Persistent influence of Proterozoic accretionary boundaries in the tectonic evolution of southwestern North America: Interaction of cratonic grain and mantle modification events

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ABSTRACT

Northeast-striking tectonic provinces and boundaries were established during 1.8–1.6-Ga assembly of juvenile continental lithosphere in the southwestern United States. This continental grain repeatedly has influenced subsequent intracratonic tectonism and magmatism. After 200 m.y. of stability, cratonic lithosphere was affected by regional, ~1.4-Ga, dominantly granitic magmatism and associated tectonism that reactivated older northeast-striking shear zones in the Proterozoic accreted terranes, but not the Archean lithosphere. In contrast, 1.1-Ga, dominantly mafic magmatism and rifting did not reactivate northeast-striking zones, but occurred along new north–south fracture zones (e.g., Rocky Mountain trend) that reflect cracking of Laurentian lithosphere at a high angle to the Grenville collision. By 500 Ma, rifting had thinned the crust and mantle in the western United States creating the north–south Cordilleran miogeocline. East of the Cordilleran hingeline, isopachs in Lower Paleozoic sedimentary rocks follow northeast-trending structures (Cheyenne belt, Transcontinental arch, and Yavapai–Mazatzal province boundary), suggesting that older boundaries influenced isostatic response of the craton during thermal subsidence of the margin. Ancestral Rockies and Laramide uplifts and basins did not strongly reactivate northeast-striking boundaries. However, Ancestral Rockies structures end at the Archean–Proterozoic boundary, and Laramide magmatism (Colorado mineral belt) and metallogenic provinces follow northeast-striking Proterozoic boundaries, both suggesting deep-seated lithospheric influences on tectonism.

Present mantle structure and topography in the Rocky Mountain region continue to record an interaction between older crustal structures and younger mantle reorganization. Zones of partially molten mantle underlie northeast-striking Proterozoic boundaries (e.g., Snake River Plain, Saint George lineament, and Jemez lineament) and the north-striking Rio Grande rift, and are inferred to record replacement of lithosphere by asthenosphere preferentially along Archean–Proterozoic, Mojave–Yavapai, Yavapai–Mazatzal, and 1.1-Ga lithospheric anisotropies. Highest topography coincides with areas of low-velocity mantle, suggesting an importance of mantle buoyancy in the isostatic balance. Changes in topographic character across ancient crustal boundaries suggests a continued influence of crustal structures in differential uplift and denudation.

Inheritance of the Proterozoic northeast grain involves two basic factors: (1) "volumetric" inheritance, in which density and fertility of lithospheric blocks of differing compositions influence isostatic and magmatic response to tectonism; and (2) "interface" inheritance, in which mechanical boundaries are zones of weakness and mass transport. "Volumetric" inheritance is suggested by the distinctive isotopic signatures of different provinces and by the observation that Archean lithosphere has been consistently less fertile for magmas than Proterozoic lithosphere, due to thicker, colder mantle, and compositional differences. We infer that distinct mantle lithospheres have been attached to their respective crustal provinces (at scales of 100 km) since accretion. "Interface" inheritance controls include mechanical reactivation of northeast-striking province boundaries and shear zones as magma conduits, zones of renewed shearing, and zones accommodating differential uplift.

KEY WORDS: Rocky Mountains, lithosphere, inheritance, Proterozoic, accretion.

INTRODUCTION

The purpose of this paper is to summarize the evolution of continental lithosphere in the interior western United States, with emphasis on the Rocky Mountains. Our goal is to examine how continental lithosphere was formed, stabilized, and modified by later intracratonic tectonic events. The western United States is an important place for such lithospheric studies, because it contains a time and space variation in tectonism of the craton. Parts of the continental lithosphere in this region were cratonic ("stable continent") since the Archean (Wyoming province), other parts became cratonic in the Proterozoic (Southern Rocky Mountains–Colorado Plateau region), and other parts were dramatically modified by plate-margin tectonic events since late Precambrian time (western Cordillera). Thus, the Rocky Mountain region contains two fundamentally different "assembly domains," Archean and Proterozoic, separated by the northeast-striking Cheyenne belt. Furthermore, we identify three "disassembly domains," defined along diffuse north to northwest-striking boundaries or transitions (see cover and Lerner-Lam et al., this issue). First, in the stable craton (Great Plains east of Kansas), the North American continent has a thick, cold mantle keel (tectosphere) that was formed during Archean and Proterozoic accretion events. Second, in the Rocky Mountain region, the cratonic lithosphere is currently being modified by the cumulative effects of Laramide–Tertiary events. And third, in the western Cordillera (west of the Cordilleran hingeline), the cratonic lithosphere was thinned and weakened twice—once during late Precambrian rifting and again during Mesozoic and Cenozoic tectonism.

This paper summarizes the nature of Proterozoic accretionary provinces and boundaries in the Rocky Mountain region, and then discusses how the early continental grain influenced successive tectonic and magmatic events. The geologic record preserved in the crust is incomplete and is only a distant recorder of the evolution of lithospheric mantle through time. Nevertheless, by summarizing past crustal history and inferred mantle interactions, we hope to better understand what processes create and maintain continental stability and what processes drive mantle reorganization. We address these questions by examining the assembly and post-assembly history of the 1.8–1.6-Ga lithosphere.

ASSEMBLY OF PROTEROZOIC LITHOSPHERE WITH NORTHEAST GRAIN

Figure 1 shows our present interpretation of crustal provinces, defined as major compositional–geochronologic terranes. These include the: (1) Archean Wyoming province, with protoliths and deformation between 2.5–3.5 Ga; (2) Mojave province, with appreciable pre–1.8-Ga crustal material incorporated into a 1.75-Ga arc; (3) Yavapai province, a 1.76–1.72-Ga juvenile arc terrane; and (4) Mazatzal province, 1.7–1.6-Ga supracrustal rocks on unknown basement (Karlstrom and Bowring, 1988, 1993).

Boundaries between provinces are northeast-striking and are of several different types. The Cheyenne belt is a discrete shear zone (suture) between Archean and Proterozoic crusts (Karlstrom and Houston, 1984; Chamberlain, this issue). The boundary between the Mojave and Yavapai provinces is a 100-km-wide change in Pb isotopes that reflects tectonic and geochemical mixing of rocks of adjacent provinces (Wooden and DeWitt, 1991; Hawkins et al., 1996). The Gneiss Canyon and Crystal shear zones (Fig. 1) help delimit the isotopic transition, and these are thrust-sense shear zones that separate blocks with different P-T-t-D histories (Ilg et al., 1996). The Yavapai–Mazatzal boundary is a wide zone, defined at its northern edge by the northern extent of 1.65-Ga deformation, and at its southern edge by the southernmost extent of Yavapai (pre–1.7-Ga) crust. This zone also contains large exposures of 1.7-Ga alkali rhyolites and associated mature quartzites that are interpreted to be fluvial and shallow marine deposits that formed on the southern edge of newly stabilized (at 1.7 Ga) Yavapai

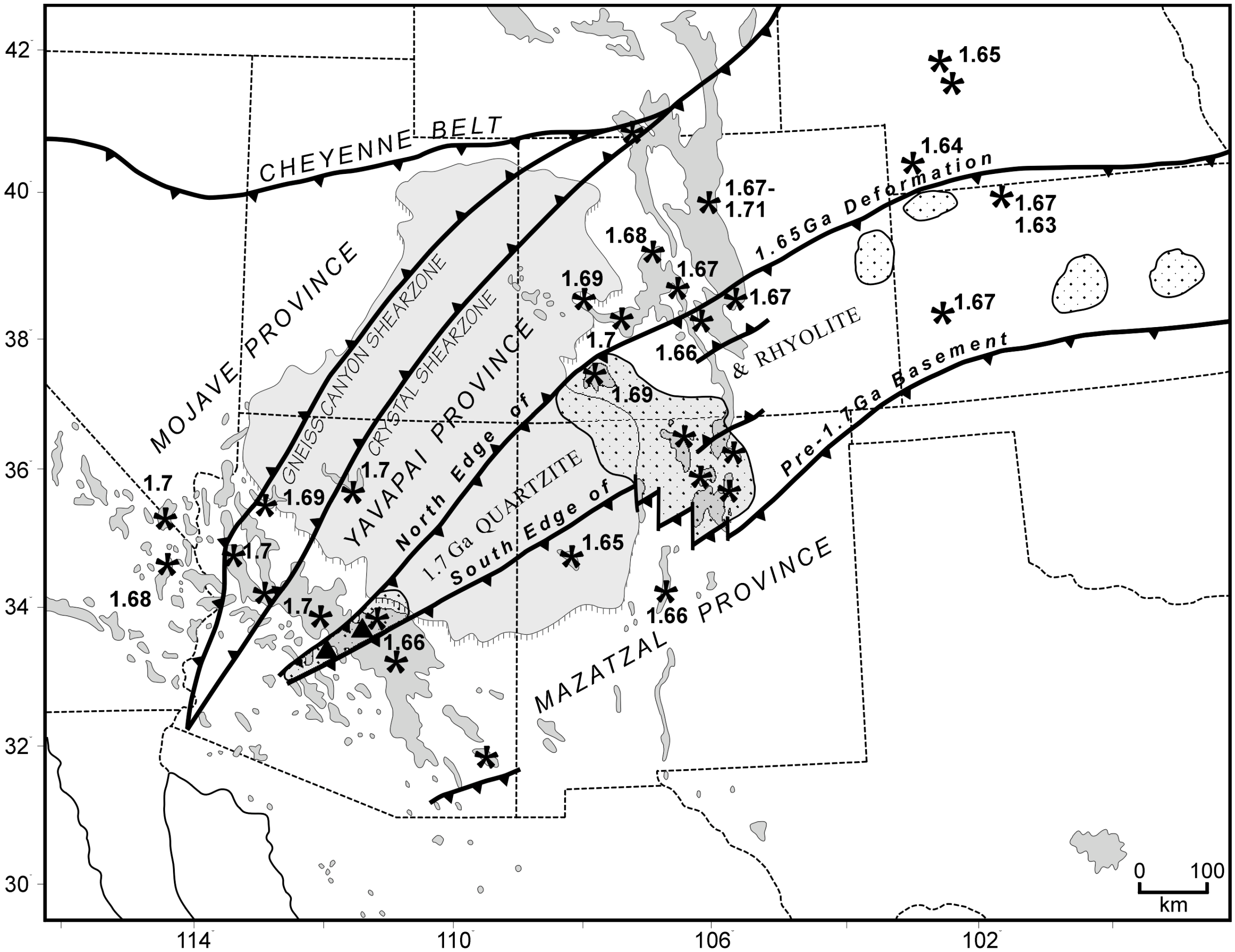

Figure 1. 1.8–1.65-Ga contractional amalgamation of lithosphere in the southwestern United States produced major northeast-striking tectonic boundaries. Cheyenne belt = Archean–Proterozoic suture; Gneiss Canyon to Crystal shear zones = distributed boundary between Mojave and Yavapai provinces; Yavapai–Mazatzal transition is marked at its northern edge by a northern limit of 1.65-Ga deformation; at its southern edge by the south limit of pre–1.7-Ga Yavapai province crust. Dot pattern shows areas of 1.7-Ga mature quartzite deposition; triangles are areas of 1.7-Ga rhyolitic calderas; stars show locations and dates of late synorogenic granitoids. Teeth indicate vergence(s) of contractional deformation. Precambrian rock outcrops are delineated in dark gray, and the Colorado Plateau is shown in light gray. In the following time slice maps, these features are merely outlined for reference purposes.

province crust. In Arizona, the boundary zone is delimited by the Moore Gulch and Slate Creek shear zones, which seem to extend northeast along the Holbrook and Jemez geophysical lineaments (Karlstrom and Bowring, 1993). The northern boundary also coincides with a marked change in crustal xenoliths in the Four Corners diatremes (Selverstone et al., *in press*) and with changes in isotopic character and timing of deformation of rocks in southern Colorado (Shaw and Karlstrom, this issue). The Jemez lineament, now marked by alignment of Tertiary volcanic centers, coincides with the southernmost extent of Yavapai basement and a change in Pb isotopic composition of the crust (Wooden and DeWitt, 1991).

The shear zones that mark province boundaries had multiple movement histories involving suturing, northwest shortening (Bergh and Karlstrom, 1992), post-assembly reactivation (Nyman et al., 1994; Tweto and Sims, 1963), and differential uplift (Bowring and Karlstrom, 1990). The Archean–Proterozoic suture is discrete because of a pronounced rheological difference between Archean and Proterozoic lithospheres. In contrast, sutures within the accreted Proterozoic orogen are not well defined, and they may be widely distributed boundaries because of similar rheology of adjacent blocks and the complex geometry of middle-crustal deformation and later reactivation (Karlstrom and Williams, *in press*). For all of these boundaries, planned geophysical studies are needed to test whether deeper expressions of sutures may be offset from exposed boundaries.

Assembly of lithospheric provinces took place by progressive shortening between 1.8 and 1.6 Ga. Initial convergence along the Cheyenne belt took place 1.78–1.75 Ga (Chamberlain, this issue). This deformation involved south-dipping subduction as shown by north-directed shear sense and the absence of arc plutons within the Wyoming province. 1.78- to 1.76-Ga rocks may represent a discrete arc fragment in northern Colorado (Foster et al., this issue). The 1.76–1.72-Ga Yavapai province arcs may have developed over a north-dipping subduction zone, as suggested by geochronology (Reed et al., 1987), geochemical studies of plutons in Arizona (DeWitt, 1989), and xenoliths at the Yavapai–Mazatzal boundary (Selverstone et al., *in press*). However, it is probable that the major provinces contain assembled smaller terranes and a complex kinematic history that culminated with 1.7–1.68-Ga shortening (Ilg et al., 1996). The 1.7–1.65-Ga supracrustal rocks of the Mazatzal province were deposited on the south margin of the newly stabilized Yavapai province, then deformed during continued contraction (north-verging) at about 1.65 Ga. Late orogenic plutons (1.7–1.65 Ga) continued to intrude older Proterozoic crust as far north as the Archean suture (Fig. 1), suggesting continued mantle and lower-crustal melting during progressive contraction. Deformation and magmatism ended by 1.65–1.6 Ga across the entire Proterozoic accreted terranes, indicating stabilization of a new 1000 km-wide zone of continental lithosphere by this time. Cessation of deformation and magmatism may indicate that this part of the continent had become distant from a plate margin and/or had developed a thick and strong mantle lithosphere.

The role of the mantle during assembly of lithosphere remains poorly constrained by geologic observations. By analogy to arc–continent collision going on between Australia and Indonesia, we speculate that convergent assembly in the southwestern United States involved amalgamation of a still unresolved mix of detached crustal flakes and more deeply rooted fragments of arc lithosphere. For blocks with attached mantle lithospheres, the observed penetrative deformation of the middle crust implies that the (usually stronger) upper mantle was partially decoupled from crustal columns, or was itself weak enough to deform under the applied forces during convergence (Karlstrom and Williams, *in press*). By the end of the contractional tectonism at 1.65 Ga, we infer that relatively thin Proterozoic arc terranes had been thickened into "normal" thickness lithosphere, not a system of high mountains. Evidence for this is the isostatic stability that seems to be indicated by slow cooling and lack of uplift of rocks from 1.65–1.45 Ga (Bowring and Karlstrom, 1990; Marcoline et al., this issue).

Isotopic data from various provinces in southwestern North American lithosphere from Wyoming to Mexico suggest that compositionally distinct lithospheres have been attached to their respective crustal blocks (at scales of 100 km) since accretion. This is shown by a regional correlation between crystallization age of crust, Nd and Pb model ages for time of crust derivation (Nelson and DePaolo, 1985; Bennett and DePaolo, 1987; Wooden and DeWitt, 1991), and isotopic character of younger magmatic rocks (Farmer and DePaolo, 1984; Livacarri and Perry, 1993) for each of the Precambrian provinces. This also implies that the upper mantle beneath the Southwest is Paleoproterozoic in age and heterogeneous in composition.

PROTEROZOIC BOUNDARIES AS PARTITIONS OF 1.4-Ga TECTONISM

Mesoproterozoic magmatism (mainly 1.45–1.35 Ga) occurred 200 m.y. after the assembly and marks the first major tectonism within the Proterozoic juvenile lithosphere. The event was regional in scale and involved mantle and crustal melting (Anderson, 1989). Magmatism was apparently concentrated and guided by older northeast-striking boundaries. Figure 2 shows the distribution of plutons (both exposed and encountered in drill holes), areas and grades of 1.4-Ga metamorphism, and kinematics of deformation associated with pluton aureoles. The Abilene gravity low has been interpreted to represent granitoids of possible 1.4-Ga age that occupy an area equivalent to the Sierra Nevada batholith (Adams and Keller, 1994). The position of a possible transpressive boundary (Nyman et al., 1994), shown in Figure 2, is conjectural, because 1.1-Ga Grenville tectonism later overprinted the south edge of the North American continent.

The causes of 1.4-Ga tectonism are not well understood, but the patterns are striking. 1.45–1.35-Ga plutons are found from Mexico to Wyoming, and from southern California well into the mid-continent. Chemically similar but progressively older (to

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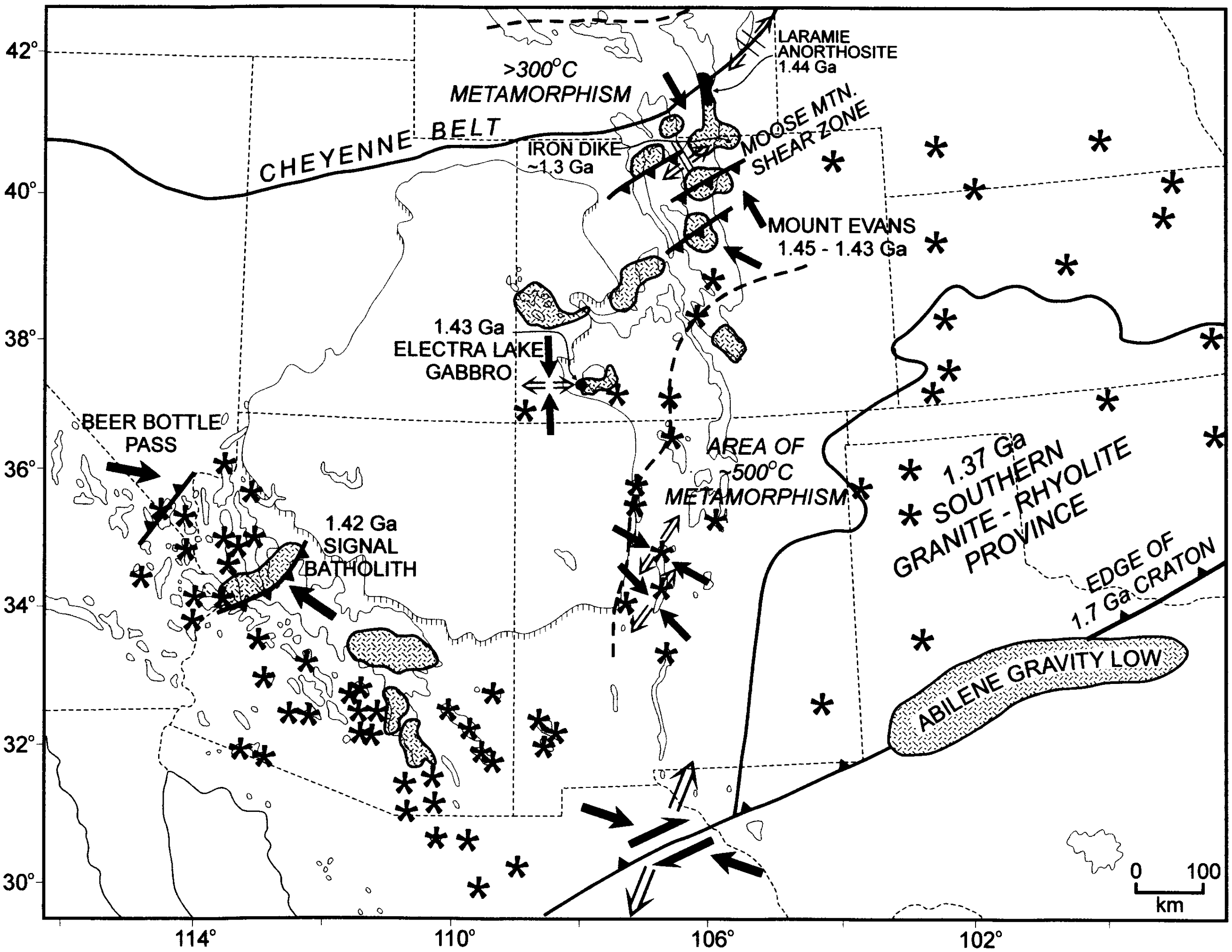

Figure 2. 1.4-Ga granitoids (stars and patterned areas) and (rarer) mafic rocks (black) penetrated older crust within the Proterozoic orogenic belt, but did not affect Archean lithosphere. Mafic plutons are found, and granitoids are most voluminous, along northeast-striking crustal boundaries. The entire region underwent 1.4-Ga regional metamorphism, with temperatures exceeding 500 °C in New Mexico, and 300 °C throughout the region. The southern granite–rhyolite province and Abilene gravity low may mark a 1.4-Ga continental volcanic arc. Kinematic studies of individual pluton aureoles (arrows) show northwest contraction and northeast extension over a wide region, implying far-field intracratonic transpressional stresses in southern Laurentia.

>1.5 Ga) plutons extend across Laurentia and Baltica (Windley, 1993). No 1.4-Ga granitoid plutons are present within the Archean Wyoming province, but the presence of 1.4-Ga mafic dikes suggests that the Archean lithosphere also was heated. However, it was less fertile, presumably because it was thicker and colder than the newly accreted Proterozoic juvenile crust. Within the Proterozoic belts, isolated plutons perforate everywhere, but larger bodies seem to be concentrated along northeast-striking province boundaries and shear zones such as the Cheyenne belt, Colorado shear zones, and Bagdad and Globe belts of Arizona (Nyman and Karlstrom, 1997; Hodgins, 1997).

Most of the 1.4-Ga granitoids fall in the range 1.45–1.35 Ga, but there is no known time–space progression that might indicate a flattening subduction zone or plume path. Instead, many plutons throughout the Rocky Mountains and Arizona fall into a 20 m.y. time range of 1.44–1.42 Ga. Younger plutons (1.38–1.35 Ga) are concentrated in the southern granite–rhyolite province (Fig. 2), but they also intruded some of the same areas as the 1.43-Ga plutons (in New Mexico and southern Colorado, along the Mojave–Yavapai boundary in Arizona, and in the Saint Frances Mountains of the mid-continent). More dates are needed to document whether the magmatism was a continuum or in pulses. Existing data show an apparent bimodality of U-Pb dates (1.43 and 1.37 Ga), suggesting pulses of magmatism, perhaps by underplating due to asthenospheric upwelling. However, the long duration (1.5–1.3 Ga) of the thermal event, and areas in which there is high-grade metamorphism without exposed plutons, might favor models that invoke a progressive build-up of radiogenic heat in the crust following accretion.

These granitoids have been termed "A-type" based on distinctive petrochemical characteristics. They are generally highly potassic, iron enriched, anhydrous, reduced, and high in U, Th, and K. Isotopic studies (Bennett and DePaolo, 1987; Farmer and DePaolo, 1984) suggest they were derived in part from melting of Early Proterozoic, 2.0–1.7-Ga crust (Anderson and Morrison, 1992), although probably there was an important mantle component (Nelson and DePaolo, 1985; Frost and Frost, 1997). The most iron enriched and reduced intrusions have chemical characteristics compatible with a derivation from partial melting of a mantle-derived tholeiitic basalt (Frost and Frost, 1997). However, the petrochemical characteristics of the granitoids vary on a regional scale (e.g., from metaluminous in the Mojave to peraluminous in southeast Arizona; Anderson and Bender, 1989) as well as on more local scale, indicating partial melting of a heterogeneous lower crust and heterogeneous mixing of crustal and mantle-derived components.

Mafic rocks probably were voluminous at depth, as shown by common dioritic enclaves that are mingled with granites (Frost and Frost, 1997). However, mafic plutons were only able to intrude to middle-crustal depths along province boundaries, especially in the Laramie anorthosite complex along the Cheyenne belt and Electra Lake gabbro along the Yavapai–Mazatzal northern boundary (Gonzales et al., 1994). Studies of enclaves, mafic plutons, and dikes exposed in several areas are needed to reconstruct the nature of the mantle-derived basaltic magmas. Enclaves are ferrodioritic and tholeiitic in composition and are mingled with granitic magmas and thus represent hybrid compositions. Dikes in Colorado and Wyoming are basaltic; dikes in California indicate a highly enriched mantle source. These rocks suggest that the 1.4-Ga magmatic event involved removal of basalt from the mantle, its emplacement into the lower crust, and consequent lower-crustal melting to form granitic magmas. It is less clear if the mafic rocks were from lithospheric or asthenospheric sources, and what tectonism may have driven this mantle-melting event.

The 1.4-Ga event also has been termed "anorogenic" because of a relative absence of pervasive deformation and metamorphism associated with pluton emplacement. However, numerous recent studies show important 1.4-Ga metamorphism, both in pluton aureoles and in areas with no 1.4-Ga plutons. Data from aureoles and plutons themselves indicate that 1.4-Ga plutons throughout the Southwest were emplaced at pressures of 2–4 kbar (~10 km). This indicates that middle-crustal rocks had not been appreciably unroofed since these rocks were stabilized at average depths of 10 km some 200 m.y. earlier (Williams and Karlstrom, 1996). Regional metamorphism was hotter over the entire region than would be expected at these shallow depths. 1.4–1.3-Ga $^{40}Ar/^{39}Ar$ hornblende dates indicate that temperatures reached $>500\,^{\circ}C$ in most of New Mexico (Fig. 2; Karlstrom et al., 1997), and metamorphic studies linked to U-Pb dating of metamorphic minerals indicate that several areas reached temperatures $>600\,^{\circ}C$ in areas with no exposed 1.4-Ga plutons (Lanzirotti and Hansen, 1997; Pedrick et al., *in press*; Read et al., this issue; Williams et al., this issue). $^{40}Ar/^{39}Ar$ and K-Ar data and metamorphic work also indicate that much of Arizona (Karlstrom and Bowring, 1993; Nyman and Karlstrom, 1997) and Colorado (Shaw et al., *in press*) reached temperatures of 300–550 °C in order to reset Ar in muscovite at 1.4 Ga, and reset or disturb Ar in hornblende (Fig. 2). We interpret the widespread metamorphism combined with the widespread perforating plutons to indicate that the heating event was driven by mantle melting and consequent mafic intrusions into the lower crust. Lower-crustal partial melting then caused major redistribution of heat and material by rise of magma.

The tectonic setting for this thermal event remains poorly understood. Numerous workers have proposed an extensional setting to allow asthenosphere to replace thinned lithosphere (Emslie, 1978; Frost and Frost, 1997). However, studies of the kinematics associated with emplacement of 1.4-Ga plutons in widely separated areas suggest that the middle crust was undergoing a strain field involving generally northwest contraction (thrusting, folding, and formation of crenulation cleavages) and northeast extension (Fig. 2). Such a strain field implies vertical intermediate stress (transpressive stresses), not vertical maximum compressive stress (lithospheric extension). This type of strain field can allow emplacement of plutons in extensional domains, and it is compatible with emplacement of plutons along older, steeply dipping shear zones that acted as conduits for magma ascent. Movement along older discontinuities accompanied by thermal softening of wall rocks by magmas and fluids can explain the association of 1.4-Ga plutons and older shear zones and the thrust reactivation observed in many regions (Fig. 2). Large regions of 1.4-Ga penetrative deformation may be present in areas that experienced the highest-grade metamorphism in New Mexico. We observe reactivation (new movements on older fabric; Read et al., this issue), but the relative importance of 1.7- and 1.4-Ga deformations in creating the observed polyphase fabrics remains controversial (Williams et al., this issue).

Our preferred model is that the 1.4-Ga event records underplating of mantle-derived basaltic magma and resulting crustal granitoid magmatism, metamorphism, and deformation in a wide transpressive intracratonic zone. The 1.4-Ga event apparently was influenced by the geometry and compositional heterogeneity of the accreted lithosphere. This event may have initiated regional surface uplift and (eventual) erosional denudation across the Southwest. However, thermochronologic data suggest continued slow cooling and lithospheric stability following 1.4-Ga plutonism (Karlstrom et al., 1997; Marcoline et al., this issue). Erosional exhumation of 1.4-Ga plutons from beneath 10 km of crust possibly began in response to isostatic imbalance created by underplating at 1.4 Ga. Differential uplift and erosion to remove imbalance, however, persisted well beyond 1.1 Ga, as shown by Ar data and the sedimentary record (see below).

ESTABLISHMENT OF NORTH–SOUTH GRAIN BY INCIPIENT RIFTING EVENTS 1.1–0.5 GA

There were also intracratonic events when the northeast crustal grain did not as markedly influence tectonism. North American lithosphere underwent a major period of incipient rifting and accompanying mafic magmatism about 1.1 Ga. Tectonism at ~1.1 Ga involved tholeiitic basaltic magmatism and east–west extension, temporally coincident with 1116–1070-Ma granitic magmatism (Walker, 1992), but near the end of Grenville contraction (Fig. 3). The mid-continent rift is the best known locus of 1.1-Ga basaltic magmatism and rifting; this resulted in massive outpourings of basalt, continental rifting, and rift formation, but did not lead to continental separation.

We propose that related zones of rifting formed along the Central Basin Platform–Rocky Mountain trend, Butte–Canyon Creek fault systems, and perhaps Death Valley–Arizona Transition Zone trend (Fig. 3). The Central Basin Platform is underlain by a 3–10 km-thick layered mafic to ultramafic intrusion of 1.16–1.07 Ma (Adams and Miller, 1995). This intrusion trends toward, and may be related to a major north–south trend that subsequently became the Rocky Mountain trend. Hints that the Rocky Mountain trend may have formed at 1.1 Ga are as follows. First, there is transition across a major north–south structure (Fig. 3) between 1.4-Ga volcanic rocks of the southern granite–rhyolite province of the west Texas subsurface and slowly cooled, 10 km-deep 1.4-Ga plutons in the New Mexico uplifts. This suggests that differential uplift (west-side-up) took place after 1.4 Ga, possibly at 1.1–0.7 Ga based on the range of dates for Ar in muscovite and K-feldspar (Heizler et al., 1997; Karlstrom et al., 1997). Second, the 1.1-Ga Pikes Peak pluton lies along the intersection of this trend and the northern Yavapai–Mazatzal boundary. And third, this trend, like the mid-continent and Butte–Canyon Creek fault structures in scale, is at a high angle to the Grenville margin. The Butte–Canyon Creek fault system in Arizona also records incipient rifting during (Shride, 1967) and after (Elston, 1989) 1.1-Ga magmatism.

The Apache Group (in the south) developed mainly before 1.1 Ga; rocks of the Grand Canyon Supergroup were deposited before, during, and well after 1.1 Ga. The uppermost units of this section, perhaps as young as 700–800 Ma, were deposited synchronously with movement on the Butte fault (Elston, 1979). Diabase sills and dikes are present throughout the Arizona Transition zone. They are most voluminous along the Mojave–Yavapai and Yavapai–Mazatzal boundaries, and are spatially associated with 1.4-Ga granites, suggesting that basaltic magmas ascended along the same discontinuities used by 1.4-Ga granitoids. Predominant orientations are horizontal, or northwest-striking subvertical dikes, indicating a strain field involving northwest contraction and northeast extension during the Grenville collision (Howard, 1991).

Granitoids of 1.1-Ga age (at Pikes Peak, in northwest Texas, and in northern Mexico) share some chemical similarities to the 1.4-Ga "anorogenic" granites (Frost and Frost; 1997; Smith et al., 1997) and also to the 1.1-Ga diabases (Hammond, 1986). Both suites are heterogeneous at subregional scale, and apparently they involved both mantle-derived basalt and variable crustal contamination. However, the proportion of mafic to felsic intrusions that reached presently exposed crustal levels at 1.1 Ga

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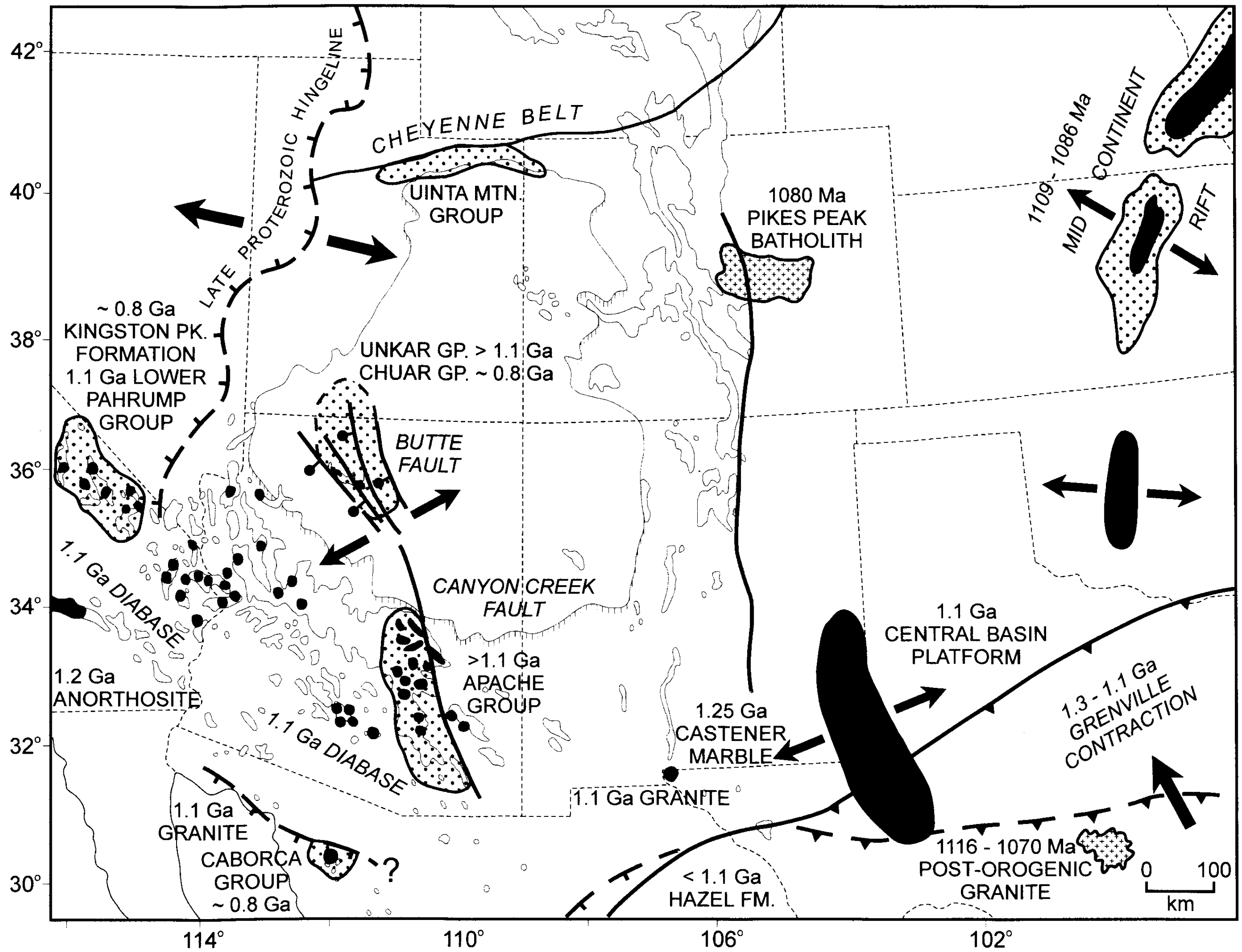

Figure 3. At 1.1 Ga, North America was simultaneously squeezed (Grenville) and rifted (mid-continent rift). This event may have created the Rocky Mountain north–south trend, the Butte–Canyon Creek fault trend and related Unkar and Apache group sedimentary basins (dot pattern in Arizona), and the Transition Zone–Pahrump trend. These major normal faults ignored earlier Proterozoic boundaries. 1.1-Ga granites (cross pattern) were emplaced at Pikes Peak, Caborca, west Texas, and the Llano uplift of central Texas. 1.1-Ga mafic rocks (black) were emplaced along the mid-continent rift, Central Basin Platform, and as diabase sheets (dots) in the Arizona Transition Zone. Successful rifting of the western United States took place in latest Precambrian time, and established the Cordilleran miogeocline and its associated cratonic hingeline.

(mostly basalts) are reversed from the 1.4-Ga event (mostly granites). This may reflect different strain fields (1.4-Ga northwest transpression versus 1.1-Ga east–west extension) and cooler and stronger lithosphere at 1.1 Ga that deformed by lithosphere-penetrating normal faults. To our knowledge, none of the 1.1-Ga failed rift zones had Early Proterozoic ancestry, and we infer that 1.1-Ga extensional stresses were orthogonal to, and hence not influenced by, older northeast fabric. Similar to the 1.4-Ga event, magmatism and extension at 1.1 Ga had little effect on the Archean lithosphere.

The Pikes Peak batholith was emplaced at 1–2 kbar (Barker et al., 1975); diabase sills were intruded at shallow crustal levels into thin sedimentary sections in the Apache, Unkar, and Lower Pahrump groups. We infer that lithosphere had cooled since 1.4 Ga, because of much more limited distribution of both mafic and granitoid magmatism and more restricted character of deformation (into narrow and shallow rift basins). Sedimentation in the Apache and Unkar basins of Arizona indicates that middle-crustal rocks had been unroofed to the surface before 1.1 Ga in some areas, but post–1.1-Ga mica Ar ages suggest that other blocks remained at temperatures >300 °C (Hodges et al., 1994; Karlstrom et al., 1997). Thus, incipient 1.1-Ga rifting created lithosphere-penetrating faults that caused important differential uplift between blocks.

From 1.1 to 0.6 Ga, western North America underwent episodic rifting events that culminated in separation of North America from western (Rodinian) continents and formation of the Cordilleran miogeocline. Like the previous period of 1.4–1.1 Ga, the time period from 1.1–0.6 Ga is generally not recorded in the Southwest, and is expressed as part of the Great Unconformity (Powell, 1876). However, sedimentary sequences occupy this hiatus in a few places, and cooling ages of Proterozoic basement attest to a period of differential uplift of blocks as the stable craton continued to be slowly uplifted and denuded (Bowring and Karlstrom, 1990). The regional extent of the Great Unconformity in the Rocky Mountain region documents a prolonged plateau uplift of the western United States. Younger sedimentation and continued extension in the Neoproterozoic are recorded in rocks of the Chuar Group of the Grand Canyon, Uinta Group of northern Utah (along the Cheyenne belt), Death Valley region, and Caborca region of northern Mexico. We infer that Neoproterozoic sedimentation represents early stages of the Cordilleran miogeocline, which was developing in pulses during Windermere (ca. 700 Ma) time (Ross, 1991), then became a passive margin by Cambrian time. Rifting modified (thinned) the lithosphere as far east as central Utah. This zone became the sedimentary hingeline of the miogeocline, and later controlled the geometry of the Sevier fold-and-thrust belt and the area of Proterozoic mantle lithosphere that was most susceptible to Tertiary extension.

PALEOZOIC STABILITY

Cambrian sediments transgressed west to east during thermal subsidence of the Cordilleran miogeocline. Lower Cambrian isopachs parallel the hingeline (Fig. 4). Upper Cambrian and subsequent Lower Paleozoic sedimentation was influenced by a northeast-trending, persistent highland called the "Transcontinental arch" that parallels the northern part of the Yavapai–Mazatzal boundary zone. The Cambrian zero isopach is also subparallel to the Yavapai–Mazatzal boundary zone (Fig. 4), suggesting that there were subtle differences in isostatic level of adjoining regions across older northeast-striking boundaries both during and after sedimentation. Apparently, the provinces responded differently to the evolving physical state of the deep lithosphere caused by differing density contrasts across the Moho or a pressure-driven eclogitization within the depressed lithosphere.

Mississippian–Pennsylvanian sedimentation was controlled by a series of north- to northwest-trending uplifts of the Ancestral Rocky Mountains. These uplifts and basins seem to ignore northeast-striking Early Proterozoic structure, but they do end at the Archean–Proterozoic boundary, suggesting that the Archean versus Proterozoic lithospheric blocks remained mechanically distinct. Ancestral Rockies structures apparently reactivated 1.1-Ga structures in the Front Range and Central Basin platform. These uplifts reflect inboard effects of either or both of the Ouachita collision to the southeast (Kluth and Coney, 1981) or an active plate boundary to the southwest (Ye et al., 1996). A lack of magmatism may suggest that this was dominantly a crustal deformation event and may not have caused major mantle modification within the craton. Likewise, late Paleozoic orogenic events on the west margin of the continent involved subduction systems that dipped west such that cratonic mantle was little modified in the North American interior. The stability of the craton east of the hingeline in the Paleozoic and Mesozoic is documented by numerous marine regressions and transgressions that chiefly reflect global eustatic changes, not tectonism. The continental surface remained at near sea level until the late Cretaceous when the Laramide orogeny was initiated.

LARAMIDE TECTONISM

This activity (roughly 75–45 Ma) overlapped in time and space with the Sevier orogeny (90–60 Ma). In two-dimensional cross section, Sevier–Laramide contraction commonly is considered to be driven by stresses from shallow-dipping subduction of the Farallon plate. West of the hingeline, Sevier deformation involved a magmatic arc, thickening of a weak lithosphere (hinterland), and development of a foreland fold-and-thrust belt in the Cordilleran miogeocline. East of the hingeline, upper crustal "Laramide-style" deformation involved contraction and reactivation of crustal zones of weakness within the crystalline basement. Deformational styles vary according to regional crustal and lithospheric properties. In the Colorado Plateau, monoclines face east and west, toward the center of the Plateau. In Arizona, these resulted from inversion of 1.1-Ga extensional fault zones (e.g., Butte and Canyon Creek faults). In the Rocky Mountain area, Laramide short-

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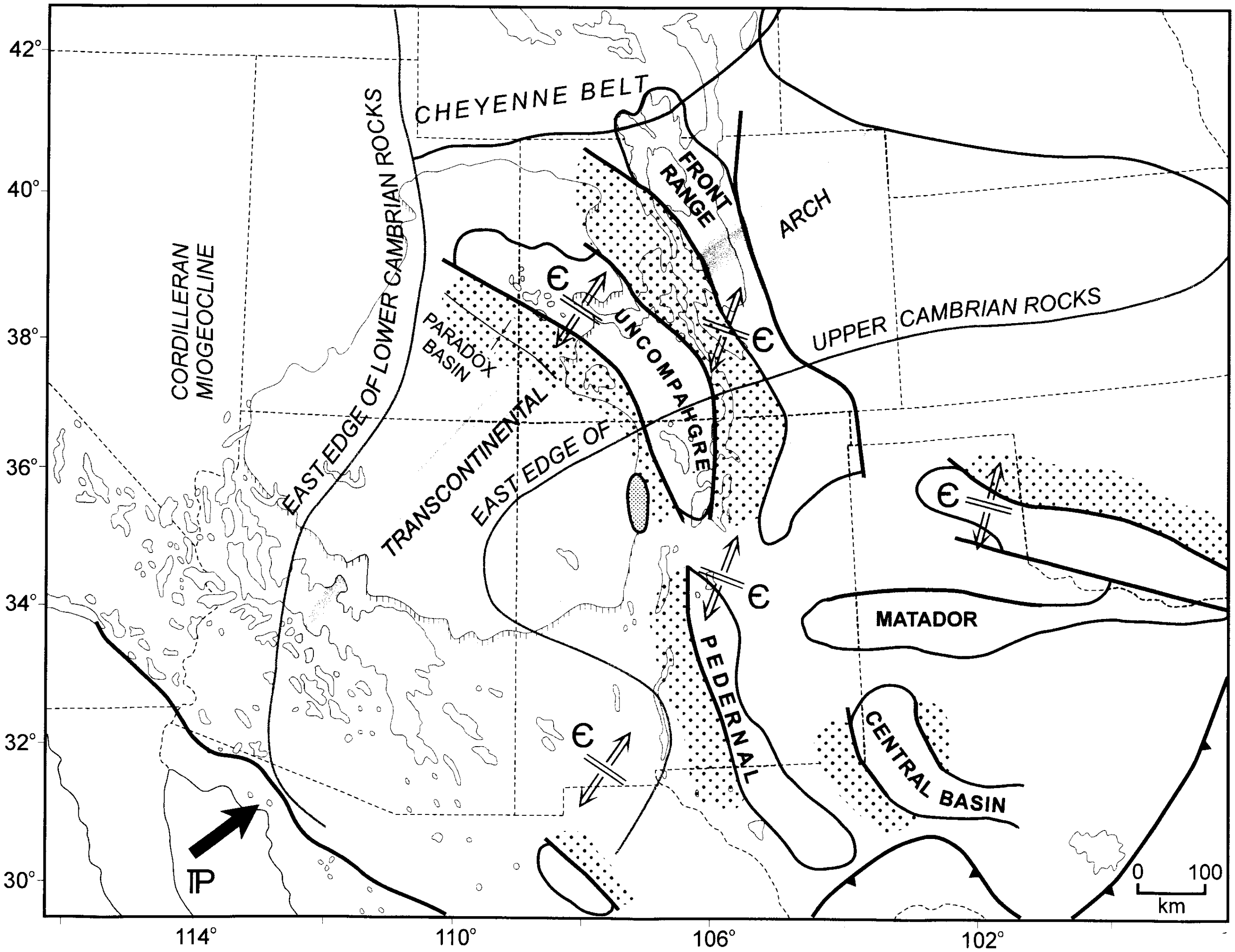

Figure 4. Late Precambrian rifting thinned the lithosphere as far east as central Utah along a north–south passive margin. Thermal subsidence of the margin reactivated northeast-trending structures, as shown by a positive region along the Transcontinental arch and southeast zero isopach of Upper Cambrian deposition. Cambrian dikes suggest northeast extension. In the middle Paleozoic, Ancestral Rockies uplifts (pale gray and labeled) and basins (dot pattern) involved contractional deformation that ignored Early Proterozoic boundaries, but reactivated 1.1-Ga boundaries.

ening reactivated a complex crustal pattern of northeast-striking shear zones, and north-striking faults (initially 1.1-Ga and Ancestral Rockies structures). Three-dimensional views of Laramide tectonism suggest transpression along the eastern side of a rigid Colorado Plateau block (Chapin and Cather, 1981) and "microplate," 10–100-km-scale movements of the Colorado Plateau relative to the adjacent Great Plains (Hamilton, 1981; Karlstrom and Daniel, 1993).

Laramide tectonism involved crustal thickening and elevation of the land surface above sea level. Present crustal thickness patterns may suggest that a pre-Laramide crustal thickness near 40 km (in unthickened Colorado Plateau) was thickened to 45–50 km in portions of Colorado and western Texas (Fig. 5; see Keller et al., this issue). Thickest crust crudely follows the eastern and northern margin of the Colorado Plateau block, possibly compatible with the microplate model. However, the upper crustal shortening ranges from <1 percent (Colorado Plateau; Huntoon, 1993) to about 10 percent (Wyoming; Stone, 1993), and was generally too small to accomplish the observed thickening. Thus, Laramide tectonism may also have included lower-crustal thickening (Bird, 1991). Details of the present crustal-thickness pattern reflect an unresolved combination of Proterozoic and Laramide effects. There is a weak suggestion of influence of northeast-striking boundaries (e.g., Jemez lineament), and thrusting at the east–west Uinta Mountains suggests a continued importance of mechanical weakness near the Archean–Proterozoic suture.

Unlike crustal shortening, Laramide magmatism was more strongly influenced by northeast-trending Early Proterozoic lithosphere composition and structure. The Yavapai–Mazatzal northern boundary marks a boundary in the Au/Ag composition of ore deposits, many associated with Laramide plutons, with higher Au/Ag ratios to the northwest (Fig. 5; Titley, 1987). This suggests different magma systems and/or block compositions. Also, the Colorado mineral belt (Fig. 5) is a zone of Eocene–Oligocene plutons and related ore deposits that follows northeast-striking Proterozoic shear zones in the Rockies (Tweto and Sims, 1963). There is no obvious age progression of plutons in this zone as might have been expected from an east-sweeping subducting slab. Instead, this seems to be a zone of weakness along which magmas developed and were emplaced during early stages of removal of the Farallon slab from the base of the lithosphere. The 35–25 Ma San Juan caldera systems at the southeast end of the mineral belt record voluminous erup-

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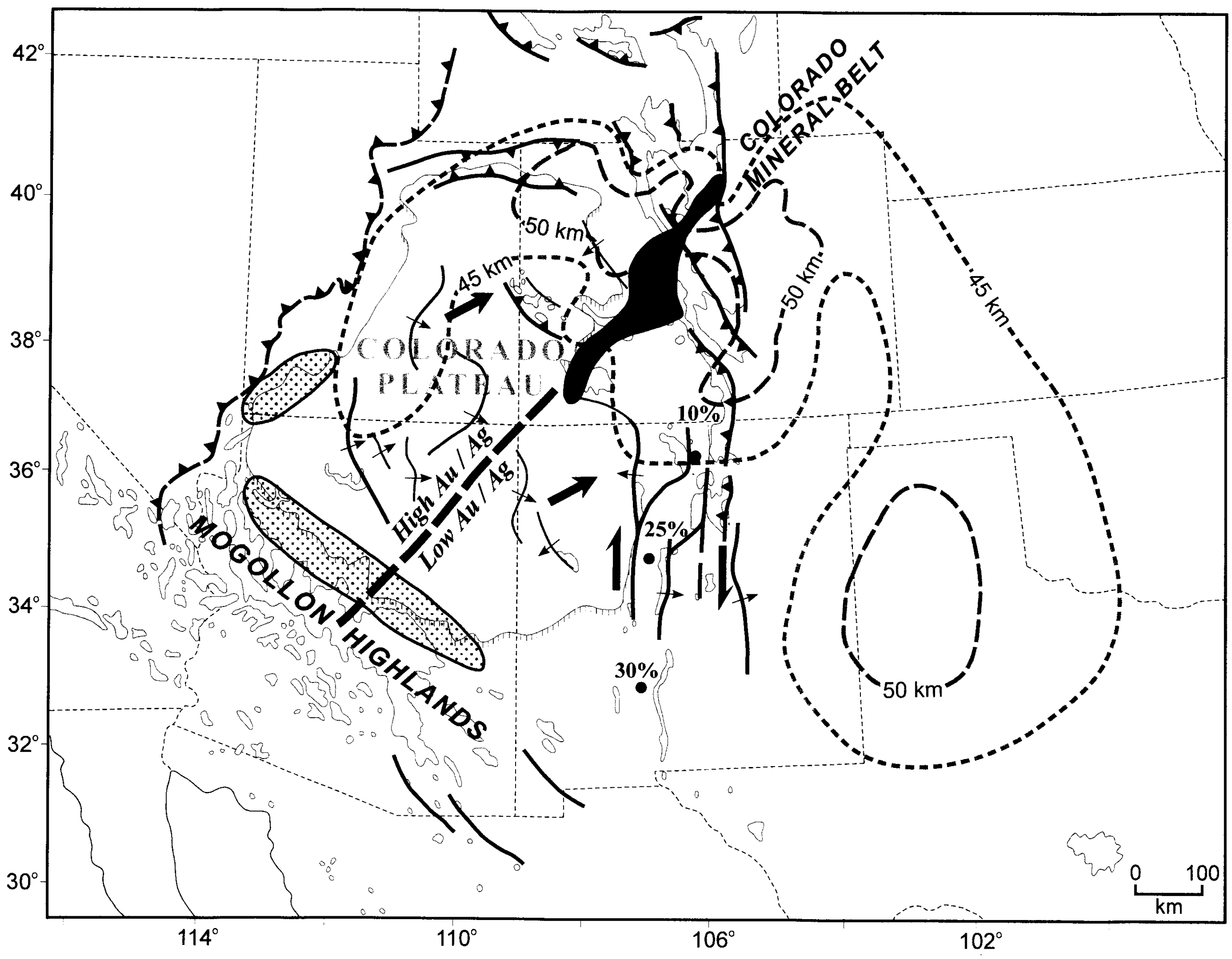

Figure 5. Laramide shortening of the craton may have produced the present-day 45–50-km-thick crustal welt (dotted lines). Thickest areas are in Proterozoic crust along the eastern and northern margins of the Colorado Plateau, especially if Miocene extension in the Rio Grande rift is restored by 10-30 percent. Monoclines and Rocky Mountain uplifts reflect upper-crustal deformation that ignored Early Proterozoic structures and reactivated 1.1-Ga and Ancestral Rockies structures. Mantle modification is expressed as different metallogenic provinces in Arizona which follow the Yavapai–Mazatzal boundary, and the Colorado mineral belt which follows northeast-striking shear zones. Dot pattern shows areas where sediments were deposited from southern and western highlands of the Sevier hinterland.

tions that were focused along the northern Yavapai–Mazatzal boundary, like the Pikes Peak granite, some billion years earlier. This suggests a mantle control on fertility, and magma accessibility through the lithosphere for both Laramide and Tertiary magmatism.

Response of the North American mantle lithosphere during the Laramide orogeny has been debated. Contrary to Bird (1988), however, isotope studies suggest at least parts of the cratonic mantle lithosphere remained attached to the crust (Livicarri and Perry, 1993). In much of the western United States, mantle lithosphere of North American affinity extends to depths of >100 km (as evidenced by isotopes, but also by the occurrence of Tertiary diatremes and lamprophyres in all central Rocky Mountain states). Tomographic images of the Colorado–New Mexico upper mantle (Hessler, 1996; Lerner-Lam et al., this issue) show velocity contrasts that suggest that lithosphere extends to depths of at least 180 km in many portions of this area.

A profound tectonic effect of the Sevier–Laramide orogeny was initiation of the broad topographic uplift that now occupies the entire western United States. Increases in crustal thickness are insufficient to account for this uplift, and hence it is clear that the Sevier–Laramide orogeny is responsible for increasing the buoyancy of the underlying mantle. Elevation in the Colorado Plateau region went from sea level in the late Cretaceous to perhaps 1–2 km before the Oligocene (Gregory and Chase, 1994; Pazzaglia and Kelley, this issue). These changes were in response to increasing buoyancy of the upper mantle and termination of dynamic subsidence that, prior to the Laramide, was associated with subduction of the Farallon slab (Mitrovica et al., 1989).

Eocene erosion of the Rockies (55–37 Ma) beveled high topography and created a high elevation (2 km) erosion surface that is continuous from the Rockies out onto the Great Plains in a few preserved remnants (Pazzaglia and Kelley, this issue). This "surface" provides further evidence that regional uplift took place in the Laramide (pre-Eocene) from Wyoming to northern New Mexico in a broad upland that was larger than the present Rocky Mountains. The Earth's surface was uplifted (relative to sea level) about 2 km, and about 4 km of rock were eroded to create the Eocene erosion surface. Rocks at the level of the Eocene erosion surface were uplifted about 6 km relative to sea level (Pazzaglia and Kelley, this issue). This broad uplift and its associated Laramide structures still control the landscape in Colorado and Wyoming, although it has been importantly modified in areas of Tertiary–Recent magmatism and deformation.

TERTIARY MODIFICATION OF THE LITHOSPHERE

The tectonic and magmatic behavior of the Rocky Mountain lithosphere during the Tertiary and the present density and seismic structure of the mantle (Fig. 6 and cover of this issue) offer clues on its physical state. We first consider the post-Laramide activity of this region, and then the present mantle structure, and evaluate the role of older crustal boundaries in ongoing tectonism.

Although sharing somewhat similar Laramide-to-Recent histories, the Rocky Mountains and Colorado Plateau have behaved and continue to behave quite differently from the region now occupied by the Basin and Range province. Outboard of the Rocky Mountains and Colorado Plateau, Phanerozoic events have reconstructed the continent such that the grain is roughly parallel to the Phanerozoic plate margin. The lithosphere is essentially Cenozoic in age, even though Precambrian rocks are caught up in it. Present mantle here is probably largely asthenosphere, and is compositionally and mechanically distinct from mantle under central North America. In the Rocky Mountains–Colorado Plateau region, the chemistry of mantle-derived basalts (Livicari and Perry, 1993) and the relatively high flexural strength (Lowry and Smith, 1994; 1995) lead us to infer that its lithospheric mantle (and structural grain) is largely inherited from the time of Proterozoic assembly.

Early Tertiary extension of the lithosphere was driven by gravitational collapse, during and following contraction (Coney and Harms, 1984; Hodges and Walker, 1992), possibly initiated by foundering of the Farallon plate, upwelling of asthenosphere, and resulting magmatic heating (Humphreys, 1995). Parts most affected include the areas now occupied by the Basin and Range province and Rio Grande rift. Regions of most intense extension in the Basin and Range province correlate with areas of greatest Mesozoic shortening, and with areas of previously intensely deformed mantle. For the regions lying west of the Cordilleran hingeline, contraction, magmatism, and extension were concentrated in the Cordilleran miogeocline, emphasizing the control exerted by late Precambrian thinning and modification of the lithosphere. The Rio Grande rift was localized along a zone of 1.1-Ga extension and Laramide strike-slip faulting. Tertiary extensional structures (normal faults and core com-

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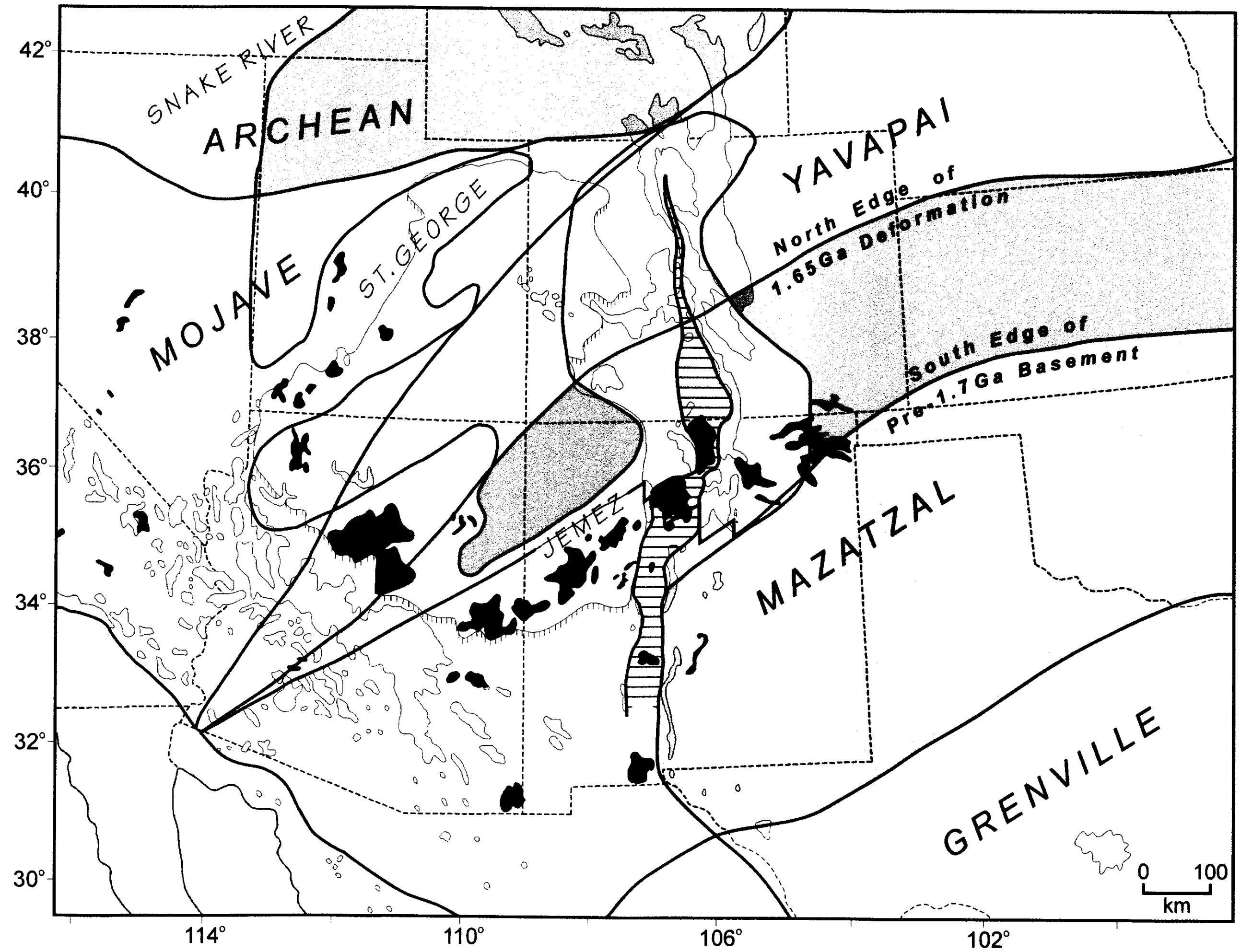

Figure 6. Present mantle structure shows three main zones. West of the Cordilleran hingeline, mantle is low velocity, hot, and Cenozoic in age. East of the Colorado–Kansas border, North American lithosphere is high velocity, cold, and Proterozoic in age. In the Rocky Mountain–Colorado plateau region, mantle is being restructured from below; fingers of hot mantle are penetrating older lithosphere using northeast- and north-striking lithospheric weaknesses. Young volcanism (black) records mantle-derived basalt in the Snake River Plain, Saint George, and Jemez lineaments. Hot mantle in the Rio Grande rift (line pattern) is reactivating the Rocky Mountain trend.

plexes) generally ignored the Early Proterozoic grain, because extensional stresses were unfavorably oriented to reactivate northeast-striking structures. However, transfer zones between blocks with different dip polarity commonly coincide with Proterozoic structures in both the Basin and Range province and Rio Grande rift.

The relative importance of "passive" extension (driven by excess potential energy resulting from Sevier–Laramide crustal thickening) and "active" rifting (driven by asthenospheric buoyancy and uplift) have been widely debated for both the Basin and Range province and Rio Grande rift. We argue that both mechanisms have contributed to the excess potential energy that drives extension. Extension generally occurred in directions away from potential energy maxima (i.e., tending to move mass away from high-standing areas). Deformation was guided by strength variations that were inherited from earlier events and that existed at a variety of scales.

Lerner-Lam et al. (this issue) show that the Colorado Rocky Mountains are underlain by low-velocity upper mantle, in contrast to the high-velocity mantle beneath the Great Plains and Colorado Plateau. The depression in velocity is suggestive of partial melt, and the contrasting structure extends to at least 160 km (Hessler, 1996). Beneath Kansas, lithosphere extends even more deeply and forms a deep (>300 km) "cratonic keel" imaged in continental- and global-scale seismic studies (Grand, 1994; Van der Lee and Nolet, 1997). The high-velocity mantle in provinces adjoining the Rocky Mountains appears to indicate that lithosphere is 160-km deep or more, for example, in the Colorado Plateau region.

Currently, the Rocky Mountains appear to be extending slowly, especially in the Rio Grande rift, and the entire region shows evidence for continued, slow uplift. As evidence for Tertiary rock uplift, there are numerous indications that there has been renewed denudation in the Rockies (Pazzaglia and Kelley, this issue). However, the extent of elevation increase is less clear. Our favored hypothesis is that the elevation drop that otherwise would result from crustal thinning due to post-Miocene denudation and local extension is approximately balanced (and locally exceeded) by contributions to elevation made by creation of mantle buoyancy. Our main evidence is the correlation between areas of highest topography, low-velocity mantle, and young volcanism (compare Figs. 6, 7, and cover). This is especially true in Colorado, where the high topography of the Rocky Mountains is underlain by low-velocity mantle (Hessler, 1996; Lerner-Lam et al., this issue). In contrast, crustal thickness in Colorado varies with no apparent correlation to the present Rocky Mountains. It is important to distinguish uplift (which relates to a change in buoyancy) and elevation (which relates to buoyancy). The relation between Colorado low-velocity and high-elevation areas is strong evidence for mantle buoyancy holding up the region, but we do not know when the mantle structure was created except that it was after the late Cretaceous.

Present topography also shows subtle differences in uplift history such that the present crust along the Rocky Mountain transect is recording differential uplift/denudation for different Proterozoic lithosphere blocks (Fig. 7; Pazzaglia and Kelley, this issue). This is presumably due to differences in mantle modification processes. Similar differential uplift along old block boundaries took place during tectonic magmatic events at 1.4 Ga (Shaw and Karlstrom, this issue) and during Laramide and Tertiary denudation (Pazzaglia and Kelley, this issue).

The Tertiary magmas in the Rocky Mountains and Colorado Plateau commonly are derived from Precambrian North American lithosphere at relatively great depth. Occurrence of alkali basalts, lamprophyres, and diatremes is widespread in the region, and melts typically are derived from depths where garnet is stable. These magmas ascend through the lithosphere with their primitive chemical signature essentially intact. More generally, magmatism appears to involve widespread partial melting of both lithosphere and asthenosphere mantles and metasomatism to the point that the distinction between lithosphere and asthenosphere becomes blurred. Such melting is thought to apply to the large volume of low-velocity upper mantle beneath the Rocky Mountains, where the high heat flow also suggests significant quantities of magmatic heat transport. This magmatic behavior also is consistent with the seismic results that show partial melt in the upper mantle.

Low-velocity upper mantle zones of seismic character similar to that imaged beneath the Basin and Range province are present as northeast-trending "fingers" that lie beneath the nearby volcanic zones, lending support to the inference that the volumes of low mantle velocity are partially molten. These nearby volcanic belts are the Snake River Plain (Yellowstone track), Saint George volcanic trend, and Jemez lineament. The low-velocity mantle fingers coincide with major Proterozoic crustal boundaries. The Snake River Plain trend is parallel to the northwestern edge of the Archean craton. The Saint George trend parallels the Mojave–Yavapai boundary. The Jemez trend parallels the southern edge of the Yavapai–Mazatzal boundary zone. In all cases, the fingers of low-velocity upper mantle may represent the mantle suture associated with these crustal sutures. Isotopic studies suggest that some remnants of lithosphere remain even in the most extended regions. They also suggest that the mantle source in parts of the Jemez and Saint George "fingers" evolved from "lithospheric" (isotopically enriched) to "asthenospheric" (isotopically depleted) within the last 4–6 m.y. This suggests either the removal of North America lithosphere beneath these regions or the complete scouring of fertile components in what remains of the original lithosphere.

Putting this in a more global context, the tectonically and magmatically active western United States is underlain by a regionally extensive, low-velocity mantle anomaly that is associated with the broad region around the East Pacific Rise. Although the origins of the anomaly are not understood, this anomalous region has been overridden by the North American continent. Slab removal following the Laramide orogeny must have unloaded the continent and placed this asthenosphere in contact with the base of the lithosphere affected by the Sevier–Laramide orogeny (a lithosphere that may well have received the fluids transported beneath the western United States by subduction). Ensuing magmatism segregated a basaltic component from the mantle,

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Figure 7. Topography in the western United States (from Simpson and Anders, 1992) records Cenozoic mantle modification. The overall high plateau in the western United States records buoyant mantle; highest topography correlates with hottest mantle, not thickest crust. Subtle differences in Rocky Mountain topography apparently correspond to Precambrian lithospheric blocks, suggesting that different columns are responding differently (magmatically and isostatically) to present mantle reorganization.

which thickened the crust, increased mantle buoyancy (Humphreys and Dueker, 1994), and contributed to regional uplift.

We infer, therefore, that western United States uplift began early with Laramide-driven crustal contraction and lithospheric hydration, but uplift has proceeded with slab unloading and the magmatic creation of buoyancy. The low upper-mantle velocities are thought to be the consequence of fluids (melt or vapor) invading the lithosphere from below, resulting in the creation of partial melt within mantle of North American affinity and movement of magma and heat toward the surface. The zones of penetration (Precambrian sutures and areas of Laramide shortening) are areas of preexisting weakness that also may be enriched in components fertile to melting. This process of magmatic generation of buoyancy is thought to be ongoing, and is driving continuing modest uplift of the whole western United States. Magmatism and uplift are thus progressing eastward beneath North America opportunistically by utilizing the Proterozoic crustal grain. The Archean lithosphere remains less susceptible to melting, as it has since 1.8 Ga.

SPECULATIONS ON PROCESSES OF LITHOSPHERE FORMATION AND MODIFICATION

Processes and history of crustal deformation and magmatism, and present lithosphere structure, are all becoming increasingly well understood for the western Cordillera. It is fruitful, therefore, to explore how the surface geologic record of sedimentation, magmatism, and deformation summarized above places constraints on the evolution of mantle lithosphere through time.

We observe that the Archean lithosphere was repeatedly less fertile for magmatism during mantle modification events at 1.8–1.6 Ga, 1.4 Ga, 1.1 Ga, and Laramide–Tertiary time. We infer that the Archean lithosphere was thicker, colder, and/or more restitic than juvenile Proterozoic mantle. These differences have persisted through a remarkable variety of intracratonic events. The Archean lithospheric keel, however, was thinned at the south edge of the Wyoming province during 2.0-Ga rifting, was essentially removed west of the Cordilleran hingeline by late Precambrian rifting, and currently is being thinned in the Rocky Mountain by attack from warm mantle at its base (see cover). The uplift of both Archean and Proterozoic rock during the Laramide orogeny indicates that the mantle beneath both regions has been modified by orogenic processes. Yet major differences between Archean and Proterozoic lithospheres are still evident today in the Rocky Mountain region based on early results from the Deep Probe experiment (see Snelson et al., this issue), the Rocky Mountain Front Broadband experiment (Lerner-Lam et al., this issue), as well as heat flow data (Decker et al., 1988) and topography. From the cumulative record, we conclude that Archean mantle is remarkably stable, but that it can be modified and even removed under the right conditions.

The present mantle shown with blue colors in central North America (cover) represents a cold, high-velocity keel under North America that extends about 150-200 km deep. Based on surface geology, crustal crystallization ages, and Nd model ages, it is evident that thick cratonic keel underlies both Archean and Proterozoic lithosphere. This keel is thickest (>300 km thick) under the Archean core of the continent (Grand, 1994; Van der Lee and Nolet, 1997), but the deep keel that moves with the North American plate is both Archean and Proterozoic in age. Thus, the mantle lithosphere is a composite feature with appreciable compositional and tectonic complexity. Like the overlying crust, it may have formed diachronously, through long periods of slow cooling and through numerous metasomatic and basalt-extraction events.

We view the degree of stabilization (and thickness) of mantle lithosphere as being related (crudely) to the cumulative record of magma-extraction events. The Archean part of the keel was relatively unaffected by Proterozoic events. Proterozoic mantle was progressively stabilized; it acquired most of its stability during its creation (1.8–1.6 Ga), but was further stabilized by extraction of basalt at 1.4 and 1.1 Ga.

Rifting at ca. 500–600 Ma and Laramide–Recent tectonism demonstrate that keels can be effectively removed and modified. Removal may have been mechanical during Laramide flat-slab subduction (possibly associated with hydration), but probably has been thermal since the Miocene. Apparently, processes that destabilize lithosphere can be plate-scale and as varied as the processes that form it. Of all the mantle modification events that have affected the western United States, successful rifting is most profound in reshaping continental grain. The Early Proterozoic rifting at the south edge of the Archean block may still be influencing lithospheric structure as the most profound boundary in the Rocky Mountain region. Likewise, late Precambrian rifting west of the Cordilleran hingeline restructured the continent between the rift margin and the hingeline. This structure controlled the form of

Paleozoic and Mesozoic tectonic activity including Sevier–Laramide subduction and the subsequent continental uplift and collapse.

We observe that the northeast grain, established during Proterozoic assembly, has influenced later crustal deformation and mantle modification. This suggests that a series of northeast-striking boundaries extends though the lithosphere. The sutures at crustal levels probably are offset from those in the mantle, but we conclude that the assembly process involved welding together of crustal and mantle blocks with an overall attachment of crusts to their respective lithospheres (at 100-km-length scales). Once established, the sutures acted as mechanical boundaries and became zones of localized reactivation, magma ascent, and isostatic adjustments. They also mark changes in compositional character of the lithosphere that have persisted over time spans of billions of years. These different compositional structures apparently influenced how blocks responded to subsequent mechanical and thermal effects and thus control lithosphere strength, fertility, and density changes.

This compositional and mechanical heterogeneity, inherited from time of assembly, has repeatedly influenced the remaking of a continent. Progressive restructuring of the continent west of the hingeline has largely overcome the old fabric and created a new continental fabric that reflects new boundary conditions. In contrast, Tertiary–Recent mantle modification in the Rocky Mountains is a snapshot of similar processes acting at early stages on the continental interior. Here, reorganization of small-scale convection in the mantle is interacting with preexisting structures to create a new lithospheric boundary separating the Rocky Mountains from the deep-keeled and stable craton. Thus, the Rocky Mountain transect is an excellent field laboratory for continued studies of the processes of formation, stabilization, and destabilization of continental lithosphere.

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REFERENCES CITED

Adams, D. C., and Keller, G. R., 1994, Crustal structure and basin geometry in south-central New Mexico, *in* Keller, G. R., and Cather, S. M., eds., Rio Grande rift: structure, stratigraphy, and tectonic setting: Boulder, Colorado, Geological Society of America Special Paper 291, p. 241-255.

Adams, D. C., and Miller, K. C., 1995, Evidence for late Middle Proterozoic extension in the Precambrian basement beneath the Permian basin: Tectonics, v. 14, p. 1263-1272.

Anderson, J. L., 1989, Proterozoic anorogenic granites of the southwestern United States, *in* Jenny, J. P., and Reynolds, S. J., eds., Geologic evolution of Arizona: Arizona Geological Digest, v. 17, p. 211-238.

Anderson, J. L., and Bender, E. E., 1989, Nature and origin of Proterozoic A-type granitic magmatism in the southwestern United States of America: Lithos, v. 23, p. 19-52.

Anderson, J. L., and Morrison, J., 1992, The role of anorogenic granites in the Proterozoic crustal development of North America., *in* Condie, K. C., ed., Proterozoic crustal evolution: Amsterdam, Elsevier, Developments in Precambrian Geology, v. 10, p. 263-299.

Barker, F., Wones, D. R., Sharp, W. N., and Desborough, G. A., 1975, The Pikes Peak batholith, Colorado Front Range, a model for the origin of the gabbro-anorthosite-syenite-potassic granite: Precambrian Research, v. 2, p. 97-160.

Bennett, V. C., and DePaolo, D. J., 1987, Proterozoic crustal history of the western U.S. as determined by neodymium isotopic mapping: Geological Society of America Bulletin, v. 99, p. 674-685.

Bergh, S. G., and Karlstrom, K. E., 1992, The Proterozoic Chaparral fault zone of central Arizona: Deformation partitioning and escape block tectonics during arc accretion: Geological Society of America Bulletin, v. 104, p. 329-345.

Bird, P., 1988, Formation of the Rocky Mountains, western United States: Science, v. 22, p. 670-671.

___ 1991, Lateral extrusion of lower crust from under high topography, in the isostatic limit: Journal of Geophysical Research, v. 96, p. 10,275-10,286.

Bowring, S. A., and Karlstrom, K. E., 1990, Growth and stabilization of Proterozoic continental lithosphere in the southwestern United States: Geology, v. 18, p. 1203-1206.

Chapin, C. E., and Cather, S. M., 1981, Eocene tectonics and sedimentation in the Colorado Plateau–Rocky Mountain area, *in* Dickinson, W. R., and Payne, M. D., eds., Relations of tectonics to ore deposits in the southern Cordillera: Arizona Geological Society Digest, v. 14, p. 33-55.

Coney, P. J., and Harms, T. A., 1984, Cordilleran metamorphic core complexes: Cenozoic extensional relics of Mesozoic compression: Geology, v. 12, p. 550-554.

Decker, E. R., Heasler, H. P., Buelow, K. L., Baker, K. H., and Hallin, J. S., 1988, Significance of past and recent heat flow and radioactivity studies in the Southern Rocky Mountains region: Geological Society of America Bulletin, v. 100, p. 1851-1885.

DeWitt, E., 1989, Geochemistry and tectonic polarity of Early Proterozoic (1700–1750-Ma) plutonic rocks, north-central Arizona, *in* Jenny, J. P., and Reynolds, S. J., eds., Geologic evolution of Arizona: Arizona Geological Digest, v. 17, p. 149-163.

Elston, D. P., 1979, Late Precambrian Sixtymile Formation and orogeny at the top of the Grand Canyon Supergroup, northern Arizona: U.S. Geological Survey Professional Paper 1092, 20 p.

___ 1989, Grand Canyon Supergroup, northern Arizona: Stratigraphic summary and preliminary paleomagnetic correlations with parts of other North American Proterozoic successions, *in* Jenny, J. P., and Reynolds, S. J., eds., Geologic evolution of Arizona: Arizona Geological Digest, v. 17, p. 259-272.

Emslie, R. F., 1978, Anorthosite massifs, rapakivi granites, and Late Proterozoic rifting of North America: Precambrian Research, v. 7, p. 61-98.

Farmer, G. L., and DePaolo, D. J., 1984, Origin of Mesozoic and Cenozoic granite in the western United States and implications for pre-Mesozoic crustal structure; 2. Nd and Sr isotopic studies of unmineralized and Cu- and Mo-mineralized granite in the Precambrian craton: Journal of Geophysical Research, v. 89, p. 10,141-10,160.

Frost, C. D., and Frost, B. R., 1997, Reduced rapakivi-type granites: The tholeiite connection: Geology, v. 25, p. 647-650.

Gonzales, D. A., Conway, C. M., Ellington, J. A., and Campbell, J. A., 1994, Proterozoic geology of the western Needle Mountains: Geological Society of America Rocky Mountain section field trip guide, 77 p.

Grand, S. P., 1994, Mantle shear structure beneath the Americas and surrounding oceans: Journal of Geophysical Research, v. 99, 11,591-11,621.

Gregory, K. M., and Chase, C. G., 1994, Tectonic and climatic significance of a late Eocene low-relief high-level geomorphic surface, Colorado: Journal of Geophysical Research, v. 99, p. 20,141-20,160.

Hamilton, W., 1981, Plate tectonic mechanism of Laramide deformation, *in* Boyd, D. W., and Lillegraven, J. A., eds., Rocky Mountain foreland basement tectonics: Contributions to Geology, University of Wyoming, v. 19, p. 87-92.

Hammond, J. G., 1986, Geochemistry and petrogenesis of Proterozoic diabase in southern Death Valley region of California: Contributions to Mineralogy and Petrology, v. 93, p. 312-321.

Hawkins, D. P., Bowring, S. A., Ilg, B. R., Karlstrom, K. E., and Williams, M. L., 1996, U-Pb geochronologic constraints on the Paleoproterozoic crustal evolution of the Upper Granite Gorge, Grand Canyon, Arizona: Geological Society of America Bulletin, v. 108, p. 1167-1181.

Heizler, M. T., Ralser, S., and Karlstrom, K. E., 1997, Late Proterozoic (Grenville?) deformation in central New Mexico determined from single-crystal muscovite $^{40}Ar/^{39}Ar$ age spectra: Precambrian Research, v. 84, p. 1-15.

Hessler, E., 1996, Mantle structure of the southern Rocky Mountains [M.S. thesis]: Eugene, University of Oregon, 122 p.

Hodges, K. V., Hames, W. E., and Bowring, S. A., 1994, $^{40}Ar/^{39}Ar$ age gradients in micas from a high-temperature metamorphic terrain: Evidence for very slow cooling and implications for the interpretations of age spectra: Geology, v. 22, p. 55-58.

Hodges, K. V., and Walker J. D., 1992, Extension in the Cretaceous Sevier orogen, North American Cordillera: Geological Society of America Bulletin, v. 104, p. 560-569.

Hodgins, M., 1997, Proterozoic metamorphic and tectonic evolution of the northern Colorado Front Range [M.S. thesis]: Albuquerque, University of New Mexico, 120 p.

Howard, K. A., 1991, Intrusion of horizontal dikes: Tectonic significance of middle Proterozoic diabase sheets widespread in the upper crust of the southwestern U.S.: Journal of Geophysical Research, v. 96, p. 12,461-12,478.

Humphreys, E. D., 1995, Post-Laramide removal of the Farallon slab, western United States: Geology, v. 23, p. 987-990.

Humphreys, E. D., and Dueker, K. G., 1994, Physical state of the western U.S. mantle: Journal of Geophysical Research, v. 99, p. 9635-9650.

Huntoon, P. W., 1993, Influence of inherited Precambrian basement structure on the localization and form of Laramide monoclines, Grand Canyon, Arizona, *in* Schmidt, C. J., Chase, R. B., and Erslev, E. A., eds., Laramide basement deformation in the Rocky Mountain foreland of the western United States: Geological Society of America Special Paper 280, p. 243-256.

Ilg, B. R., Karlstrom, K. E., Hawkins, D. P., and Williams, M. L., 1996, Tectonic evolution of Paleoproterozoic rocks in the Grand Canyon: Insights into middle-crustal processes: Geological Society of America Bulletin, v. 108, p. 1149-1166.

Karlstrom, K. E., and Bowring, S. A., 1988, Early Proterozoic assembly of tectonostratigraphic terranes in southwestern North America: Journal of Geology, v. 96, p. 561-576.

___ 1993, Proterozoic orogenic history of Arizona, *in* Van Schmus, W. R., Bickford, M. E., and 23 others, Transcontinental Proterozoic provinces, *in* Reed, J. C., Jr., and 6 others, eds., Precambrian: Conterminous U.S.: Boulder, Colorado, Geological Society of America, The Geology of North America, v. C-2, p. 188-211.

Karlstrom, K. E., Dallmeyer, R. D., and Grambling, J. A., 1997, $^{40}Ar/^{39}Ar$ evidence for 1.4 Ga regional metamorphism in New Mexico: implications for thermal evolution of lithosphere in the southwestern U.S.: Journal of Geology, v. 105, p. 205-223.

Karlstrom, K. E., and Daniel, C. G., 1993, Restoration of Laramide right-lateral strike slip in northern New Mexico by using Proterozoic piercing points: Tectonic implications from the Proterozoic to the Cenozoic: Geology, v. 21, p. 1139-1142.

Karlstrom, K. E., and Houston, R. S., 1984, The Cheyenne belt: analysis of a Proterozoic suture in southern Wyoming: Precambrian Research, v. 25, p. 415-446.

Karlstrom, K. E., and Williams, M. L., 1998, Heterogeneity of the middle crust: Implications for strength of continental lithosphere: Geology (*in press*).

Kluth, C. F., and Coney, P. J., 1981, Plate tectonics of the Ancestral Rocky Mountains: Geology, v. 9, p. 10-15.

Lanzirotti, A., and Hansen, G. N., 1997, An assessment of the utility of staurolite in U-Pb dating of metamorphism: Contributions to Mineralogy and Petrology, v. 129, p. 352-365.

Livaccari, R., and Perry, F., 1993, Isotopic evidence for preservation of Cordilleran lithospheric mantle during the Sevier–Laramide orogeny, western United States: Geology, v. 21, p. 719-722.

Lowry, A. R., and Smith, R. B., 1994, Flexural rigidity of the Basin and Range–Colorado Plateau–Rocky Mountain transition from coherence analysis of gravity and topography: Journal of Geophysical Research, v. 99, p. 20,123-20,140.

___ 1995, Strength and rheology of the western U.S. Cordillera: Journal of Geophysical Research, v. 100, p. 17,947-17,963.

Mitrovica, J. X., Beaumont, C., and Jarvis, G. T., 1989, Tilting of continental interiors by the dynamical effects of subduction: Tectonics, v. 5, p. 1079-1094.

Nelson, B. K., and DePaolo, D. J., 1985, Rapid production of continental crust 1.7–1.9 b.y. ago: Nd isotopic evidence from the basement of the North American midcontinent: Geological Society of America Bulletin, v. 96, p. 746-754.

Nyman, M. W., and Karlstrom, K. E., 1997, Pluton emplacement processes and tectonic setting of the 1.42 Ga Signal batholith, SW U.S.A.: Important role of crustal anisotropy during regional shortening: Precambrian Research, v. 82, p. 237-263.

Nyman, M., Karlstrom, K. E., Graubard, C., and Kirby, E., 1994, Mesozoic contractional orogeny in western North America: Evidence from ca. 1.4 Ga plutons: Geology, v. 22, p. 901-904.

Pedrick, J. N., Karlstrom, K. E., and Bowring, S. A., 1998, Reconciliation of conflicting tectonic models for Proterozoic rocks of northern New Mexico: Journal of Metamorphic Geology (*in press*).

Powell, J. W., 1876, Exploration of the Colorado River of the West: Smithsonian Institution, 291 p.

Reed, J. C., Jr., Bickford, M. E., Premo, W. R., Aleinikoff, J. N., and Pallister, J. S., 1987, Evolution of the Early Proterozoic Colorado Province: Constraints from U-Pb geochronology: Geology, v. 15, p. 861-865.

Ross, G. M., 1991, Tectonic setting of the Neoproterozoic Windermere Supergroup revisited: Geology, v. 19, p. 1125-1128.

Selverstone, J., Pun, A., and Condie, K. C., 1999, Xenolithic evidence for Proterozoic crustal evolution beneath the Colorado Plateau: Geological Society of America Bulletin (*in press*).

Shaw, C. A., Snee, L. W., Selverstone, J., and Reed, J. C., Jr., 1998, $^{40}Ar/^{39}Ar$ thermochronology of Mesoproterozoic metamorphism in the Colorado Front Range: Journal of Geology (*in press*).

Shride, A. F., 1967, Younger Precambrian geology in southern Arizona: U.S. Geological Survey Professional Paper 566, 89 p.

Simpson, D., and Anders, M., 1992, Tectonics and topography of the western United States—an application of digital mapping: GSA Today, v. 2, p. 117-121.

Smith, D. R., Barnes, C., Shannon, W., Roback, R., and James, E., 1997, Petrogenesis of mid-Proterozoic granitic magmas: Examples from central and west Texas: Precambrian Research, v. 85, p. 53-79.

Stone, D. S., 1993, Basement-involved thrust-generated folds as seismically imaged in the subsurface of the central Rocky Mountains foreland, *in* Schmidt, C. J., Chase, R. B., and Erslev, E. A., eds., Laramide basement deformation in the Rocky Mountain foreland of the western United States: Geological Society of America Special Paper 280, p. 271-318.

Titley, S. R., 1987, The crustal heritage of silver and gold ratios in Arizona ores: Geological Society of America Bulletin, v. 99, p. 814-826.

Tweto, O., and Sims, P. K., 1963, Precambrian ancestry of the Colorado mineral belt: Geological Society of America Bulletin, v. 74, p. 991-1014.

Van der Lee, S., and Nolet, G., 1997, Upper mantle S velocity structure of North America: Journal of Geophysical Research, v. 102, p. 22,815-22,838.

Walker, N., 1992, Middle Proterozoic evolution of the Llano uplift, Texas: Evidence from U-Pb geochronology: Geological Society of America Bulletin, v. 104, p. 494-504.

Williams, M. L., and Karlstrom, K. E., 1996, Looping P-T paths and high-T, low-P middle crustal metamorphism: Proterozoic evolution of the southwestern United States: Geology, v. 24, p. 1119-1122.

Windley, B. F., 1993, Proterozoic anorogenic magmatism and its orogenic connection: Geological Society of London Journal, v. 150, p. 39-50.

Wooden, J. L., and DeWitt, E., 1991, Pb isotopic evidence for the boundary between the Early Proterozoic Mojave and central Arizona crustal provinces in western Arizona, *in* Karlstrom, K. E., ed., Early Proterozoic geology and ore deposits of Arizona: Arizona Geological Society Digest 19, p. 27-50.

Ye, H., Royden, L., Burchfiel, C., and Schuepbach, M., 1996, Late Paleozoic deformation of interior North America: The greater Ancestral Rocky Mountains: American Association of Petroleum Geologists Bulletin, v. 80, p. 1397-1432.

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