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Geology 1996;24;267-270
doi:10.1130/0091-7613(1996)024<0267:XCOTTH>2.3.CO;2

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Xenolith constraints on the thermal history of the mantle below the Colorado Plateau

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ABSTRACT

Analyses of minerals in xenoliths from the Grand Canyon volcanic field (≤1 Ma) and published results from the Navajo field (20–30 Ma) constrain the history of the mantle below the Colorado Plateau. The Navajo xenoliths establish that the mantle was cool to a depth of at least 140 km, until heated by magma just before eruption, and so no frictional heating was recorded from shallow subduction below the plateau in Cenozoic time. The temperature record is consistent with a low elevation of the plateau until uplift consequent to igneous events at ~25 Ma. Rims of minerals of Grand Canyon spinel peridotite xenoliths record mantle temperatures in the range 800–1000 °C at ≤1 Ma. Orthopyroxene grains in two rocks, however, contain interior domains with Ca like that of grain rims, but with much lower Al and Cr. The zonation of orthopyroxene records heating and annealing over a period of at least several million years, and this history is consistent with the isotopically unusual Grand Canyon xenoliths being from mantle lithosphere that persisted through a period of shallow subduction. Temperatures recorded by rims of minerals typically are cooler by about 100 °C than those of xenoliths from similar localities in the Basin and Range province, consistent with seismic studies that indicate relatively faster velocities for the uppermost mantle of the plateau.

INTRODUCTION

Relations among surface elevation, mantle processes, and continental tectonics are poorly known, partly because changes in mantle temperatures are difficult to document. These relations can be clarified by interpretation of temperatures recorded by mantle xenoliths from the Colorado Plateau (Fig. 1). We combine published data from Navajo field xenoliths, erupted about 25 Ma, and new data for Grand Canyon field xenoliths, erupted at <1 Ma. The resulting constraints on temperature history contribute to resolution of the following problems. First, the xenoliths yield information on effects of shallow subduction thought to have occurred below the region during part of the Cenozoic (Dickinson and Snyder, 1978). Second, the xenoliths provide evidence about causes of changes in elevation attributed to diverse processes (Beghoul and Barazangi, 1989; Bird, 1979, 1994; Morgan and Swanberg, 1985; Parsons and McCarthy, 1995). Third, the relatively stable plateau abuts the extended Basin and Range province (Fig. 1), and comparisons of xenoliths from the two regions provide data with which to evaluate the influence of mantle temperatures on tectonic stability.

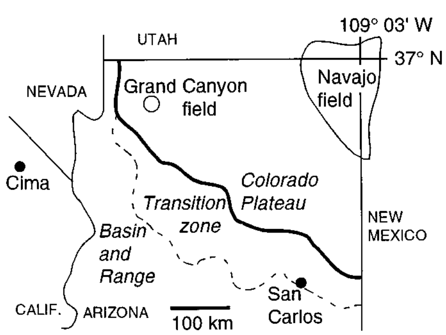

Figure 1. Locations of Navajo and Grand Canyon fields on Colorado Plateau, and Cima and San Carlos localities (solid circles) in Basin and Range province. Heavy curve marks edge of Colorado Plateau within state of Arizona, and dashed line represents edge of transition zone between southern part of plateau and Basin and Range.

The significance of the temperature histories of these xenoliths is interpreted by following the adage that "it's best if it's cool." The coolest temperatures recorded at any depth are best for tectonic reconstructions that depend upon conditions in large volumes of the mantle, because transient heating by magmas may affect the small source volumes of xenoliths (Irving, 1976). Moreover, on a scale that can be analyzed by electron probe, mantle minerals cease to record cooling below blocking temperatures in the range 500–800 °C (e.g., Smith and Barron, 1991). Thus, if the coolest recorded temperatures are below about 800 °C, the mantle may have been even cooler than the calculated values. Compositional gradients in xenolith minerals provide information on the magnitude and rate of temperature change.

DATA

Navajo Xenoliths

Navajo xenoliths are hosted by diatremes of serpentinized ultramafic microbreccia and by minettes, most of which were emplaced between 20 and 30 Ma; the peak activity was near 25 Ma (Laughlin et al., 1986; McDowell et al., 1986). The ultramafic diatremes contain a great variety of xenoliths, including peridotite and eclogite (McGetchin and Silver, 1972; Smith, 1995). The trace element geochemistry of clinopyroxene from spinel peridotite is similar to that in ocean lithosphere (Roden and Shimizu, 1993), but minerals of two spinel peridotites from these diatremes have unusual Nd isotopic ratios that plot well off the Sr-Nd "mantle array" (Roden et al., 1990), and eclogites have a range of model ages attributed to metasomatic changes of Precambrian protoliths (Wendlandt et al., 1993). These rocks are not isotopically like Mesozoic or Cenozoic oceanic lithosphere. Some Navajo minettes contain garnet peridotite xenoliths (Ehrenberg, 1982; Smith et al., 1991). Sr and Nd isotopic ratios of mineral separates from the garnet peridotites are appropriate for ocean-island basalts (Roden et al., 1990; Alibert, 1994), but Alibert (1994) found that garnet and clinopyroxene separates are in isotopic disequilibrium and concluded that the isotopic signatures were affected by interaction with melt shortly before eruption. Hence, the isotopic data do not necessarily constrain the mantle histories of these garnet peridotites before 25 Ma.

Temperatures of 1120 to 1250 °C at 120–150 km depth were calculated from analyses of rims of minerals in garnet peridotite xenoliths by Smith et al. (1991). Although mineral rims in one rock equilibrated at about 1170 °C and 140 km, Ni contents of garnet cores in that rock record ~900 °C, and the heating documented by zonation of Ni must have taken place within tens of thousands of years before eruption (Smith et al., 1991). The heating was attributed to injection of magma, and the 900 °C value is the best indication of temperatures in this depth range before the magmatism.

A variety of Navajo xenoliths provide information about the 45–80 km depth range. Olivine inclusions in garnet megacrysts from the ultramafic diatremes record cooling to near or below 500 °C (Smith and Wilson, 1985; Wang et al., 1995), and so the megacrysts must have been at least that cool at the time of eruption. Chlorite-garnet pairs of mantle origin in the ultramafic diatremes yield temperatures in the range 410–510 °C (Smith, 1995), and although the depths of extraction of these xenoliths are not well defined, these unusually cool temperatures may provide the most accurate constraint on the geotherm in the shallow mantle at 25 Ma.

Grand Canyon Xenoliths

Grand Canyon basalts erupted at ≤1 Ma, and those at the Vulcan's Throne locality in this field erupted at about 10 ka, as summarized by Wenrich et al. (1995). Most xenoliths are spinel peridotite, but garnet websterite and peridotite are present (Best, 1974, 1975). Depths of extraction of the spinel peridotites can be constrained only to the interval between the Moho at about 45 km (Wolf and Cipar, 1993; Zandt et al., 1995) and the transition to garnet peridotite, which takes place at about 1.8 GPa, or about 60 km depth (Ionov et al., 1993). The Sr and Nd isotopic characteristics of the spinel peridotites are unusual: clinopyroxene separates from these rocks have a range of epsilon Nd values from −2 to +147, but $^{87}Sr/^{86}Sr$ ratios are from 0.7038 to 0.7048 (Riter and Smith, 1993; Alibert, 1994).

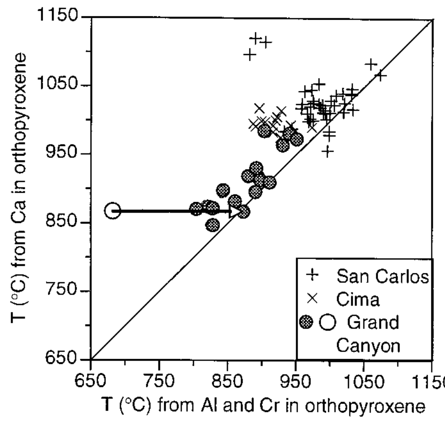

Figure 2. Temperatures calculated for spinel peridotite xenoliths from Grand Canyon field and for type I spinel peridotite xenoliths from Cima and San Carlos fields in Basin and Range (Frey and Prinz, 1978; Galer and O'Nions, 1989; Hervig et al., 1986; Wilshire et al., 1991). Thermometer based upon Ca in orthopyroxene (Brey and Kohler, 1990) responds more quickly to temperature changes than thermometer based upon Al and Cr in orthopyroxene (Witt-Eickschen and Seck, 1991). Open circle represents low temperature calculated from Al- and Cr-poor interior domain in large orthopyroxene grain; temperature is approximate, because Al and Cr contents are below those in calibration. Arrow extends to temperature calculated from rim composition.

To investigate temperature histories, 18 spinel peridotite xenoliths were analyzed by electron probe. Most temperatures calculated from compositions of mineral rims are in the range 800–1000 °C. The Ca-in-orthopyroxene thermometer of Brey and Kohler (1990) yields higher temperatures than the Al-Cr orthopyroxene method of Witt-Eickschen and Seck (1991) for many of these rocks (Fig. 2), and the slight systematic difference may indicate a calibration problem, but large differences record disequilibrium. Orthopyroxene grains >1 cm in length and containing numerous inclusions of olivine are a distinctive and unusual textural feature of many Grand Canyon rocks (Best, 1974). Although the grains are nearly homogeneous in most xenoliths, Al-poor domains irregular in shape were found within interiors of orthopyroxene in two rocks from Vulcan's Throne. In rock VT-19, comparative compositions (weight percent, orthopyroxene rim to interior) are: Al_2O_3, 3.0 to 0.4; Cr_2O_3, 0.31 to 0.05; CaO, 0.44 to 0.41 (Table 1). Whereas grain rims and interiors close to spinel inclusions are relatively rich in Al and yield temperatures near 870 °C, the Al-poor domains yield temperatures near and below 700 °C, on the basis of an extrapolation of the Al-Cr orthopyroxene thermometer of Witt-Eickschen and Seck (1991).

Best (1975) deduced from textures that the garnet websterites formed as cumulates long enough before eruption to record significant postcumulus reequilibration. Orthopyroxene grains in rock X52 are zoned from core to rim from 7.3 to 4.5 wt% Al_2O_3 (Table 1), consistent with the deduced cooling history. Rim compositions of minerals in two xenoliths yield ~1000 °C and ~1.4 GPa by the two-pyroxene plus garnet thermobarometry of Brey and Kohler (1990).

INTERPRETATION AND COMPARISON

Temperatures deduced for Colorado Plateau xenoliths are compared in Figure 3 to two steady-state conductive geotherms calculated for continental lithosphere. The assumption of a steady state is not appropriate for the Cenozoic mantle below the plateau (Morgan and Swanberg, 1985; Spencer, 1994), and so the geotherms serve only as reference curves for low (40 mW/m^2) and more typical (56 mW/m^2) continental heat flows. For comparison, the average of ten heat-flow determinations tabulated by Sass et al. (1994) for northeasternmost Arizona is 63 mW/m^2.

The mantle lithosphere below the Navajo field was cool at 25 Ma. The lowest temperatures calculated for the xenoliths are the most meaningful for this comparison, and those for Navajo xenoliths plot near a 40 mW/m^2 geotherm (Fig. 3). The hotter values at 120–150 km cluster about the 56 mW/m^2 geotherm, but they must record heating caused by infiltration of magma shortly before eruption (Smith et al., 1991; Alibert, 1994).

The mantle represented by the Grand Canyon spinel peridotites at <1 Ma was warmer, but it remained cooler than the temperatures recorded by most xenoliths from Basin and Range localities (Fig. 2). The gradients of Al and Cr within orthopyroxene in two of the Grand Canyon rocks constrain thermal history before eruption. The temperatures near and below 700 °C calculated for the low-Al interiors with an extrapolation of the thermometer of Witt-Eickschen and Seck (1991) may not be accurate, both because of the extrapolation and because the low-Al orthopyroxene may have formed in a different mineral assemblage; however, at least part of the increase in Al and Cr from interiors to rims probably

TABLE 1. ELECTRON PROBE ANALYSES OF POINTS ON MINERALS OF TWO XENOLITHS FROM THE GRAND CANYON FIELD

	1	2	3	4	5	6	7	8	9	10	11
	VT19 5 Olivine	VT19 32 Spinel	VT19 25 Clinopx	VT19 7 Orthopx	VT19 347 Orthopx	VT19 60 Orthopx	X52 81 Garnet	X52 50 Clinopx	X52 32 Orthopx	X52 42 Orthopx	X52 21 Spinel
SiO_2	41.3	0.03	53.8	57.1	58.1	58.3	40.8	50.7	53.5	52.5	0.05
TiO2	0.01	0.05	0.08	0.04	na	0.03	0.15	0.80	0.18	0.24	0.21
Al_2O_3	0.01	49.6	2.19	3.03	0.41	0.89	22.9	6.49	4.47	7.30	63.2
Cr_2O_3	0.02	17.6	0.47	0.31	0.05	0.07	0.06	0.02	nd	0.02	0.36
Fe as FeO	8.32	12.4	1.93	5.60	5.32	5.63	12.9	5.30	11.2	11.4	16.9
MnO	na	na	na	na	0.12	0.13	0.43	0.13	0.15	0.16	0.05
MgO	50.6	19.6	17.0	34.5	35.5	35.5	16.8	14.6	29.8	28.6	18.5
CaO	0.03	nd	23.9	0.44	0.41	0.43	5.74	20.7	0.75	0.67	nd
Na_2O	nd	nd	0.11	nd	nd	nd	nd	0.78	0.04	0.03	nd
Total	100.3	99.3	99.5	101.0	99.9	101.0	99.8	99.5	100.1	100.8	99.3

Note: na = not analyzed, nd = not detected. Analyses 1 through 4 are considered to represent an equilibrium assemblage. Analyses 5 and 6 are not thought to have been in equilibrium with the compositions represented by analyses 1 through 4. Analysis 5 is a low-Al point analyzed in the orthopyroxene interior, and analysis 6 is a representative Al-poor point. Analyses 7, 8, and 9 are considered to represent an equilibrium assemblage. Analysis 10 is in the high-Al interior of an orthopyroxene grain. Analysis 11 is of spinel that is rimmed by garnet. Best (1975) discusses textures in the rare, unusual xenolith suite of which rock X52 is a member. Analyses of minerals in Grand Canyon xenoliths without textural context have been published by Alibert (1994) and Best (1974, 1975).

records a temperature increase. Although reequilibration of Al and Cr in orthopyroxene during heating and annealing was limited by element mobilities, Ca reequilibrated throughout the large grains (Table 1). Similar relative gradients and implications for rapid diffusion of Ca compared to Al and Cr were discussed by Witt-Eickschen and Seck (1991), but no absolute measurements of the diffusivities are available. The shape of one zoned, irregular, and inclusion-filled orthopyroxene grain can be approximated by a cylinder of 1700 μm radius. A relation calculated for Fe-Mg interdiffusion in orthopyroxene by Ganguly and Tazzoli (1994) yields a diffusion coefficient of 5.7×10^{-21} m^2/s at the 870 °C appropriate for rim compositions in the rock. With this diffusion coefficient, it would take more than 10 m.y. to homogenize a cylinder by diffusion inward from the surface, on the basis of curves calculated by Crank (1975). Ca is unlikely to diffuse faster than the smaller Fe and Mg cations, and so heating and annealing of the irregular grain took at least a few million years. The conditions calculated for the two garnet websterite xenoliths, about 1000 °C and 1.4 GPa (Fig. 3), indicate that these rocks cooled at or very near the 45 km Moho, and these garnet websterites may have formed from Cenozoic magmas that pooled at that depth.

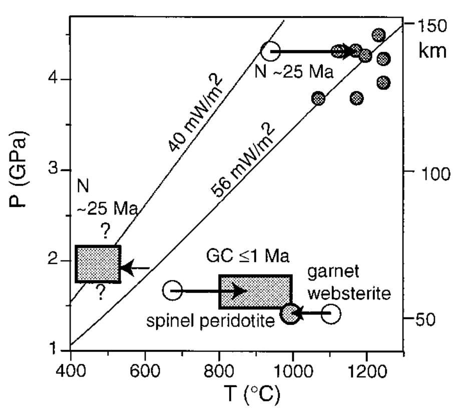

Figure 3. Temperature and pressure constraints from analysis of Navajo xenoliths (N) and Grand Canyon xenoliths (GC), and two steady-state geotherms for reference. Open circles represent conditions recorded by cores of zoned grains. Arrows represent temperature changes recorded by mineral zonation. Patterned circles at pressures near 4 GPa represent garnet peridotite inclusions in Navajo minette. Rectangle for Navajo xenoliths at about 2 GPa represents inclusions in ultramafic diatremes, and arrow pointing to that rectangle is based on temperatures calculated from olivine inclusions within garnets. Conditions calculated from rims of minerals in spinel peridotite xenoliths from Grand Canyon field fall within shaded rectangle extending from 800 to 1000 °C, and open circle represents conditions in Al- and Cr-poor orthopyroxene core. Cooling is shown for two garnet websterites from Grand Canyon based on core to rim zonation of orthopyroxene. Reference geotherms for 56 and 40 mW/m² surface heat flow were calculated for mantle heat fluxes of 27 and 20 mW/m², respectively, conductivity of 3.35 W/mK, and 10 km length scale for decrease in heat production, using approach of Turcotte and Schubert (1982, equation 4-31).

DISCUSSION

The preservation of cool mantle at 25 Ma constrains possible thermal effects above the subducted slab. Although the existence of a shallow slab below the plateau in part of Cenozoic time has been generally accepted (Severinghaus and Atwater, 1990; Bohannon and Parsons, 1995), the importance of frictional heating above the slab is unclear (e.g., Spencer, 1994). The xenoliths establish that the mantle at 140 km was cool before rapid heating at about 25 Ma, and so frictional heating appears to have been negligible. The temperature recorded at 140 km could be a direct result of cooling caused by subduction, as modeled by Spencer (1994). If the depth to the slab was at least 140 km, however, the temperatures at 45 to 80 km (Fig. 3) are not plausible results of conductive cooling, because a characteristic "conduction length" (Lachenbruch and Sass, 1977) for rock with a thermal diffusivity of 10^{-6} m^2/s is 71 km for 40 m.y. Such a deep slab would not have caused significant cooling of the uppermost mantle solely by conduction. The cool geotherm at 25 Ma may therefore have been at least partly established before shallow subduction.

Interactions between slabs and overlying mantle are not well understood, and Bird (1979, 1994) suggested that mantle below the Colorado Plateau was sheared away during shallow subduction. The unusual Nd isotopic ratios of many Grand Canyon peridotite xenoliths record Precambrian depletion (Riter and Smith, 1993; Alibert, 1994), however, and they are distinct from ratios of both oceanic and continental basalts. Isotopic ratios in xenolith clinopyroxene are not likely to have been changed during ascent, and so the xenoliths appear to be from a Precambrian mantle root. Livaccari and Perry (1993) also argued for the preservation of a mantle root, but one that is isotopically different from the Grand Canyon xenoliths, and so the root may contain diverse volumes. Two of the spinel peridotite xenoliths appear to record heating to 870 °C from cooler temperatures, a thermal history unlikely for mantle that recently flowed up from greater depths. Hence, the present root does not appear to have formed from hot mantle that flowed into place after shallow subduction ceased, as suggested by Bird (1994), but seems to have had a long history as cool lithosphere. The garnet peridotite xenoliths from about 140 km depth could be from the slab or from some other source, because their Sr and Nd isotopic signatures may not be diagnostic due to the inferred melt interactions shortly before eruption.

The cool mantle temperatures established from garnet core compositions, and the evidence of heating just before magmatism at about 25 Ma, form a starting point for calculations of subsequent uplift due to thermal expansion. The low elevation of the Colorado Plateau from Late Cretaceous to mid-Cenozoic time discussed by Morgan and Swanberg (1985) is a probable consequence of the cool mantle. The heating calculated from xenolith mineralogy is consistent with the small-volume igneous rock occurrences formed between 20 and 30 Ma within the plateau (Laughlin et al., 1986; McDowell et al., 1986; Nelson et al., 1992). The igneous activity is a plausible consequence of replacement of cool mantle by asthenosphere, as discussed by Bird (1979), but replacement must have been below about 75 km. Slab removal at about 25 Ma is also consistent with the evidence for surface uplift from about 26 to 18 Ma summarized by Morgan and Swanberg (1985). Lucchitta (1979) suggested that the southwestern Colorado Plateau has also been uplifted by 880 m relative to sea level in the past 5.5 m.y., but Patchett and Spencer (1995) have presented new data and have contested the validity of some stratigraphic interpretations upon which part of this uplift history was based. The high southwestern Colorado Plateau is isostatically compensated by warm mantle (Parsons and McCarthy, 1995), and mantle warming related to uplift may have coincided with at least part of the heating and annealing recorded by compositional gradients in orthopyroxene of the Grand Canyon xenoliths. When diffusion rates for Ca and Al are established for orthopyroxene, quantitative constraints on the timing of that mantle heating can be calculated.

The Grand Canyon xenoliths are appropriate for comparison to samples from the Basin and Range, because they erupted at similar times in similar host rocks, and most record temperatures at least 100 °C cooler than those from the Basin and Range (Fig. 2). Parsons and McCarthy (1995) have proposed that the mantle below the southwest margin of the Colorado Plateau may be about 100 °C warmer than that below the interior, and so the mantle below the central plateau may be at least 200 °C cooler than below typical Basin and Range xenolith localities. That temperature difference supports the interpretation of Beghoul and Barazangi (1989) that the uppermost mantle

P-wave velocity beneath the Colorado Plateau is significantly faster than beneath the Basin and Range.

ACKNOWLEDGMENTS

Supported by National Science Foundation grant 9218864 (Smith) and by the Geology Foundation of the University of Texas at Austin. Initial collecting was supported by Sigma Xi and the Geological Society of America Foundation (Riter) and expedited by the National Park Service. M. G. Best provided several critical samples as well as the framework that made our studies of the Grand Canyon xenoliths possible. S. P. Grand, R. A. Ketcham, P. Morgan, M. F. Roden, and R. L. Rudnick made helpful comments.

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Manuscript received August 28, 1995
Revised manuscript received December 7, 1995
Manuscript accepted December 14, 1995