THE ROLE OF RHEOLOGY IN THE TECTONIC HISTORY OF THE COLORADO PLATEAU

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ABSTRACT

Interpretation of the geophysics, petrology, and structure of the Colorado Plateau indicates that it is a rheologically distinct element of the Cordillera. During the Phanerozoic Era, areas surrounding the Colorado Plateau have been subjected to repeated tectonism, including contraction, extension, and magmatism while the plateau has been little affected by these processes. Deformation and magmatism mostly wrap around the Colorado Plateau, suggesting the plateau is a rigid body that has often transmitted forces across itself. Compiled geophysical and petrologic evidence indicates that the lithosphere of the Colorado Plateau has a higher strength than regions to the east, south and west. Strength differences may be attributed to a mafic crustal composition and long-term lower crust and mantle geothermal gradients, especially relative to the Basin and Range Province. Estimates of crustal and lithospheric thickness indicate that the ratio of the thickness of mantle to crust in the northern Basin and Range Province ranges from 0.8 to 1, whereas the same value in the Colorado Plateau is about 1.2. Given that mantle rocks are stronger on average than crustal rocks, the ratio of crust to mantle and the greater total thickness of the Colorado Plateau lithosphere also make it inherently strong.

Some evidence suggests that fertile or hydrated mantle may exist beneath the Colorado Plateau. Rock strength data show that mafic rocks in the crust and high pyroxene and amphibole contents in the upper mantle may enhance lithospheric strength, or, at a minimum, provide no reason to presuppose that a fertile, hydrated mantle should be weak.

The Colorado Plateau, although inferred to be stronger than regions to the west, south, and east, may not be as strong as the Archean Wyoming Province to the north. Higher seismic velocities in the lower crust and upper mantle north of the Cheyenne belt imply a higher strength in the middle Rocky Mountains. In this context, the Uinta aulacogen, which separates the Wyoming Province and the Colorado Plateau, developed as a "pop up" structure during Mesozoic to early Tertiary contraction. Thus, in understanding the tectonic history of the western U.S., or any region for that matter, it is important to assess the relative compositional and thermal structure of the lower crust and upper mantle. These factors have exerted considerable control over the partitioning of strain and magmatism throughout the Cordillera in the Colorado Plateau region during the last 1 Ga. Similar factors play an important role in the architecture of mountain systems throughout the world.

INTRODUCTION

The Colorado Plateau region demonstrates how basement thermal structure and composition influences the distribution of strain in orogens. The anomalous tectonic behavior of the Colorado Plateau relative to surrounding parts of the Cordillera during the Phanerozoic Era is manifest by its immunity to large-scale internal deformation and magmatism. The purpose of this paper is to present structural, geophysical, petrologic, and isotopic data that combine to demonstrate how the rheology arising from a mafic bulk composition of Colorado Plateau basement differs from that in surrounding regions, and how these differences account for its unique tectonic behavior.

Present-Day Geology of the Colorado Plateau

The central Colorado Plateau is underlain by 45-50 km thick crust (e.g. Thompson and Zoback, 1979; Allmendinger and others, 1986, 1987; and Beghoul and Barazangi, 1989) and some workers conclude that its thickness may even locally exceed 50 km (Hauser and Lundy, 1989). Therefore, the Colorado Plateau has a thickness that approximates that of the Laramide Orogen and the Great Plains region (Prodehl and Lipman, 1989). However, the crustal thickness of the plateau exceeds that of the Basin and Range Province by about 1/3 to 1/2 (Zandt and others, 1995; Allmendinger and others, 1987). A veneer of late Proterozoic to Tertiary sediments covers the plateau. This veneer is thinner than the massive wedge of sediments deposited along the passive margin of the western U.S. west of the Colorado Plateau that developed during late-Proterozoic time (Stewart, 1972).

Previous studies indicate that basement rocks in the region range from 1.6-1.8 Ga (Bennett and DePaolo, 1987; Karlstrom and others, 1987; Bowring and Karlstrom, 1990). One of the features that attests to the unique character of the Colorado Plateau is the paucity of exposures of Precambrian crystalline rocks that can be directly dated or otherwise examined. Exposures of such rocks within the plateau are nearly limited to the Uncompahgre uplift and the deeper

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portions of the Grand Canyon. Around the plateau margins, tectonism has brought numerous exposures of early Proterozoic basement rocks to the surface. Wendlandt and others (1993), however, clearly demonstrated that the entire crustal column of crystalline rocks within the Colorado Plateau is consistent with a crust-forming event in early Proterozoic (1.7-1.9 Ga) time.

Margins of the Colorado Plateau

The Colorado Plateau has traditionally been defined as a physiographic province. In this paper, we wish to define the plateau as a tectonic domain within North America, and to demonstrate how its tectonic history and crustal structure gave rise to its physiography. In particular, the structural boundaries of the plateau are important to delineate.

The western boundary of the Colorado Plateau is presently defined by eastern limit of Sevier-style fold-thrust deformation and Basin and Range extension, which commonly coincide. It is likely, however, that this boundary was first established by the rifting event that created a passive margin in western North America in Late Proterozoic to early Cambrian time (figure 1). In essence, the western margin of the Colorado Plateau is the eastern limit of crust that was extended during rifting. Subsequent tectonic events have mostly "honored" this crustal boundary (figures 2-4), including the eastern limit of voluminous mid-Tertiary magmatism (figure 3).

The southern margin of the Colorado Plateau is very similar to the western margin in that Mesozoic and Tertiary deformational features most likely are controlled by pre-existing crustal boundaries established during Precambrian crustal assembly and dispersal. The present boundary is defined by the northeastern limit of large-scale mid-Tertiary extension, which propagated slightly beyond Sevier-age contractional structures, such that the belt of metamorphic core complexes in southern Arizona has separated the fold-thrust belt away from the southern edge of the Colorado Plateau (figure 2). The limits of these phases of deformation are similar to those of mid-Tertiary silicic magmatism (figure 3) and later mafic magmatism (figure. 5). A boundary between two Precambrian provinces of contrasting age and composition (Karlstrom and others, 1987) exists near this region, but the nature of that boundary and its possible control of younger structure is poorly constrained.

The eastern and northern margins of the plateau are differentiated by the distribution of Laramide-style contractional deformation. However, the eastern margin, like the western margin, has been repeatedly occupied by subsequent tectonic events. These events include formation of the Rio Grande Rift (figure 2), and mid-Tertiary magmatism (figure. 3) as well as the formation of more recent mafic volcanic fields (figure 5). The northern margin of the Colorado Plateau is perhaps the longest lived of its four boundaries. It more or less follows the Precambrian Cheyenne suture zone between the Archean Wyoming Province and Proterozoic terranes to the south. Since its formation, the boundary has been reactivated as a failed rift during late Proterozoic continental breakup and by contractional and strike-slip deformation, as well as magmatism, during the Phanerozoic Era.

EVIDENCE FOR A MAFIC CRUST

In this section we summarize evidence from geological, geophysical, petrologic, and isotopic studies that all indicate an average composition of the crust within the Colorado Plateau that is significantly more mafic than surrounding provinces, especially the Basin and Range. There are also indications that the mantle lithosphere beneath the Colorado Plateau has a different composition or has a different thermal structure compared to surrounding regions. This may exert a strong influence on the net rheological properties of the plateau. However, available data make crustal composition (and strength) contrasts easier to evaluate. In any case, these compositional differences are important to understand because of the strong influence they may have on the rheology of the plateau.

Geophysical Studies

Recent geophysical measurements indicate a mafic lower crust in the Colorado Plateau and its southwestern margin. Wolf and Cipar (1993) report seismic refraction data and velocity models that show lower crust in the plateau and transition zone with moderately high p-wave velocities of 6.8-7.3 km/s, consistent with mafic lithologies (figure 6a). McCarthy and Parsons (1994) report somewhat lower velocities (6.55-6.65 km/s) in the Colorado Plateau and transition zone, but even lower crustal velocities in the Basin and Range by 0.2-0.3 km/s; thus, although these velocities may not agree with Wolf and Cipar (1993), contrasts in lower crustal velocity are consistent with differences in composition. Most refraction studies have crustal p-wave velocity models in which the highest values in the Basin and Range are significantly less than lower crustal values of the Colorado Plateau, or high velocity lower crust in the Basin and Range is significantly thinner (McCarthy and Parsons, 1994; Wilson and others, 1991; McCarthy and others, 1991; Goodwin and McCarthy, 1990; Benz and others, 1990; Pakiser, 1989; Smith and others, 1989; Keller and others, 1979; Thompson and Zoback, 1979).

Prodehl and Lipman (1989) present a north-south crustal structure model for the Colorado Rockies east of the Colorado Plateau. This model shows lower crustal velocities that average 6.6 km/s, but velocities are interpreted to increase gradually from 6 km/s at the base of the upper crust to 7.1 to 7.3 km/s just above the moho. Thus, this crust may be somewhat less mafic than the Colorado Plateau, although the evidence is not as compelling as the contrast between the Colorado Plateau and Basin and Range Province.

Zandt and others (1995) reported bulk crust Poisson's ratio (σ) measurements of a transect across the eastern Basin and Range Province into the Colorado Plateau (figure 7). The ratio σ is particularly sensitive to composition; values

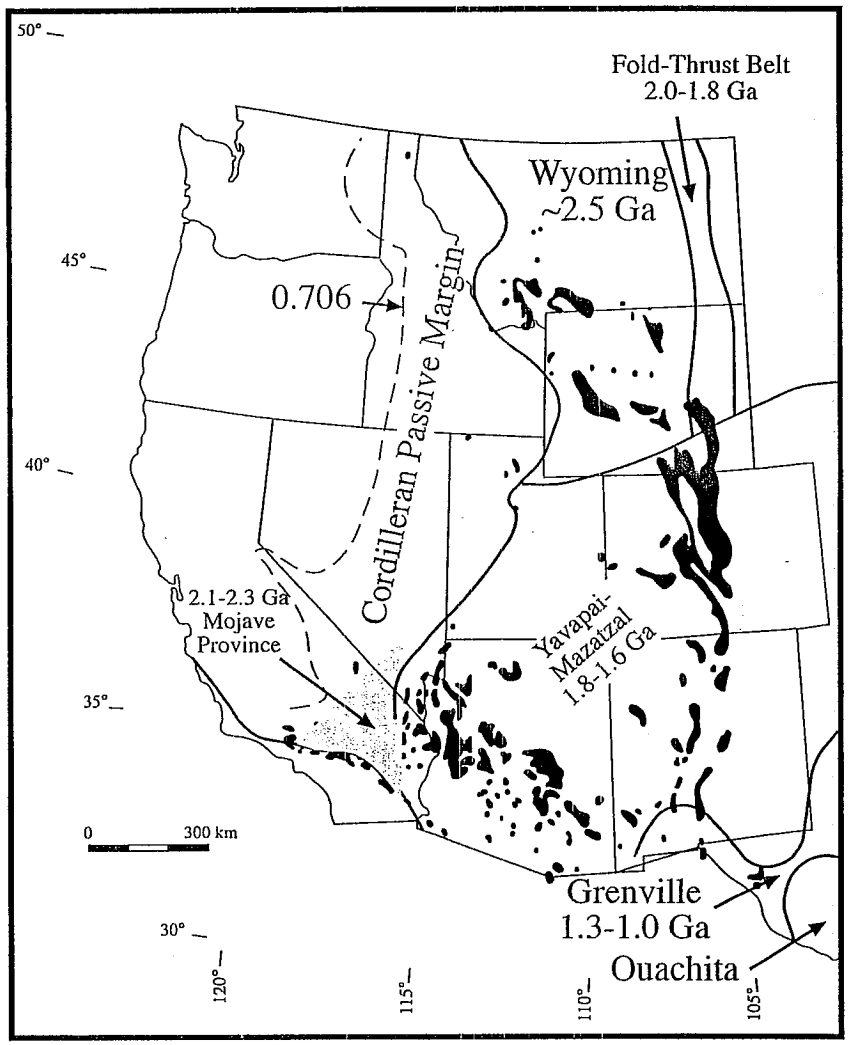

Figure 1. Map showing the age provinces of basement rocks in the western U.S., as well as basement outcroppings. The 0.706 line (Kistler and Peterman, 1973; 1978) represents the initial $^{87}Sr/^{86}Sr_i$ value of igneous rocks and is usually interpreted to represent the westernmost limit of Precambrian lithosphere in North America. (Simplified from Burchfiel et al., 1992).

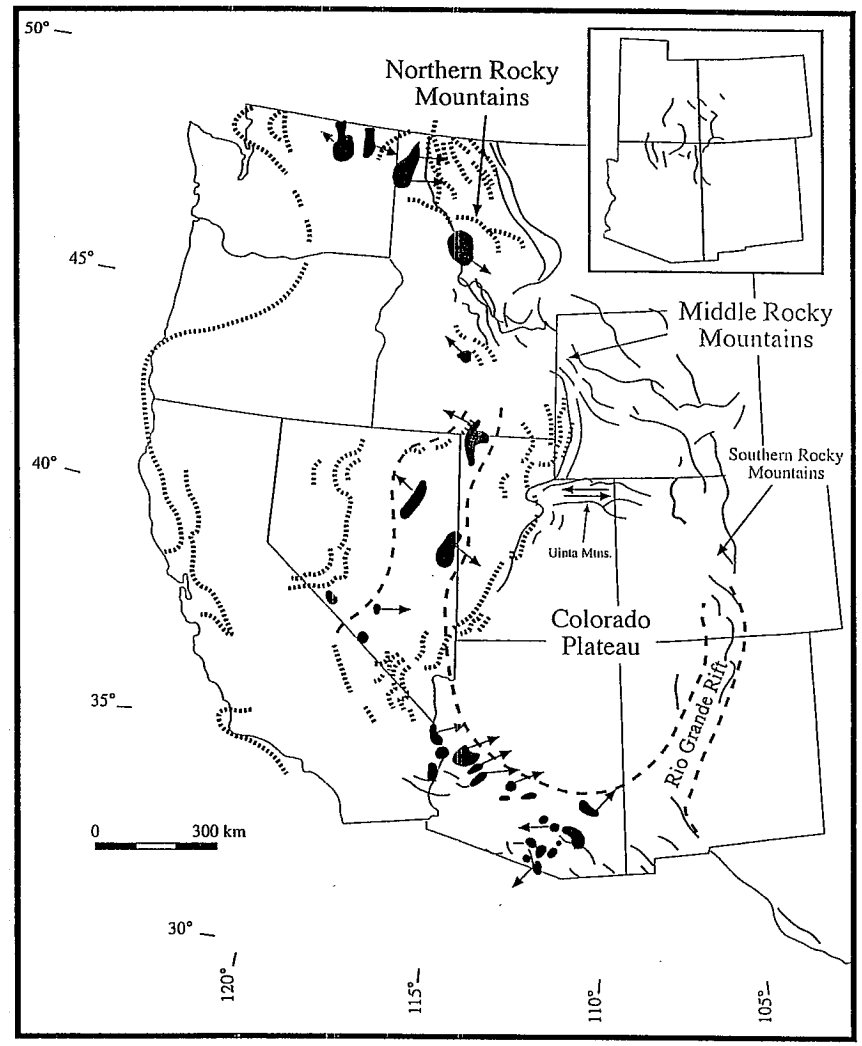

Figure 2. Map showing the distribution of mid-Tertiary metamorphic core complexes superimposed upon mid-Mesozoic through Eocene contractional faults. Sevier-age structures are shown in dashed lines, whereas Laramide-age structures are shown in solid lines. The inset shows the distribution of Colorado Plateau monoclines. A northward component of stress forced Colorado Plateau against the even more rigid lithosphere of the Wyoming Province and the eastward component of stress forced the Colorado Plateau to the east. This resulted in the uplift of the Uinta Mountains,

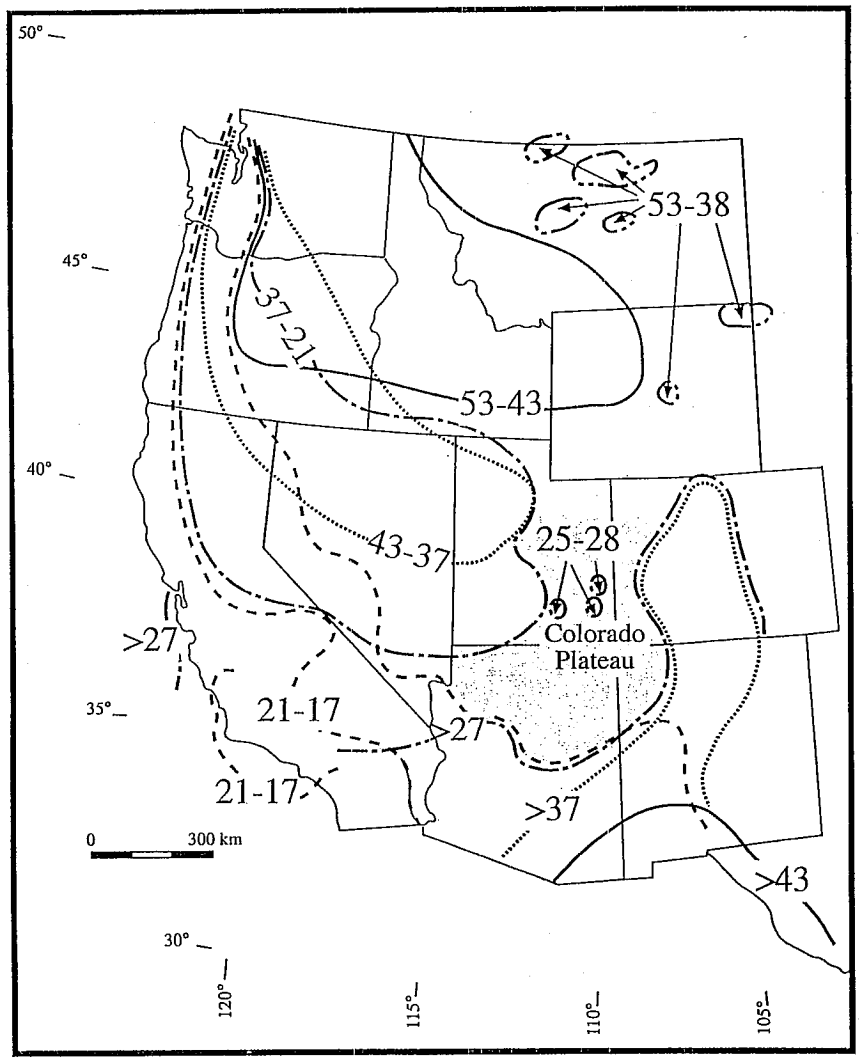

Figure 3. Map showing the time-space patterns of intermediate and silicic volcanism in the western U.S. during mid-Tertiary time. The numbered contours represent millions of years in the past and the shaded region shows that area of the Colorado Plateau that is generally devoid of Cenozoic igneous rocks. The Henry, La Sal, and Abajo Mountains, represented by small, closed contours in southeastern Utah, are of the same approximate age as voluminous magmatism to the east, west and south of the plateau, although they represent much smaller volumes of near-surface magma. (Simplified from Burchfiel et al., 1992).

Figure 4. Map showing the distribution and orientation of Basin and Range faults in the western U.S. (simplified from Burchfiel et al., 1992).

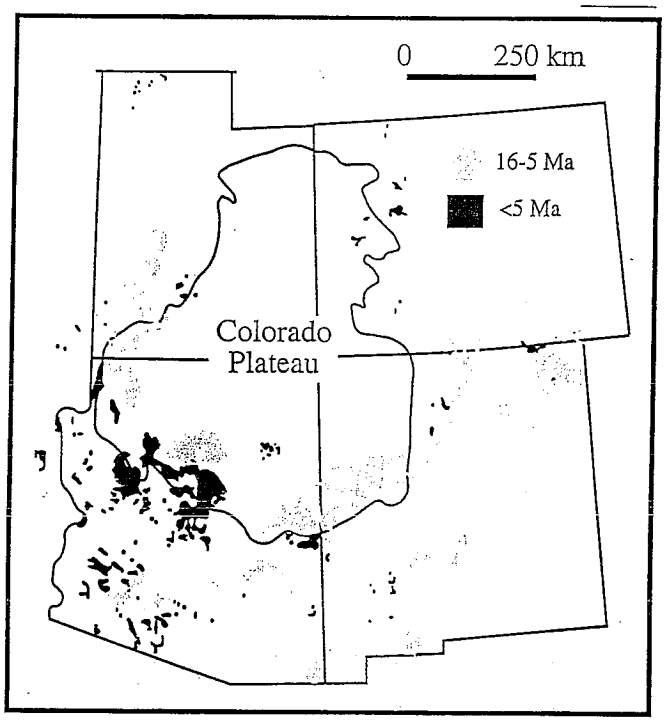

Figure 5. Map showing mid-Cenozoic through recent basalts, largely surrounding the Colorado Plateau. An outline of the physiographic margins of the Colorado Plateau is shown for reference. Modified from Fitton and others (1991).

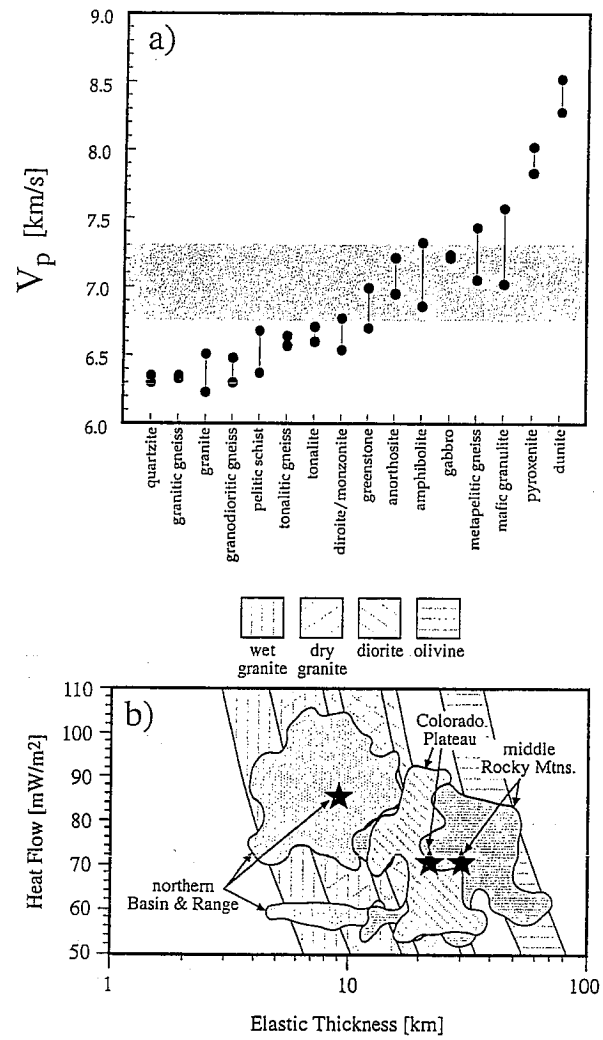

Figure 6. a) P-wave (V_p) velocity as a function of rock type as determined at 10 kbar pressure. The shaded band represents lower crustal velocities typical of the Colorado Plateau and corresponds to dominantly mafic lithologies (data from Fountain and Christiansen, 1989). b) Effective elastic thickness as a function of heat flow and contoured by rock type. Stars denote average values for the provinces indicated. Modified from Lowry and Smith (1994).

<0.24 are found in rocks with high quartz content including quartzites, granites, felsic gneisses, and granulites, whereas mafic rocks have values >0.25. Zandt and others (1995) noted that at the westernmost end of the transect, σ has a value of about 0.20. This value increases to about 0.25 near the Grand Wash Fault (the marginal structure of the Colorado Plateau). Inside the plateau, σ increases to about 0.29 and indicates that the bulk composition of the Colorado Plateau is significantly more mafic than that of the adjacent Basin and Range Province. Other studies confirm measurements of σ. Goodwin and McCarthy (1990) found a value for σ of 0.27± 0.2 for the lower crust in the transition zone near Baghdad, Arizona. Kilbride and Keller (2000) also report σ-values of 0.29-0.30 in the southern Colorado Plateau of Arizona and New Mexico, concluding that the crust is more mafic than average continental crust.

Pakiser's (1989) review of the large-scale geophysical characteristics of the western U.S. also show evidence of a mafic, high-strength and cooler lithosphere in the Colorado Plateau. Bouger gravity is higher in much of the plateau relative to surrounding regions, consistent with mafic crust. As discussed above, heat flow measurements are also lower in the central Colorado Plateau (figure 6b; see also Morgan and Gosnold, 1989), indicating that cooler lithosphere increases the strength of the plateau. Smith and others (1989) show that historic seismicity is concentrated along the western margin of the Colorado Plateau, with far fewer earthquakes in the plateau interior. A recent study by Lowry and Smith (1995), however, provides some of the best evidence that the Colorado Plateau is substantially stronger than the northern Basin and Range, and slightly weaker on on average than the middle Rocky Mountains north of the Colorado Plateau. Figure 6b shows that in addition to lower heat flow, estimates of effective elastic thickness are consistent with the plateau being stronger and cooler than the northern Basin and Range Province.

Petrologic and Isotopic Evidence

With the exception of the inner gorge of the Grand Canyon, very little basement rock is exposed at the surface within the Colorado Plateau interior. Xenolith studies, however, provide some direct additional evidence of mafic

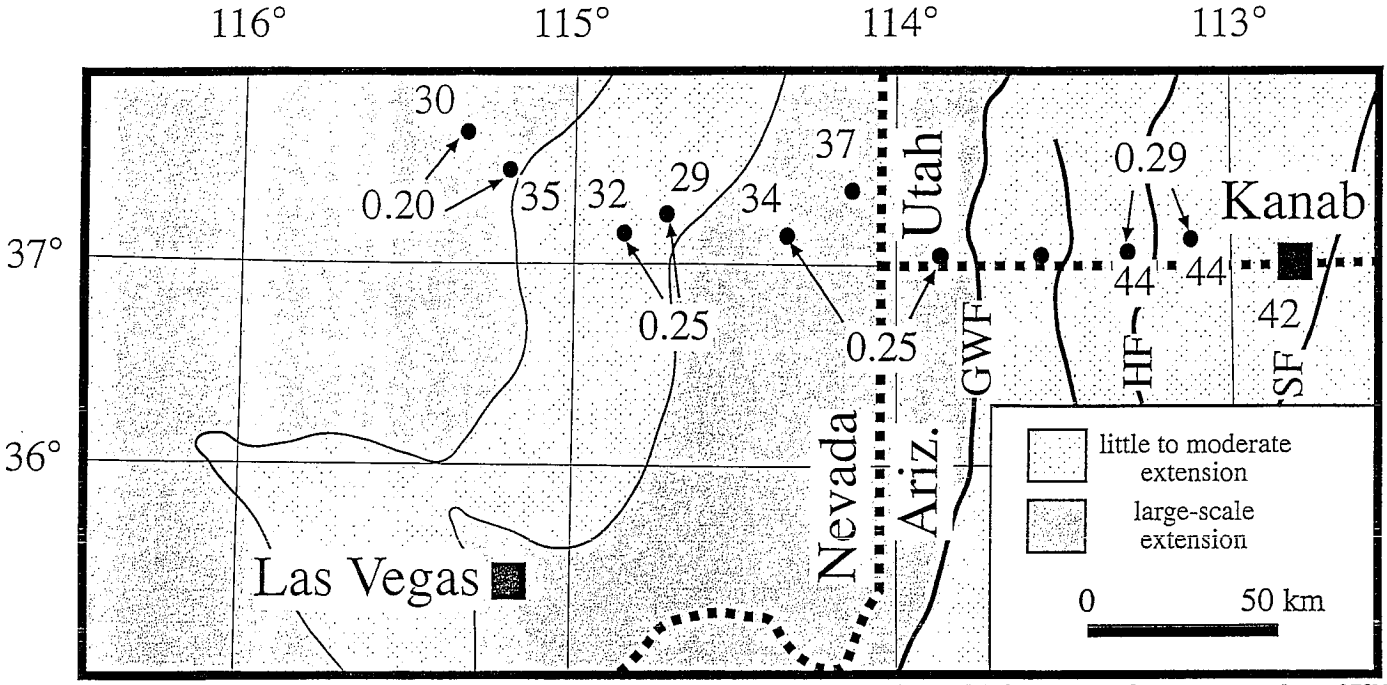

Figure 7. Map showing crustal thicknesses (whole numbers) and poisson's ratio (decimals) for a crustal transect at about 37°N latitude. Black circles represent seismic recording stations. Arrows associated with poisson's ratio (σ) indicate pairs of stations between which σ was calculated. GWF=Grand Wash Fault, HF=Hurricane Fault, SF=Sevier Fault. (Simplified from Zandt and others, 1995).

crust. For example, more than 95% of 285 randomly collected xenoliths from the laccoliths of the Henry and La Sal Mountains are mafic rocks (Hunt, 1953; 1958). Nelson and others (1992) also documented that xenolithic material has become dis-aggregated and dispersed throughout these intrusions. McGetchin and Silver (1972) reported that >65% of crustal xenoliths in the Moses Rock dike, a mid-Tertiary diatreme in the four corners region of the Colorado Plateau, are basaltic in composition and could represent a mean anhydrous crustal composition for the crust of 54% SiO_2, and 8% MgO. They further proposed a crustal model for the plateau that includes diorite, gabbro, metabasalt, amphibolite, and mafic granulite as dominant lithologies in the crust, and spinel or garnet lherzolite in the upper mantle. Granitic rocks are only a minor component (~20%) of the model crust (McGetchin and Silver, 1972). Wendlandt and others (1993) reported lower-crustal xenoliths (n=32) from four Colorado Plateau xenolith-bearing dikes and diatremes that included mafic granulites (44.74-51.15% SiO_2, n=9), amphibolites (47.07-50.76% SiO_2, n=9), paragneisses (45.74-66.45 SiO_2, n=6), and eclogites (47.34-54.99 SiO_2, n=8). Esperanca and others (1988) also reported a suite of mafic lower-crustal xenoliths from the southwest margin of the Colorado Plateau that included mafic granulites, amphibolites and eclogites with a mean composition of 45.4 ± 3.6% SiO_2(n=19).

Although there are many affinities of the laccoliths to surrounding contemporaneous magmatism in terms of time-space-composition patterns (Nelson and others, 1992), the laccoliths themselves show evidence of interaction with mafic crust, discussed below. Nelson and Davidson (1993; 1998) reported that that there are two principal lithologies, both alkalic, in the Henry and La Sal Mountains: (1) a Na-dominated intermediate composition plagioclase- and hornblende-bearing porphyry comprising about 95% of the intrusive volume, and (2) syenite porphyry. Both exhibit evidence for interaction with mafic crust. Looking beyond crustal input, however, these rocks exhibit unusually high alkali contents. Alkaline mantle-derived magmas are often ascribed to the presence of phlogopite ± amphibole in the mantle source. The dominance of Na over K in these laccoliths suggests the magmas may have been derived from an amphibole-bearing mantle.

The plagioclase hornblende porphyry, although dominantly of intermediate composition, has silicic and mafic endmembers. Although fractional crystallization played an important role in the major element evolution of these magmas, isotopic data require open system interaction with the crust at a relatively high proportions of mass assimilated to mass fractionated (Nelson and Davidson, 1993; 1998). Normative mineralogy of the plagioclase hornblende porphyry exhibits evidence of magma mixing between the mantle-derived magma series and partial melts of amphibolite (Nelson, 1991). In particular, one satellite intrusion in the Henry Mountains (the Horn Laccolith) has a tonalitic normative mineral composition quite similar to amphibolite melts (Nelson, 1991).

Syenite porphyry in the Henry Mountains, however, exhibits even clearer evidence of interaction with mafic crust (Nelson and Davidson, 1993). Syenite varies from feldspathoid-bearing (nepheline-normative) to quartz-normative within a single intrusive body (Mt Pennell) as well as showing two liquid lines of descent (figure 8). In the field, there is clear evidence for magma mixing between

TABLE 1. Magma-Mixing Models Using IGPET (M. Carr). All are data normalized to 100%.

Element	Parent PENL-16	Amphibolite Melt*	Hybrid PENL-7	Calculated Hybrid	Residuals r
SiO_2	61.78	74.42	64.97	65.04	-0.03
Al_2O_3	19.75	16.00	18.70	18.79	-0.04
FeO	2.92	1.43	2.29	2.53	-0.24
MgO	0.57	0.00	0.48	0.42	0.06
MnO	0.11	0.00	0.14	0.08	0.06
CaO	3.03	2.54	3.24	2.90	0.34
Na_2O	6.82	3.70	6.42	6.02	0.40
K_2O	4.59	1.80	3.46	3.87	-0.42
TiO_2	0.34	0.10	0.24	0.28	-0.04
P_2O_5	0.09	0.00	0.06	0.07	-0.01
Model 1	74% parent	26% amphibolite melt			$\sum r^2=0.52$
SiO_2	61.78	73.94	64.97	64.87	0.04
Al_2O_3	19.75	13.83	18.70	18.65	0.03
FeO	2.92	3.15	2.29	2.99	0.70
MgO	0.57	0.91	0.48	0.64	-0.16
MnO	0.11	0.13	0.14	0.12	0.02
CaO	3.03	3.15	3.24	3.08	0.17
Na_2O	6.82	2.96	6.42	6.05	0.36
K_2O	4.59	1.19	3.46	3.90	-0.45
TiO_2	0.34	0.59	0.24	0.40	-0.16
P_2O_5	0.09	0.15	0.06	0.10	0.04
Model 2	80% parent	20% amphibolite melt			$\sum r^2=0.91$

*Amphibolite melt for model 1 from Helz (1976); model 2 from Beard and Lofgren (1991).

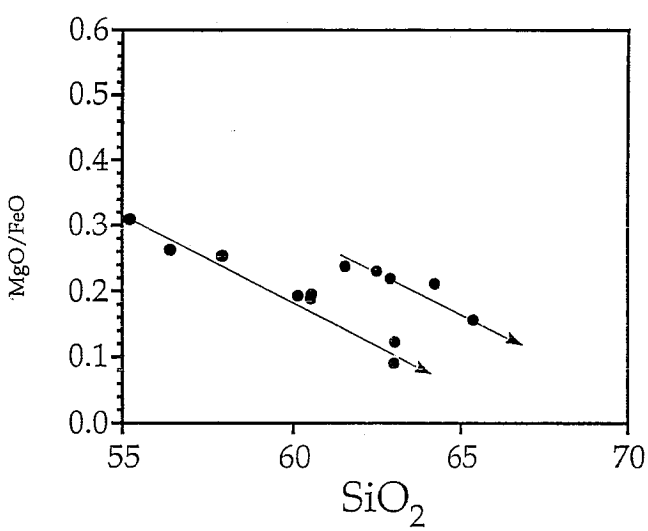

Figure 8. MgO/FeO plotted versus wt. % SiO_2 for Henry Mountain's syenite porphyry. Note that two liquid lines of descent are implied by these data.

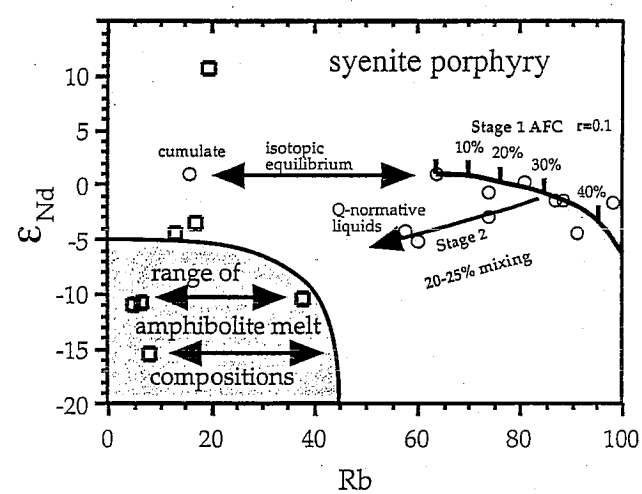

Figure 9. AFC model (DePaolo, 1981) for syenite porphyry plotting εNd versus Rb. An AFC (stage 1) and magma-mixing models (stage 2) are shown for syenite porphyry. Shaded region illustrates the range of potential compositions for amphibolite melts, with Rb concentrations that are very sensitive to the degree of partial melting. Note that the cumulate and most primitive syenite magmas must be related by fractional crystallization, given that they are in isotopic equilibrium. (From Nelson and Davidson, 1993).

these two liquids (Nelson and Davidson, 1993). Mixing between amphibolite melts and the most primitive syenite porphyry produces intermediate composition syenites with a good fit (table 1). Assimilation fractional crystallization models (AFC; DePaolo, 1981) using trace element and isotopic data also implicate the involvement of amphibolite melt in the evolution of syenite porphyry (Nelson and Davidson, 1993). Quartz-normative syenite porphyry shows deviations from an AFC trend that are best explained by magma mixing with melts of amphibolite basement having lower ε_{Nd} and Rb than syenite porphyry (figure 9). The model requires mixing with amphibolite melts rather than bulk mixing as only the melts are sufficiently enriched in silica to saturate the syenite porphyry for reasonable degrees of mixing. These data strongly suggest that not only is the approach to silica saturation in syenite porphyry due to AFC, but it is also related to mixing with partial melts of amphibolite.

STRENGTH OF MAFIC ROCKS

Compilations of brittle and dry ductile rock strength data (figure 10a,b) indicate a general increase in strength with decreasing quartz content. Although there is considerable variability, even within a given class of rocks, mafic rocks are clearly stronger than felsic lithologies (e.g. Kirby, 1985; Hacker and Christie, 1990). These differences may account for the contrast in rheological properties between the Colorado Plateau and surrounding regions. It is also possible that the strength contrast is accentuated by differences in mantle composition and heat flow. For instance, figure 10c suggests that pyroxene-rich rocks are stronger than dunite. Thus, fertile mantle (lherzolite) may also have a higher strength than depleted mantle (harzburgite or dunite).

Water content has a well-know effect on rock strength. Experiments on "wet" quartzite and dunite have markedly decreased strengths relative to dry material (Evans and Kohlstedt, 1984). Moreover, it is important to distinguish between rock strength experiments using wet starting materials and "hydrated" mantle. In a petrologic sense, the latter can be conceptualized as a typical 4-phase mantle (olivine, orthopyroxene, clinopyroxene, spinel or garnet) plus phlogopite or amphibole as the water-bearing phase. There is no reason to presuppose that such rocks should be weak. In Kirby and McCormack's (1984) compilation, the rock with the greatest ultimate strength (at 5 kbar, 500°C, and strain rate = 1.7×10^{-4} s^{-1}) is amphibolite and mica-bearing gneisses are also strong. Hacker and Christie (1990) also report high strengths for amphibolite. We recognize the importance of textural and grain size differences on rock strength, but we do not consider these to be significant over the spatial scale of the Colorado Plateau.

The alkalic Cenozoic igneous rocks of the Colorado Plateau (mafic and silicic) can be interpreted as derivative of phlogopite- or amphibole-bearing mantle. Thus, one may infer the plateau's mantle lithosphere to be at least locally hydrated. Na-rich amphibole bearing xenoliths and Na-rich

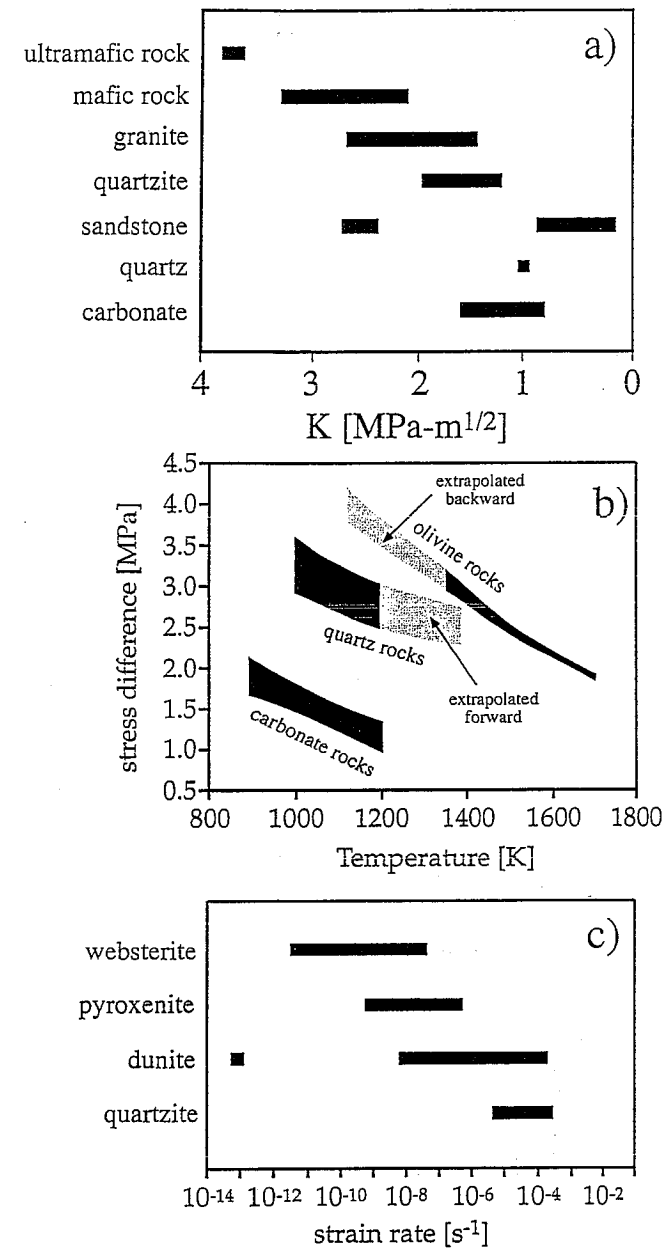

Figure 10. Comparative rock strengths. a) The fracture toughness of rocks as a function of composition (after Meredith and others, 1984). b) The stress differential, as a function of temperature, of olivine versus quartz rocks (carbonate rocks shown for comparison) as recalculated from Evans and Kohlstedt (1984). Resulting curves, calculated for dry conditions, are summarized as shaded bands. c) The power-law strain rates are for the indicated rock types under a differential stress of 4 kbar, temperature = 900°C, and confining pressures from 5-15 kbar. Note that not only are olivine-rich rocks stronger than quartz-bearing lithologies, but pyroxene-bearing rocks may be stronger still. (Calculated from Kirby and McCormack, 1984).

amphibole megacrysts are common in the western Grand Canyon area (Best, 1975; Best 1974). Phlogopite-bearing

mantle xenoliths, although rare, are also found (M.G. Best, personal communication, 2000).

Colorado Plateau mantle xenoliths are mostly lherzolite and harzburgite. No xenoliths of highly depleted mantle (dunite) are documented. (M.G. Best, personal communication, 2000). Compilations of ductile strength data for ultramafic rocks (figure 10b,c) and detailed studies of ophiolites (Nicolas and Rabinowicz, 1984) indicate that peridotite strength increases with pyroxene content. It does not necessarily follow that hydrated or fertile mantle is weak. We argue that fundamental differences in lithospheric structure, composition and heat flow exerted a major influence on the long-term lithospheric strength between the Colorado Plateau and surrounding parts of the Cordillera.

The strength of rocks is also affected by temperature. Long-term radiogenic heat production in the Colorado Plateau should be low due to the mafic composition of the crust (50% of the estimate for average continental crust) and the low proportion of crust to mantle (0.45). Relative to the Basin and Range, geophysical studies indicate that present heat flow is 50% lower in the Colorado Plateau lithosphere (Morgan and Gosnold, 1989); thus, the present and long-term contrast in strength between the Colorado Plateau and Basin and Range may be enhanced by both compositional and thermal contrasts. Relatively reduced upper-mantle P_n velocities suggest hotter (weaker) mantle. Smith and others (1989) report that P_n velocities are ~7.8 to 7.9 km/s in the upper mantle below the Basin and Range, whereas other studies indicate higher P_n velocities of ~8.1 km/s (Beghoul and Barazangi, 1989; Hauser and Lundy, 1989). Recent work (Henstock and others, 1998), however, suggests that upper mantle P_n velocities beneath the Colorado Plateau and southern Rocky Mountains are only 7.9 to 8.0 km/s.

These fundamental differences in the composition and strength of the lithosphere most likely date back to Precambrian assembly and rifting of the Colorado Plateau region. Mantle lithosphere beneath the Colorado Plateau is demonstrably thick (Zandt and others, 1995; Pakiser, 1989) and cold (Morgan and Gosnold, 1989). Although this contrast may explain the sharp western boundary through time, long-term differences in lithospheric strength can only be accounted for in differences in lithospheric mantle structure and composition, and long-term heat flow characteristics.

MANIFESTATIONS OF HIGH-STRENGTH CRUST

Given the evidence for a thick, cold and strong crust and lithosphere in the Colorado Plateau, it is not surprising that strain and magmatism has mostly been distributed around the plateau. Some Phanerozoic deformation is clearly observed (e.g. Yin, 1994; Davis, 1999), but its magnitude has been subdued relative to surrounding areas. Compilations of deformational features surrounding the Colorado Plateau clearly show that it has behaved mostly as a rigid "puck" that transmitted horizontal stresses into adjacent regions and impeded the rise of magmas. Thus, abundant evidence of a rheological contrast should be seen in the geologic history of the western U.S.

Accretion

Rheological differences in the crust and mantle of the Colorado Plateau were first established as the mafic Yavapai-Mazatzal crust beneath the plateau accreted to the Wyoming Province at the beginning of the middle Proterozoic (Fig. 1). Exposures of this crust indicate it is most likely composed of a collage of intra-oceanic island arcs (e.g. Knoper and Condie, 1988; Boardman and Condie, 1986). A modern analog of this accretion process exists within the assemblage of island arc terranes and trapped oceanic basins in the western equatorial Pacific region (Silver and Smith, 1983). Throughout the accretion processes in this region, strain has been partitioned along the boundaries of the trapped oceanic lithosphere, while continental fragments and island arcs deformed internally. More mafic regions conducted stress to weaker lithosphere (Pubellier and Cobbold, 1996), producing local regions of high strength bounded by belts of deformation. In most cases the high strength is attributed to mafic crustal compositions, thick mantle lithosphere, and low heat flow. Some of these areas include the Banda, Celebes and Sulu Seas of eastern Indonesia; Tarim, Junggar, and Turpan Basins of Asia; Black Sea, Pannonian Basin, Tyrrhenian Sea and Alboran Sea of the Tethys; Bering Sea and Yukon-Koyukuk Province of Alaska; and Great Valley and Sierra block of California (e.g. Harris, 1992).

Passive Margin Development

The late Proterozoic to early Paleozoic rift event that formed the western edge of North America established a long-lived rheological boundary that continues to influence the tectonic development of the Cordillera (e.g. Smith and others, 1989; Powell and others, 1993; Stewart, 1972; Stewart and Poole, 1974; Bond and Kominz, 1984). The rift cut mostly N-S across the tectonic grain of accreted terranes, with an arm propagating eastward near the Cheyenne suture to form the Uinta aulacogen (Karlstrom and Houston, 1984).

The tectonic thinning of continental lithosphere and crystalline basement rocks in these regions was most likely the rheological modification that set the stage for locating future tectonism along the western margin of the Colorado Plateau. Thinning of mantle lithosphere of the Great Basin to the west would have preferentially weakened this region. As a result, a long history of tectonism and magmatism has kept this lithosphere relatively weak and susceptible to large-scale modification west of the Colorado Plateau. The modern expression of this weakness may be the crustal uplift and thinning of the northern Basin and Range between the coherent blocks of the Colorado Plateau and the batholith of the Mesozoic Sierra Nevada arc.

The eastern edge of mostly intact or undeformed crust in Utah and Arizona is defined by the western edge of the Colorado Plateau, establishing the "Wasatch Line." Precambrian extension was distributed westward from this zone to around the 0.706 line, representing the westernmost location of preserved Proterozoic and Archean lithosphere in

North America (figure 1). The establishment of this boundary is inferred from passive margin depositional patterns that persisted in the western U.S. during much of the Paleozoic Era. The sedimentary wedge associated with the passive margin accumulated west of the Wasatch Front leaving only relatively thin deposits on the Colorado Plateau. For example, in the Canyonlands National Park area within the plateau, between 1250 and 3100 m of Paleozoic strata are found, whereas in the Gold Hill area on the Utah—Nevada border, 7000—8300 m of Paleozoic rocks are preserved (Hintze, 1988).

Mid-Mesozoic—Eocene Shortening

From Jurassic through early Tertiary time the Cordillera was affected by tectonic contraction that produced fold and thrust belts that virtually surround the Colorado Plateau. Internal shortening of the Colorado Plateau during this same time is estimated at less than 1% (Davis, 1978). The easternmost margin of significant thin-skinned thrusting correlates very nearly with the western margin of the Colorado Plateau (figure 2). Although many of the thrusts surface east of the "Wasatch Line," the basal detachment of the thrust system is rooted much further to the west. However, the contractional stresses that shortened the Cordillera were transmitted through the Colorado Plateau which responded mostly as a rigid block while basement-cored uplifts and basins developed to the north and east (figure. 2). Evidence for the transmission of these stresses across the plateau include minor coeval internal deformation as well the "wrap around" pattern of contractional faults (figure 2).

The Uinta Mountains form the northern physiographic and structural boundary to the Colorado Plateau. They expose a thick (>7 km) collection of clastic sedimentary rocks (Uinta Mountains Supergroup) that are interpreted to have accumulated in a failed rift valley (e.g. Sears and others, 1982) subsequently inverted by Laramide deformation.

The Wyoming Province north of the Unita Mountains yields seismic velocities in the lower crustal and upper mantle that are greater than the Colorado Plateau (Henstock and others, 1998). Therefore, the Wyoming Province (middle Rocky Mountains) may be composed of material even stronger than the Colorado Plateau (figure 6b). The weakness of the Cheyenne crustal suture and its reactivation as a failed rift has played a critical role in providing a weak northern boundary to the plateau, which may have preserved it from extensive internal shortening. The contrast in strength between the Uinta Basin and the rigid blocks that bound it to the north and south is most likely the cause of basin inversion during the Laramide orogeny. In addition, the rigid lithosphere of the Wyoming Province may have prevented indentation, forcing the Colorado Plateau to translate eastward along left-lateral strike-slip faults during basin inversion (Molzer and Erslev, 1995; Paulsen and Marshak, 1998). Eastward translation was accommodated by E-W shortening in Colorado (figure 2). Sevier structures, which are oriented NE—SW to the west of the Colorado Plateau, were most likely rotated clockwise as the Colorado Plateau translated eastward against the southern edge of the Wyoming Province (figure 2).

Mid-Tertiary Extension

Mid-Tertiary metamorphic core complexes surround the Colorado Plateau in an arcuate belt on its west and south sides. Extensional strain directions in these localized zones of orogenic collapse are nearly perpendicular to the plateau margin (figure 2), which may indicate that the rheology of the plateau influenced the pattern of strain. Metamorphic core complexes also separate the Colorado Plateau from contractional structures in southern Arizona and southeastern Nevada. Thus, it appears as if the crust to the southwest "broke away" from the southern Colorado Plateau margin by mid-Tertiary low-angle normal faulting (figure 2). In this sense, the southern margin of the Colorado Plateau was re-established by large-scale extensional tectonics.

Two other features of this period of extension are worth noting. First is the development of the Rio Grande Rift, which is contemporaneous with extension recorded in the metamorphic core complexes (Christiansen and others, 1992). Thus, the Rio Grande Rift forms an eastern structural boundary to the Colorado Plateau. The second feature is seen as a lack of contractional faults in large areas of westernmost Utah and eastern Nevada (figure 2), appearing as if this region were also underlain by strong lithosphere (Armstrong, 1968). However, these faults developed prior to extension, and subsequent tectonic events have been superimposed, obscuring the contractional history. Many contractional faults may be buried in basins or by the voluminous magmatism that occurred in that area in mid-Tertiary time (figure 3). But perhaps more importantly, the contractional faults in western Nevada and central Utah were separated to some degree by the extreme extension manifested in metamorphic core complexes (figure 3).

Mid-Tertiary Magmatism

The mid-Tertiary "ignimbrite flare-up" produced voluminous magmatism of intermediate to silicic composition to the west, south and east of the Colorado Plateau that was contemporaneous with the volumetrically minor mid- to late-Oligocene magmatism of the Henry, La Sal and Abajo Mountains (Nelson and others, 1992) (figure 3). Locally, pyroclastic rocks and lavas spill onto the plateau on its west, south, and east sides. In all, mid-Tertiary magmatism produced 5 x 10^5 km^3 of ignimbrite and associated rock types (Johnson, 1991), with individual calderas responsible for the emplacement of thousands of km^3 (e.g. Best and Grant, 1987).

By contrast, the Henry, La Sal, and Abajo Mountains have a total volume of only 140 km^3 of magma (Nelson and Davidson, 1998). Some evidence suggests that laccolith emplacement was controlled by the intersection of northeast and northwest trending basement structures (Blank and others, 1998; Huffman and Taylor, 1998). Ross (1998) provided specific evidence that the La Sal Mountains were emplaced along such basement faults or at their intersections, and that such features were zones of weakness

facilitating the ascent of magma. The limited volume of mid-Tertiary magma that was able to penetrate high-strength lithosphere may have required a flaw to accommodate its ascent. Certainly some mafic underplating of the crust could have occurred at this time, but this cannot explain the overall mafic character of the crust. Although compositionally diverse, crustal xenoliths typically have Sr- and Nd-isotope ratios consistent with a Proterozoic age (e.g., Wendlandt and others, 1993; Nelson and Davidson, 1993).

Nelson and Davidson (1998) summarized the relationship of the Colorado Plateau laccoliths to contemporaneous magmatism in the San Juan and Reno-Marysvale fields. The magmas all appear to have shared some strong petrogenetic affinities, although the laccoliths are distinctly alkaline (Nelson and Davidson, 1998; Nelson and Davidson, 1993). Thus, it is difficult to imagine that such disparate volumes of temporally and genetically related magmas should occur without some fundamental controlling factor in the lithosphere of the Colorado Plateau such as high-strength crust or upper mantle.

Mid-Tertiary magmatism also bears on the northern margin of the Colorado Plateau. A series of intrusions (e.g. Bingham, Alta, and Clayton Peak stocks) and volcanic rocks (Keetley volcanics) were emplaced in an east-west belt west parallel to the Uinta arch (Vogel and others, 1997) along the Cheyenne belt. This is additional evidence that the crustal suture has persisted as an important zone of weakness between the Colorado Plateau and the Wyoming Province.

Late Cenozoic Magmatism

During the last 16 Ma, basaltic magmatism was largely restricted to areas outside the Colorado Plateau interior such as the outer rim or structural transition zone between the Colorado Plateau and the Basin and Range Province and the Rio Grande Rift (figure 5). Near the western and southern plateau margin, older basalts (16-5 Ma) lie outboard of younger (<5 Ma) lavas. Some geologists have interpreted this distribution of volcanism to reflect a tectonic erosion or migration of the boundary of the plateau towards its interior (Aldrich and Laughlin, 1984; Thompson and Zoback, 1979) in response to extension. Nelson and Tingey (1997) noted that the geochemistry of basalts in Southwest Utah and vicinity were consistent with maximum lithospheric thinning near the plateau—transition zone boundary.

There is little late Cenozoic basaltic magmatism in the Colorado Plateau interior, however. One exception is a dike and sill swarm in the San Rafael Swell (Delaney and Gartner, 1997), the plumbing system for a late Miocene to earliest Pliocene mafic volcanic field (figure 11a). Nelson and Tingey (1997) described the Pahranagat—San Rafael belt extending from southeastern Nevada that terminates at the San Rafael dike and sill swarm (figure 11b). This belt exhibits many of the expected characteristics of a hot-spot trace or plume, including: (1) an elongate belt (aspect ratio of about 6), (2) ages that show a statistically significant correlation with position along the belt, (3) the migration vector was antiparallel to the absolute motion of North America, (4) a migration rate similar to that of North America, and (5) the rough overlap of the magmatic belt with areas of low velocity sub-lithospheric mantle (Humphrey and Dueker, 1994). Activity in the magmatic belt took place between about 15 and 3.5 Ma. Assuming that the melting anomaly still exists within the mantle, any surface manifestation of migrating basaltic volcanism has been absent during the last 3.5 Ma. Given its time-transgressive nature, magmatism should be expressed >100 km to the northeast of the exposures of the 3.5 to 5 Ma dike and sill swarm. However, the crust may be too strong and lack sufficient deep-seated flaws to allow a rather small sub-lithospheric-melting anomaly to continue to produce magmas that reach the surface.

Basin and Range Extension

Extensional deformation affected areas surrounding the Colorado Plateau at around the same time as peripheral Neogene magmatism. Although the Colorado Plateau and the northern Basin and Range Province share high structural relief relative to the stable craton of North America (1680 and 1980 m mean elevations, respectively; Lowry and Smith, 1995), the plateau was affected by extension only on its margins. The rheology of the Colorado Plateau may explain why it has not experienced an extensional collapse like the surrounding regions. Within the western transition zone (high plateaus of central Utah), west dipping normal faults decrease in offset eastward as the expression of Basin and Range extension dies out. Blank and others (1998) discussed a pattern of arcuate crustal features peripheral to the Colorado Plateau that probably represent gravitational collapse resulting from Neogene uplift. To the west and south, this resulted in classic Basin and Range topography. But along the margins of the plateau, such strain is subdued due to the increase in lithospheric strength.

CONCLUSIONS

The unusual response of the Colorado Plateau to tectonic activity during the Phanerozoic Era can be explained by rheological differences of its lithosphere relative to surrounding terranes. Differences in crustal strength have been manifested in several tectonic episodes, including contractional tectonics, extensional tectonics, and magmatism. The rheological differences appear to arise due to contrasts in composition, temperature and thickness of the plateau lithosphere. There is a large and diverse body of evidence indicating that the plateau crust is cooler and more mafic than surrounding regions, especially the Basin and Range Province. The rifting event that produced the western margin of the plateau cut Proterozoic structures at a high angle, indicating that rifting rather than compositional differences *per se* established the western margin. Yet, both geological and geophysical data indicate that Basin and Range crust is less mafic. The apparent paradox between crustal composition gradients (and rifting) occurring at a high angle to structural grain of the plateau basement is one of the important puzzles to yet to be solved in the Cordilleran geology. Evidence for weaker crust in the southern Rocky Mountains relative to the Colorado Plateau

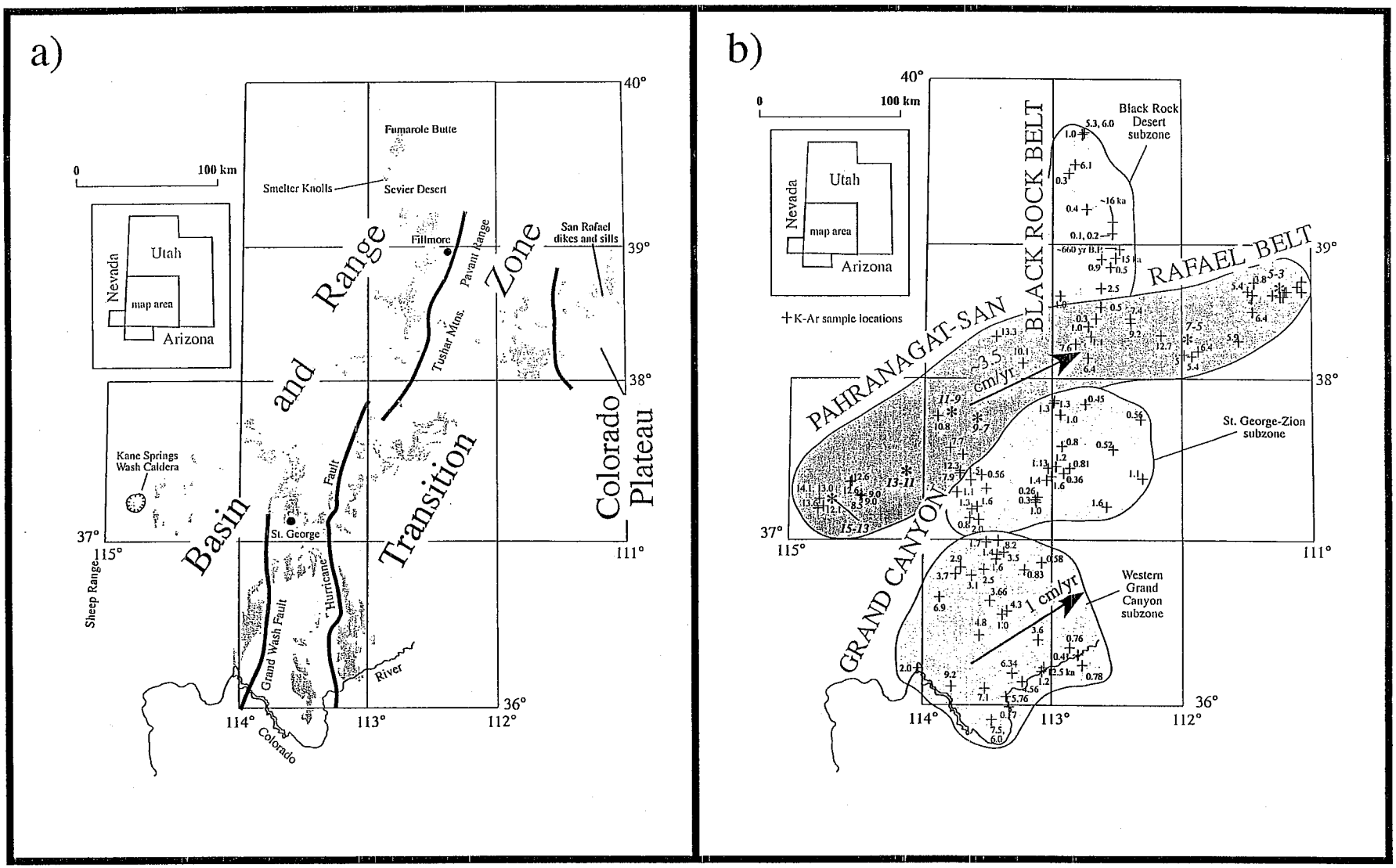

Figure 11. a) Index map showing the distribution of late-Cenozoic basaltic rocks and their relationship to the Basin and Range Province, Transition Zone, and Colorado Plateau interior, including structural features that separate the Transition Zone from the Basin and Range. Many locations mentioned in the text are also represented. b) Crosses represent locations of most samples dated by the K-Ar technique. Note that the basalts form two zones (outlined), the Pahranagat-San Rafael and Black Rock-Grand Canyon belts, that are separated in space and time. One arrow represents the rate of apparent northeastward migration of magmatic activity in the Pahranagat-San Rafael belt. Stars represent the geographical center of dated samples in 2 Ma time slices. The true location of the 15-13 Ma time slice should be located more to the southwest as indicated by the large volume of mafic lavas of that age in the vicinity of the Kane Springs Wash caldera. Lavas in the western Grand Canyon also tend to be younger to the northeast. (From Nelson and Tingey, 1997).

is circumstantial in that strain and magmatism have been preferentially partitioned there rather than the plateau.

Although much of this paper has focussed on evidence of a mafic crust in the Colorado Plateau, it is only because the evidence for contrasting strength is easier to illustrate for the crust than it is for the upper mantle. Recent data from the southwestern margin of the Colorado Plateau (Zandt and others, 1995) indicate that the Basin and Range crust is 30-35 km thick with a total lithospheric thickness of 60 km. The ratio of mantle to crustal thickness is on the order of 0.8 to 1. On the other hand, the Colorado Plateau has a thickness of 45 km and a total lithospheric thickness of 100 km, producing a mantle to crustal ratio of 1.2. Given that mantle rocks are inherently stronger than crustal rocks, the Colorado Plateau should be stronger simply on the basis of crust and mantle proportions that overlie weak asthenosphere. This contrast in strength is enhanced when consideration is given to the greater integrated thickness, lower heat flow, and mafic composition of the Colorado Plateau crust. Some evidence suggests that the mantle beneath the Colorado Plateau may have been hydrated. However, there is no reason to presuppose that this should result in its weakening. In fact, rock strength data suggest that amphibole- and pyroxene-bearing mantle may have enhanced strength.

The northern boundary of the Colorado Plateau is of particular significance. This boundary is the location of a basement suture where Proterozoic rocks were accreted to the southern boundary of the Archean Wyoming Province. Like other boundaries, it has repeatedly been strained and has controlled the ascent and emplacement of magma. As a failed late Proterozoic rift arm filled with thick clastic sediments, it was reactivated during the Laramide orogeny by SW—NE contractional stresses. The weakness of this boundary resulted in inversion of the former aulacogen into a pop-up structure (Uinta Mountains). The Colorado Plateau experienced less than 1% shortening during these episodes of contraction and uplift relative to stable craton of North America. Extensional collapse of Laramide structures only affected the edges of the Colorado Plateau. Thus, the lack of internal shortening, extension and magmatism of the Colorado Plateau illustrate the importance of *relative* lithospheric strength. The Colorado Plateau is stronger than terranes to the east, south and west, but may be weaker than the lithosphere to the north, and these relative differences in strength have exerted considerable influence on the partitioning of strain and magmatism for nearly 1 Ga.

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