focused on relatively small areas of the orogen and recognized a single penetrative fabric. In a recent paper, Anderson (1989b) has proposed a model for deformation in Arizona that involves "vertical tectonics". According to this model, deformation, although ultimately driven by plate tectonic interactions, was a response to density-driven rise of plutos and sinking of volcanic belts. The dominant northeast strike of the foliation and the position of high strain zones were predetermined by the original northeast strike of volcanic belts and sedimentary basins. Deformatonal fabrics formed diachronously across the orogen, with cycles of deformation (and accompanying metamorphism and plutonism) progressing towards the southeast. Fabrics are interpreted to reflect a constrictional pure shear kinematic regime where shortening took place in all horizontal directions in association with pronounced vertical material transport.

These deformatonal models are difficult to reconcile with recent structural studies that recognize multiple generations of fabrics in numerous localities (O'Hara and others 1978; Karlstrom, 1989; Burr, this volume; Bergh and Karlstrom, in press; Albin and Karlstrom, this volume). In all of these studies, early folds and tectonic foliations and lineations are reported to be overprinted by the dominant northeast-striking subvertical fabric of the orogen. As summarized below, U-Pb dating combined with geologic studies indicate that deformation timing on the early fabrics varied from 1.74 to 1.70 Ga, and that the dominant northeast-striking fabric formed at about 1.70 Ga in northwestern Arizona and 1.65 Ga in southeastern Arizona (Karlstrom and Bowring, 1988, Conway and Silver, 1989). Thus, tectonic models for the Proterozoic of Arizona must explain both the northeast-striking fabric which defines the dominant structural grain, and earlier, more cryptic, deformatonal events, such as northwest-trending fabrics in central to northwestern Arizona (Fig. 1). Models involving a single deformation do not explain the observed overprinting relationships unless that deformation was a long and complex progressive event. Kinematic models must explain superposition of shortening strains on regions of earlier shallowly and steeply dipping L-S fabric. A single deformation involving regional constriction (Anderson, 1989) cannot explain observed fabric geometries, nor the presence of shallowly-dipping fabrics and is not supported by finite strain studies that show a predominance of L-S tectonites. Constrictional strains are rare worldwide, presumably because of major strain incompatibility problems (Ramsay and Huber, 1983).

NORTHWEST- AND NORTH-STRIKING DEFORMATONAL FABRICS

This section reviews evidence for early northwest-striking deformatonal fabrics in Arizona. Regional north- to northwest-striking orogenic fabrics have long been recognized in central Arizona (Anderson and Creasey, 1958; Krieger, 1965). The Ash Creek and Green Gulch blocks contain steeply dipping northwest-striking foliation and transposed bedding, isoclinal folds, and steeply west-plunging stretching lineations. Deformatonal of the Ash Creek Group is tightly bracketed between 1.74 Ga, the age of deformed rhyolite in the Jerome area, and 1.735 Ga, the age of the late syn- or post- deformatonal Cherry batholith (Table 1). In the Green Gulch block, deformation was also syn- to post- emplacement of the 1.74 Ga granitoids (Krieger, 1965; Anderson and others, 1971; Bergh and Karlstrom, in press). In both blocks, the early fabric is overprinted by deformation in block-bounding shear zones.

There is also evidence for a somewhat younger, pre-1.70 Ga, deformation that produced shallowly dipping northwest-striking tectonic fabrics. In the Verde Monocline area (Fig. 1) 1.72 Ga quartz diorite contains a moderately north-dipping
Figure 1. Generalized foliation patterns in Early Proterozoic rocks of Arizona. Northeast-striking shear zones segment the orogen into tectonic blocks: Mo = Mojave block, H = Hualapai block, G = Green Gulch block, B = Big Bug block, A = Ash Creek block, M = Mazatzal block, S = Sunflower block, P = Pinal block. Major shear zones are: GC = Gneiss Canyon, MB = Mesa Butte, CH = Chaparral, SH = Shylock, MG = Moore Gulch, SC = Slate Creek. These shear zones overprint earlier deformational fabrics. Numbers correspond to areas for which there are U-Pb constraints on timing of deformation -- keyed to Table 1.
U-Pb constraints on timing of deformation and metamorphism in Arizona. 

<table>
<thead>
<tr>
<th>Area and Rock Type</th>
<th>Age (Ga)</th>
<th>Interpretation</th>
<th>Ref</th>
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<tbody>
<tr>
<td>1) New York Mountains</td>
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<tr>
<td>a) pre-tectonic granitoids</td>
<td>1.76-1.73</td>
<td>pre-D&lt;sub&gt;2&lt;/sub&gt;</td>
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<tr>
<td>b) syntectonic granitoids</td>
<td>1.71-1.70</td>
<td>syn-D&lt;sub&gt;2&lt;/sub&gt;</td>
<td>1</td>
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<tr>
<td>c) post-tectonic granitoids</td>
<td>1.69-1.64</td>
<td>post-D&lt;sub&gt;2&lt;/sub&gt;</td>
<td>1</td>
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<tr>
<td>2) Old Woman Mountains</td>
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<td></td>
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<tr>
<td>a) Fenner gneiss</td>
<td>1.68</td>
<td>post-D&lt;sub&gt;2&lt;/sub&gt;</td>
<td>1</td>
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<tr>
<td>3) Lost Basin Range - Gold Butte</td>
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<tr>
<td>a) Lost Basin granitoid</td>
<td>1.69</td>
<td>pre- or syn-D&lt;sub&gt;2&lt;/sub&gt;</td>
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<tr>
<td>b) monzogranite of Gold Butte</td>
<td>1.68</td>
<td>post-D&lt;sub&gt;2&lt;/sub&gt;</td>
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<tr>
<td>4) Lower Granite Gorge, Grand Canyon</td>
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<td>a) granodiorite of Diamond Creek</td>
<td>1.73</td>
<td>pre- or syn-D&lt;sub&gt;1A&lt;/sub&gt;</td>
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<td>5) Grand Wash Cliffs</td>
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<td>a) granodiorite</td>
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<td>6) Peacock Mountains</td>
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<td>a) amphibolite</td>
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<td>syn-D&lt;sub&gt;2&lt;/sub&gt;</td>
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<td>7) Hualapai Mountains</td>
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<td></td>
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<td>metamorphic zircons</td>
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<tr>
<td>b) granite</td>
<td>1.69</td>
<td>syn- or post-D&lt;sub&gt;2&lt;/sub&gt;</td>
<td>5</td>
</tr>
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<td>9) Chino Valley area</td>
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<td>a) Mazatzal Quartzite</td>
<td>Pb-Pb ages 1.93-1.65 (detrital zircons)</td>
<td>syn-D&lt;sub&gt;2&lt;/sub&gt;</td>
<td>6</td>
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<tr>
<td>10) Verde Monocline</td>
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<td></td>
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<tr>
<td>a) quartz diorite</td>
<td>1.72</td>
<td>syn-D&lt;sub&gt;1B&lt;/sub&gt;</td>
<td>6</td>
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<tr>
<td>b) granite dikes</td>
<td>1.72</td>
<td>post-D&lt;sub&gt;1B&lt;/sub&gt;</td>
<td>6</td>
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foliation that is cross-cut by undeformed 1.72 Ga granite dikes (Chamberlain and others, 1991). Similarly, in the Brady Butte area where overprinting of fold generations was first documented (O’Hara and others, 1978, O’Hara, 1980; Karlstrom, 1989), subhorizontal S₁ fabric in the Texas Gulch Formation is overprinted by upright S₂ fabric. S₁ is axial planar to subcumbent folds and parallel to small thrusts, and is associated with top-to-the-west movement. The age of about 1.72 for detrital zircons from the Texas Gulch Formation suggests that this deformation took place between 1.72 and 1.70 Ga and represents a separate deformation from the 1.74-1.735 northwest-striking foliation. This shallow fabric is also present in the southern Big Bug block (Burr, this volume) and may be linked to progressive shortening that formed the dominant northeast-trending fabric (Karlstrom, 1989; Burr, this volume).


A synthesis of the regional tectonic and kinematic significance of the early northwest-striking fabrics is not yet possible because of overprinting by 1.70-1.69 Ga northwest-southeast shortening. Timing data suggest that steeply-dipping foliation formed at 1.74-1.735 Ga and that shallowly dipping fabric formed at 1.72-1.70 Ga, suggesting separate events. However, these “events” may have been related to a longer period of northeast-southwest or east-west convergence that lasted from 1.74-1.70 Ga.

Because of the regional distribution of northwest-striking fabrics (Fig. 1), we speculate that all initially northwest-trending fabrics were related to the development and deformation of a northwest-trending magmatic arc system that roughly paralleled the present northern Transition Zone of Arizona. This area is the approximate locus of known 1.73-1.74 Ga calc-alkaline granodiorites. This hypothesis, that strike of foliation may be subparallel to the original trend of the arc, assumes that development and subsequent deformation of the were both related to the same subduction system.

This proposed northwest-striking magmatic arc may initially seem at odds with geochemical data that indicate that granodiorites are generally enriched in alkalies and incompatible trace elements towards the northwest (DeWitt, 1989). This trend was interpreted by DeWitt (1989) in terms of derivation of these rocks from a northwest-dipping subduction zone. However, these granodiorites may range in age by 50-300 m.y. and it is tenuous to consider them all to be the products of a single subduction system. Even if they are, similar geochemical variations are observed along strike in arcs, and can reflect changes in the upper plate crustal chemistry.

In the Mojave block, there is isotopic evidence in plutonic rocks as old as 1.74 Ga for the incorporation of older crust. In contrast, 1.74 Ga plutonic rocks in central Arizona are juvenile (Bennett and DePaolo, 1987; Wooden and DeWitt, this volume). A wide zone of transition, corresponding to the Hualapai block (Fig. 1), shows a complex mixture of isotopic signatures of the two provinces (Wooden and others, 1988, Wooden and DeWitt, this volume). Thus, the proposed 1.74 Ga northwest-trending arc may have been built across an early lithospheric transition from younger, perhaps oceanic crust in central Arizona (or crust derived from depleted mantle), to older, perhaps continental crust in the Mojave (or crust derived from enriched mantle). The 1.73 Ga Payson ophiolite, with its north- to northwest-striking sheeted dikes (Fig. 1), is interpreted to be a back-arc or intra-arc spreading center (Dann, 1991a). The ophiolite has arc affinities in terms of its geochemistry and intrudes and extends 1.75 Ga crust composed of granitoids. The ophiolite apparently developed after deformation in the Ash Creek block; and before the 1.72-1.71 Ga subhorizontal fabric in the Big Bug and Green Gulch blocks. Its geographic position would be compatible with back-arc or intra-arc spreading northeast of the 1.75-1.73 northwest-trending arc. The northwest strike of sheeted dikes also suggests back arc or intra-arc spreading of a northwest-striking arc.

NORTHEAST-STRIKING DEFORMATIONAL FABRICS

The main orogenic fabric in the Proterozoic of the Southwest strikes northeast. This fabric has traditionally been assumed to record the successive addition of magmatic arcs on and against the Archean craton (Condie, 1982; Anderson 1989a) and/or to be the product of collisions of tectonic fragments (Grambling and others, 1988; Karlstrom and Bowring, 1988). Timing of deformation associated with development of northeast striking fabrics is variable, both across the orogen (Reed and others, 1987), and in Arizona. In Arizona, the northeast-striking fabrics have been interpreted to record two main orogenic pulses, the 1.70-1.69 Ga Yavapai orogeny and the 1.65 Ga Mazatzal orogeny, as discussed below.

Yavapai Orogeny: 1.70-1.69 Ga Northeast-striking Fabric

Blocks as far southeast as the Mazatzal block (Fig. 1) were deformed at about 1.70 Ga. This deformation records partitioned crustal shortening, presumably accompanied by thickening and uplift of crustal blocks. The widespread distribution of northeast-striking foliation in the orogen suggests that this deformation was a major event, and may
record the amalgamation of lithospheric fragments to North America.

As described by Karlstrom (1989), Bergh and Karlstrom (in press), and Albin and Karlstrom (this volume), foliation associated with this deformation strikes northeast to north, is subvertical, and is axial planar to upright folds that have variable plunge, from horizontal to vertical. Stretching lineations are dominantly subvertical. Deformation is strongly partitioned at every scale. In zones of high strain, early fabrics are obliterated and the northeast fabric can be either a composite $S_1$/$S_2$ fabric resulting from intense shortening and transposition ($S_1$ is still recognizable in microlithons and porphyroblast inclusion trails), or a zone of progressive shearing (eg. the Chaparral and Cleator shear zones, Bergh and Karlstrom, in press; Darrach and others, 1986 and this volume).

Darrach and others (this volume) and Bergh and Karlstrom (in press) suggested that shear zones such as the north-trending Shylock and northeast-trending Chaparral zones were initiated as zones of high shortening strain and were progressively overprinted by strike-slip movements (sinistral and dextral respectively) which accommodated further bulk crustal shortening as the Big Bug block escaped to the south (and up). Conjugate shear zones occur on a variety of scales. Regionally, they record a predominance of northwest-side-up dip-slip shear (Albin and Karlstrom; this volume; Bergh and Karlstrom, in press; Burr, this volume). The regional decrease in metamorphic grade to the southeast may in part reflect continuation of northwest-side-up displacements after peak metamorphism. However, peak pressures appear to be nearly isoobaric across the orogen and temperature of metamorphism was apparently locally controlled by heat from plutons (Williams, this volume), suggesting that much of the regional shortening and associated west-side-up movement on shear zones pre-dated peak metamorphism.

Timing of deformation is constrained to be 1.7-1.69 Ga throughout the northwestern part of the orogen. In southeastern California 1.71±0.01 Ga plutons are strongly deformed and 1.68-1.65 Ga plutons are relatively undeformed (Wooden and Miller, 1990). Deformation in the Grand Wash Cliffs of northwestern Arizona is bracketed between 1.69 and 1.68 Ga (Chamberlain and Bowring, 1989), and in the Hualapai Mountains between 1.7 and ca 1.68 Ga, if the 1.68 date on metamorphic zircons is considered to be close to time of deformation (Chamberlain and Bowring, 1989). Shortening deformation in the Cottonwood Cliffs is post-1.715 Ga, the age of the Valentine Granite and before ca 1.62 Ga undeformed granite dikes (Albin and others, 1991). Similarly, deformation near Bagdad is constrained between 1.71 and 1.69 Ga (Bryant and Wooden, 1986, and this volume). Deformation in the Big Bug block, and by inference in the adjacent Shylock and Chaparral shear zones, was synchronous with emplacement of the 1.70 Ga Crazy Basin Monzogranite (Conway and others, 1987; Karlstrom and Williams, in prep.).

There was also a sedimentary response to deformation associated with the Yavapai orogeny. Ca 1.70 Ga sedimentary rocks of the Mazatzal block (Mazatzal Group, and perhaps parts of the Tonto Basin Supergroup) and the 1.72-1.70 Ga unconformity in the Mazatzal block (Wrucek and Conway, 1987; Anderson, 1989b; Dann, 1991b) may reflect syntectonic sedimentation in response to Yavapai convergence. This unconformity separates tightly folded rocks of the 1.72 East Verde River Formation, and perhaps of the 1.71 Ga Alder Group (Wessels and Karlstrom, this volume), from flat-lying rocks of the 1.70 Ga Red Rock and Mazatzal groups. Recognition of the regional extent of this unconformity (Dann, 1991b) suggests that deformation in the shear zones that bound the Mazatzal block in part reflects 1.70 Ga deformation and in part reflects later (1.65 Ga) deformation.

The 1.70 Ga deformation (and metamorphism) was intrinsically associated with granitoid emplacement. This association culminates in migmatites and granulite facies metamorphism in the northwest, where plutons are abundant (Thomas and others, 1988; Young and others, 1989; Wooden and Miller, 1990), and diminishes to the southwest, where rocks are greenschist grade and 1.70±0.01 Ga plutons are absent (the Green Gulch and Ash Creek blocks). The Big Bug block apparently records higher grades and more penetrative shortening due to the presence of the Crazy Basin Monzogranite (Williams, this volume). This pluton may be part of the eastern edge of a major 1.70±0.01 Ga batholithic complex in western Arizona, as suggested by a 20 mgal gravity anomaly across the boundary between the Big Bug and Ash Creek blocks (the southern Shylock shear zone) which shows less dense crust west of the Shylock shear zone (Leighty and others, this volume).

There is an important temporal connection between 1.70±0.01 Ga plutonism and development of the regional northeast-trending deformational fabric. This implies that by 1.70 Ga, major convergent boundaries were northeast-trending. There may have been one or more northeast-trending subduction-related convergent zones active at this time. Alternatively, the 1.70 Ga magmatic activity may be viewed in terms of collision-related lower crustal melting and deformation-enhanced pluton emplacement.

One key to understanding the relationship between magmatism and deformation is to evaluate the magmatic gap across the Ash Creek block. Voluminous magmatism took place in the Mazatzal, Big Bug, and Hualapai blocks at 1.70±0.01 Ga, but not in the intervening Green Gulch and Ash Creek blocks. Central Arizona blocks are interpreted to be spatially linked at this time, and metamorphic data suggest that presently exposed rocks of all of these blocks (with the possible exception of the Mazatzal block) may have been at close to the same depth (Williams, this volume). Tectonic models must explain differences in character and depth of emplacement of 1.70 Ga plutons and the apparent magmatic gap across the Ash Creek block.

The 1.70 Ga magmatic rocks of the Mazatzal block are shallow-level, high-silica, high-alkali rocks that were probably the product of voluminous caldera-related rhyolitic magmatism (Conway, 1976). Mazatzal block volcanic rocks
could perhaps represent shallow level equivalents to the 1.70 Ga plutonism in western Arizona. If so, extrusion of voluminous ash flows in the Mazatzal block needs to be reconciled with synchronous crustal shortening at 3 kb in the area of the Crazy Basin Monzogranite to the west (Karlstrom and others, 1987). However, the high silica and alkali content of Mazatzal block granites and ryolites contrast with calc-alkalic and alkali-calcic plutons to the northwest. This difference, and the magmatic gap between these igneous rocks in the Ash Creek block, seem more compatible with different sources for the two 1.70 Ga plutonic complexes with no magmatic rocks from either system reaching the present level of exposure in between.

It is unclear how either magmatic system might reflect subduction processes, as positions and polarity of possible subduction zones remain speculative. Timing of deformation data suggest that magmatism may reflect final collisional amalgamation of crustal blocks, not subduction. Lower crustal melting of juvenile crust in central Arizona and older crust in northwestern Arizona may have been a delayed product of conductive heating of crust that was thickened earlier (ca. 1.74 Ga) or of collision-related basaltic underplating. Thus, differences in composition of granites may reflect chemical heterogeneities of crustal columns.

Mazatzal Orogeny: ca. 1.65 Ga

Northeast-striking fabric

Rocks in southeastern Arizona are also dominated by northeast-striking subvertical foliation that is axial planar to upright folds. This fabric is variably developed and essentially dies out in portions of the northern Mazatzal block. Deformation in the Mazatzal block is characterized by generally upright folds and thrusts. Thrust systems in the Mazatzal Mountains record northwest-directed movement, with 30-50% shortening accomodated by duplex formation and related folding in the Mazatzal Mountains (Doe and Karlstrom, this volume). In the Sierra Ancha, comparable shortening is accomodated by moderately-plunging upright folds cut by high angle faults (Gastil, 1958), that may merge at depth with a decollement zone (Sherlock and Karlstrom, this volume; Labrene and Karlstrom, this volume). Peak metamorphic temperatures of less than 250-400 C are suggested by phyllosilicate assemblages and fluid inclusion data (Gillentine and others, this volume). This low-grade metamorphism is compatible with the observed brittle style of deformation.

Intensity of deformation, as recorded in high shortening strains and associated well-developed subvertical cleavage, increases in the southeasternmost Mazatzal block, and in the Slate Creek shear zone (Roller and Karlstrom, 1986). The shear zone is a zone of subvertical foliation, steeply west-plunging stretching lineation, transposition of bedding, and grain size reduction of basement granite (Wessel and Karlstrom, this volume). The zone is 1-4 km wide, has been mapped for a strike length of more than 40 km, and is a regional-scale deformation zone that records mainly shortening. Metamorphic grades in rocks of the Tonto Basin Supergroup are similar across the zone at its north end. However, in several areas southeast of the Slate Creek shear zone (including one locality less than one km south of the zone), kyanite and andalusite-bearing quartzite are present and suggest appreciable south-side-up movement (Roller, 1987).

The Sunflower block, although less well studied contains several areas of higher grade rocks (Williams, this volume), more ductile deformation, and a higher volume of granites, including voluminous 1.65 and 1.4 Ga granites (Karlstrom and others, 1990). The Pinal block is also characterized by subvertical northeast-striking foliation, which apparently developed at greenschist facies (Erickson and Bowring, 1990).

In the Mazatzal block, folding and thrusting post-dated 1.70-1.69, the youngest deformed rocks, and pre-dated 1.65 intrusion of the Young Granite (Table 1; Labrene and Karlstrom, this volume). In the Sunflower block, deformation post-dated deposition of the 1.66 Ga Redmond Formation (Karlstrom and others, 1990) and post-dated 1.65 Ga Young Granite and 1.63 Ga Sunflower granite (Conway and Silver, 1989). In the Pinal block, deformation postdated 1.67 deposition of Pinal metavolcanic rocks and pre-dated emplacement of the 1.65 Ga Somner "gneiss" (Erickson and Bowring, 1990), and the 1.625 Ga Johnny Lyon Granodiorite (Cooper and Silver, 1964; Silver, 1978).

These data suggest a regional deformation in the interval 1.66-1.65 Ga. Deformation appears to die out towards the north, where style of deformation becomes more brittle and is similar in style to shallow foreland thrust belts. Thus, deformation is interpreted to be a result of collisions to the south, perhaps of the Pinal block with the Sunflower block, or across a boundary farther south.

The Mazatzal orogeny was closely followed by emplacement of 1.65-1.63 Ga granites. To date, granitoids, and associated volcanic rocks of this age are known to occur only in areas southeast of the Slate Creek shear zone, suggesting that the shear zone may be an important crustal boundary that influenced locus of ascent and emplacement of magma. Similar age granitoid plutons have been identified in the Mojave block (Wooden and Miller, 1990), but the tectonic relationship of these plutons with those of the Sunflower and Pinal blocks remains unknown.

In southeastern Arizona, plutons intrude high level supracrustal sequences, including fluvial sandstones and alkali rhyolites (Conway, 1976), and can be interpreted as part of a continental magmatic arc system, perhaps related to a northwest- or north-dipping subduction system located towards the southeast or south (Anderson, 1989a). Plutonism and deformation at 1.66-1.60 Ga were the final tectonic events in the Early Proterozoic orogeny. After this time the entire orogenic belt was insulated from further tectonism for about 200 m.y., until emplacement of the 1.4 Ga granitoids.

DISCUSSION

Available data on timing and styles of deformation place the following constraints on tectonic models for assembly of continental lithosphere in the Southwest: 1) Several periods
or pulses of convergent tectonism have been identified in Arizona; 1.74-1.73 Ga, 1.72-1.70 Ga, 1.70-1.69 Ga, and 1.66-1.65 Ga. 2) Each pulse of deformation appears to be broadly linked geographically and temporally to a period of granitoid emplacement. 3) In central to northwestern Arizona, there is evidence that the 1.70 Ga shortening event overprinted earlier deformational fabrics. 4) Each pulse records different regional kinematic regimes; 1.74-1.73 Ga subvertical fabrics in central to northwestern Arizona record NE-SW shortening and the Payson ophiolite records NE-SW back-arc extension; 1.72-1.70 deformational fabrics were subhorizontal and presumably related to thrusting; 1.70-1.69 Ga subvertical deformational fabrics record NW-SE shortening in central to northwestern Arizona; and 1.65 Ga deformation involved NW-SE shortening by thrusting and folding in southeastern Arizona.

It is still uncertain whether these deformational episodes should be interpreted as part of a longer progressive deformation or as temporally and/or spatially separate events. Albin and Karststrom (this volume, Fig. 17) propose two possible kinematic interpretations for the orthogonal northwest- and northeast-striking fabrics in northwestern Arizona. One involves about 40 m.y. of progressive deformation; the other involves several discreet events. Both interpretations satisfy the constraints discussed above in that they involve significant reorientation of the shortening direction between 1.74 and 1.69 Ga, with early deformational fabrics strongly overprinted by partitioned 1.70-1.69 Ga NW-SE shortening. The intensity of the 1.70-1.69 Ga shortening is such that it is difficult to decipher the kinematic history of the earlier deformations and U-Pb constraints on timing of early deformation(s) are not yet sufficient to decide between progressive versus discrete deformation models.

In a progressive deformation model, 1.72-1.70 Ga shallowly-dipping foliation might represent early thrust-related shortening that was progressively overprinted by the subvertical shortening fabric. However, the 1.74-1.73 Ga steeply-dipping northwest-trending fabric is more difficult to explain in a progressive deformation model, especially as it seems to be present throughout most of central and northwestern Arizona (Fig.1). It is perhaps possible that the present steeply-dipping orientation of the northwest-striking fabric in northwestern Arizona represents rotation of initially subhorizontal fabrics in response to subvertical material flow during 1.70 Ga shortening (Albin and Karststrom, this volume; Fig. 17-Model 1). However, this explanation does not explain the steeply-dipping northwest-striking 1.74-1.735 fabric in the Ash Creek and Green Gulch blocks, where 1.7 Ga shortening strains were very weak and nonpenetrative.

An alternative model, and the one favored here, involves discrete orogenic events for formation of northwest- and northeast-striking fabrics (Albin and Karststrom, this volume, Fig. 17-Model 2). The 1.74-1.73 Ga deformational event can be interpreted as the development and deformation of a northwest-trending magmatic arc system. This would explain the northwest-trend of 1.74 deformational fabric in central and northwestern Arizona and of 1.73 Ga sheeted dikes in the Payson ophiolite. Such an arc and back arc system may have been oceanic in central Arizona, as suggested by juvenile isotopic signatures, but built upon an older microcontinental fragment in northwestern Arizona, as suggested by isotopic evidence for involvement of older crust in the Mojave and parts of the Hualapai blocks. There is no evidence that 1.74 Ga arc rocks in Arizona were close to the Wyoming Province, as suggested by Anderson (1989a).

The 1.70-1.69 Ga Yavapai orogeny is interpreted as the amalgamation of terranes to North America because of the regional pervasiveness of the northeast-striking fabric and its parallelism to the south margin of the Wyoming Archean craton (Karststrom and Houston, 1984). The deformation that produced the northeast-striking deformational fabrics had the effect of partitioned shortening of the earlier arc system. This interpretation suggests that the 1.70 Ga deformation probably did not involve collision of exotic terranes in central Arizona, in agreement with Wooden and DeWitt (this volume) and DeWitt and Reynolds (this volume), although it may have involved appreciable relative shuffling, during amalgamation, of new and relatively unstable continental lithosphere (Darrach and others, this volume).

Regional-scale shear zones were active at 1.70; these are interpreted to be crustal and perhaps lithospheric in scale because they are 40-60 km long and several km wide, and they appear to have influenced ascent and emplacement of magmatism. These shear zones, and associated partitioning of strain created the present block architecture of the orogen and obscured earlier tectonic fabrics. The role of collisions of exotic tectonic fragments during each pulse of deformation remains unconstrained as sutures have not been documented. However, the possibility of sutured terranes is not eliminated by our present inability to identify sutures, as we are just beginning to recognize the complexity of deformational overprinting and the long history of deformation. As is true in most orogenic belts, sutures may be present as cryptic boundaries or boundary zones, and early accretionary boundaries may have been reactivated during later shortening such that major shear zones may have complex histories.

The Mazatzal orogeny is interpreted in terms of development of a 1.65-1.62 Ga continental margin batholith that may have developed above a northwest-or north-dipping subduction system located in what is now southeastern Arizona (Anderson, 1989a). It is considered to be a continental arc because 1.65-1.62 granites intrude mature quartzite and thick alkali rhyolite successions that are probably of continental affinity (Conway, 1976). Deformation during the Mazatzal orogeny, 1.66-1.65 Ga, is interpreted to be the result of collision of a relatively large continental mass to the south. A major collision would help explain the termination of orogenic activity in the Southwest by about 1.60 Ga. Such a collision may have insulated the orogenic belt in the Southwest from further plate margin activity for 200 m.y.

Thus, the deformational episodes or pulses are interpreted here in terms of the interaction of multiple convergent sys-
tems that involved subduction-related arc magmatism followed (and accompanied) by shortening deformations caused by collision of tectonic fragments at subduction zones and/or stresses generated by subduction. Complex interacting convergent systems, like those envisioned for the Proterozoic of the Southwest, are presently active in the Indonesian region (Hamilton, 1988).

An alternate interpretation is that the close spatial and temporal association of plutonism and deformation reflects pluton-driven deformation (Anderson, 1989a; Reed and others, 1987). However, in Arizona, most plutons appear to be late during the deformation event they are associated with (e.g., Karlstrom and Williams, in prep.). Furthermore, there is no simple correlation between location of plutons and degree or style of deformation. Instead, foliation and lineation define regional kinematic frameworks into which plutons were emplaced (Albin and Karlstrom, this volume). Thus, plutons appear to have punctuated longer periods of convergent orogeny, and kinematic regimes appear to be regional in scale and not related to individual plutons. Apparently, the lower crustal melting that resulted in the granitoids, and orogenic deformation of the crust, were both responses to convergent tectonism.

REFERENCES CITED


