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Final Report

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"Characterization of potential sources of magnetic anomalies within the crust in a tectonically active region: amphibolites and migmatites from Potrillo Maar, New Mexico

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Objective of the study

The purpose of this study was to characterize the oxide mineralogy and petrology of samples collected from Potrillo Maar, New Mexico with the goal of explaining the magnetic anamoly that is observed over this region from remote sensing.

Approach

Potrillo Maar is a diatreme that has brought rocks from all depths in the crust to the surface almost instantaneously. The samples are therefore thought to be representative of the crust as it exists today below this portion of the Rio Grande Rift. It is generally believed that oxide minerals (magnetite, hematite, *etc.*) are responsible for the magnetic signature of the crust. The samples from Portillo Maar therefore offer a unique opportunity to examine the magnetic mineralogy of the entire crust. The results from the petrology are to be integrated with data on the magnetic properties of these rocks collected by P. J. Wasilewski.

Results

The rocks recovered from Potrillo Maar are varied in composition, mineralogy and history. These types include granitic and mafic gneisses characteristic of the lower crust, tonalitic and other intrusive rocks characteristic of the intermediate crust which are associated with amphibolites and greenschists. Characteristic of practically all of the rocks of the suite are complex reaction histories and sequences of mineral parageneses, which suggest multiple events of both igneous and metamorphic activity have affected the crust of this region. It was quickly realized that any interpretation of these events would require analysis of the silicate mineralogy as well as the oxide mineralogy, and the project immediately grew in proportion to this additional objective.

The two most significant "events" are hydration and mylonitization (not necessarily simultaneously). Many of the samples contain multiple generations of hydrous silicates that overgrow one another in complex fashions. For example, pyroxene

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is variably replaced by amphibole which is in turn replaced by chlorite. The mylonitization appears to have affected some samples extensively but not others suggesting that shear zones are localized in the crust at specific depths.

The oxide mineralogy is similarly complex. Magnetite and ilmenite are the principal oxide minerals, but hematite and rutile are also present. Many of the reactions that resulted in the hydration of the silicates also involved the oxide minerals resulting in a great diversity of assemblages depending on the original rock type and the degree of hydration.

By combining phase equilibria analysis of the silicate and oxide mineralogies, a preliminary senario for the evolution of the crust beneath Potrillo Maar can be presented. The lower crustal rocks are largely unaffected by the hydration events but the middle crustal rocks are almost prevasively hydrated and mylonitized. This suggests a large scale fluid infiltration in the middle crust, which we propose is at least in part, related to the shear zones and mylonitization. The infiltration of these fluids also resulted in the general oxidation of the crust, which has the result of converting Fe-bearing silicate minerals into Mg-bearing silicates + oxide minerals. These oxides are dominantly hematite and magnetite and will enhance the magnetic signature of the crust. Therefore, our preliminary suggestion is that the magnetic anamoly observed over the Rio Grande Rift may ultimately be a consequence of the tectonic activity that caused mylonitization of the rocks and allowed the infiltration of oxidizing fluids. Further verification of this hypothesis will come from correlation with the magnetic data on these samples.

Papers, abstracts and reports

Published abstracts (abstracts attatched)

Padovanni E. and Hart, S.R., Geochemical constraints on the evolution of the lower crust beneath the Rio Grande Rift, _in_ Papers presented to the conference on the processes of planetary rifting. LPI contribution no 457, p 149-152, 1981.

Wasilewski, P.J. and Padovanni, E. Magnetization in the lower crust, EOS, v. 61, p 222, 1980.

Wasilewski P.J. and Padovanni, E., Crustal magnetization beneath the Rio Grande Rift based on xenoliths from Kilbourne Hole and Potrillo Maar, _in_ Papers presented to the conference on the processes of planetary rifting. LPI contribution no. 457, p 153-155, 1981.

Invited lectures

Padovani E., Granulites and Migmatites from Kilbourne Hole and

Potrillo Maar, Harvard - M.I.T. symposium on deformation mechanisms in the lower crust, 1982.

Papers in preparation

Padovanni, E. and Spear, F.S. Characterization of potential sources of magnetic anamolies within the crust in a tectonically active region: amphibolites and mylonites from Potrillo Maar

Wasilewski, P.J. and Padovanni, E., Magnetic properties of the lower crust beneath the Rio Grande Rift

Padovanni, E., Spear, F.S. and Wasilewski, P.J., Effects of decompression melting on oxide mineralogy and physical properties crustal xenoliths reversal individually disagree, yet the overall mean pole of the four sampled sites (49.6°N, 108.3°E) agrees well with the previous Lower Triassic poles for the Chugwater Formation published by various authors.

Results of this study suggest: (1) After the removal of secondary components by means of thermal cleaning the polarity transition exists and can be correlated between sites, (2) The dipole field which decays substantially before the polarity reversal occurs, thereby perhaps allowing the nondipole field to predominate during a portion of the transition.

GP 64

THE NON-DIPOLE FIELD DURING GEOMAGNETIC FIELD REVERSALS

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Virtual geomagnetic pole (VGP) paths from various records of the last reversal show a dependence on the observation site meridian. This suggests that the transition field is non-dipolar yet dominated by low order zonal harmonics (Hoffman 1977, Hoffman and Fuller 1978). Predictions from quadrupolar or octupolar transition fields have been compared with the available VGP data. However these VGP paths do not determine which of the two geometries is most important.

As an alternative approach we have used the low order zonal harmonics to model the change of inclination and intensity during a transition. The dipole energy is reduced and distributed amongst the other harmonics in a variety of "reasonable" ways.

It is interesting that neither a purely octupole nor quadrupole intermediate field fits the observed behaviour of inclination. A combination of the two fields models the data better. This analysis suggests that the decrease in intensity will not be symmetric about the change in inclination. Both the intensity change and the apparent time taken for the transition, are dependent upon the latitude of the observation site.

GP 65

ON THE DOMINANT GAUSSIAN COEFFICIENTS OF THE TRANSITION FIELD DURING THE MATUYAMA-BRUNHES REVERSAL

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A model of the reversing geodynamo based on the assumptions (1) that reversals start in a localized region of the core and (2) that upon its onset this reversed region extends, or "floods" both north-south and east-west until the entire core is affected, has recently been shown to successfully simulate existing paleomagnetic records of the reversing field during the Matuyama-Brunhes transition (Hoffman, 1979). An analysis of the modeled field during the transition reveals that the dominant components at the time of total axial dipole decay include an axial octupole (g_3^0) and a non-axial quadrupole (g_2^1, h_2^1). Given the distribution of sites corresponding to the available records of the Matuyama-Brunhes, the existence of a significant axial quadrupole field component cannot be ruled out; however, the role of any equatorial dipole component can be neglected. The modeled minimum field intensity is found to be dependent on both site latitude and longitude. For the Matuyama-Brunhes the modeled minimum strength experienced, say, at mid-northern latitudes is about 10% of the full polarity strength, yet such values differ from site to site by more than a factor of 3.

Although not a unique solution, the findings from this analysis may be considered to be independent of the phenomenological model from which they were derived. For example, whether the above determined transitional field geometry is modeled to be produced by configurational changes of the reversing geodynamo or alternatively, to be of a stationary (non-reversing) origin has little effect on the calculated VGP path localities for a given site. These two possible situations, in principle, should be distinguishable given sufficient transition data corresponding to back-to-back (R+N and N+R) reversals.

GP 66

STOCHASTIC MODELS FOR THE POLARITY BIAS OF GEOMAGNETIC REVERSALS

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The main statistical features of the geomagnetic reversal process are simulated quite well by a variety of deterministic and stochastic models. However bias in the lengths of polarity intervals such as that at the end of the Mesozoic (normal polarity bias) and that at the end of the Paleozoic (reversed polarity bias) has not as yet been modeled either deterministically or stochastically. Two classes of stochastic models are presented to account for polarity bias. In the first, instabilities in the dynamo process which accompany reversals are assumed to occur at a higher rate during one polarity than during the other. In the second, the rate at which instabilities occur remains constant but a different fraction of instabilities are infertile in the two polarity states. The most likely cause of changes in reversal frequency and changes in polarity bias is mass transfer in the lower mantle capable of producing undulations and temperature variations at the core mantle interface, the latter providing the boundary conditions for the dynamo. Symmetry considerations require the presence of odd zonal harmonics in these boundary conditions during times of polarity bias. Moreover because changes in polarity bias occur with a much longer characteristic time than do changes in reversal frequency, the lower mantle processes responsible for changes in bias may well have longer time and length scales than do the processes responsible for changes in frequency. An interesting speculation is that changes in reversal frequency may reflect shifts in the location of individual lower mantle convective cells whereas changes in polarity bias may reflect changes in the entire pattern of mantle convection such as might, for example, be associated with a regrouping of the continents.

GP 67

GEOMAGNETIC SECULAR VARIATION IN SOUTHERN ITALY AND ITS APPLICATION TO ARCHEOLOGICAL DATING

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M.E. Evans

The lavas from nine eruptions of Mount Vesuvius have been sampled at 20 sites, the dates of the eruptions (1631-1944 A.D.) covering the complete range of historically recorded lava flows. In addition, the mud flow resulting from the Plinian eruption of 79 A.D. was sampled at Herculaneum. Eleven archeological baked features (kiln, hearth, or oven) of well-determined archeological date covering the interval from the eighth century B.C. to the fourth century A.D. were also sampled.

Site mean magnetic directions from the lavas are precise (typically α_{95} is $\leq 2°$ for N=5) and yield an elliptical secular variation curve for the last few centuries which is in agreement with observed data for Rome after allowing for dipole variation in inclination. The (detrital?) remanence of the 79 A.D. deposit is stable and is not aligned with the present field direction.

An archeomagnetic date (lying in the second half of the first century A.D.) for a kiln situated in a *villa rustica* at San Giovanni di Ruoti has been derived using data from this study and this date is consistent with the circumstantial archeological evidence relating to the kiln.

GP 68

MAGNETIZATION IN THE LOWER CRUST

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Elaine Padovani (Dept. of Earth & Planetary Science, MIT, Cambridge, MA 02139)

Deep crustal and mantle xenoliths from numerous sources along the Rio Grande rift and the Colorado plateau, granulites from high grade metamorphic terrain in North America, India, Brazil, and Africa, and a profile across the Ivrea zone have been studied in order to evaluate the distribution of magnetization in the deep crust. These preliminary studies provide additional confirmation of our idea that the Moho is a magnetic boundary. There is no evidence of exotic magnetic mineralogy or metal in any of the rocks studied. Naturally reduced basaltic rocks containing a range of titanomagnetite from $Fe_{2.4}Ti_{0.6}O_4$ to Fe_2TiO_4 with increasing dominance of ilmenite and finally metallic iron are used to model what might be expected magnetically with increasing degrees of reduction in the lower crust. The fO_2-T conditions at depth will determine the Curie point of the oxide minerals and the geothermal gradient will determine the depth at which this mineralogy is non-magnetic. Several preliminary models of continental crust magnetization are presented based on the magnetic measurements, since no single model is likely to hold for the entire continental crust. The magnetic properties of deep crustal rocks may reside entirely along the present geomagnetic field. The magnetization contrast is made up of three terms: $\chi_o H$-the induced component dependent an amount, composition and grain size of the magnetic mineralogy, M_v-the viscous magnetization which is enhanced with depth because of increasing temperature at depth and $\chi_H \cdot H$ - presently not well defined contributions due to pressure and the effect of susceptibility enhancement within 100°-150°C of the Curie point.

GP 69

AEROMAGNETIC INTERPRETATION OF THE ARCHEAN VOLCANICS IN THE KIRKLAND-LARDER LAKE AREA OF ONTARIO

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D.W. Strangway (Toronto)
(Sponsor: D.W. Strangway)

High resolution total field aeromagnetic data for the 2.7 billion year old volcanic sequences north of Kirkland Lake are being operated on by geophysical filtering techniques. This is done to enhance the data in order to derive geological information. Magnetic properties such as susceptibilities, NRM directions and intensities and known geological information are being used as a control over the interpretation. Data enhancement techniques have focused on three approaches; first vertical derivation, downward continuation and apparent susceptibility mapping. The latter technique which reduces anomaly overlap and allows for an accurate location of formation boundaries was the most useful for interpretative purposes. Five major rock types were found in this area, these being magnesium and iron-rich tholeiitic flows, calc-alkaline volcanics and various mafic and felsic intrusives. The iron-rich tholeiites are in general extremely magnetic and the calc-alkalines only weakly magnetic. The paleomagnetic results suggest that the remanent magnetization of the iron-rich tholeiites and the ultramafic intrusives are the main source of the anomalies while negative susceptibility contrasts due to the magnesium-rich tholeiites are observed. Thus detailed geologic mapping of the thick stratigraphic sequences is possible.

GP 70

AN ALTERNATIVE EXPLANATION FOR INTERMEDIATE WAVELENGTH MAGNETIC ANOMALIES

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Harrison and others have examined very long magnetic-field profiles and have calculated their one-dimensional power spectra. In these they expected to see, but did not find, a minimum in power at intermediate wavelengths, between 65 km and 1500 km (from sea-floor

GEOCHEMICAL CONSTRAINTS ON THE EVOLUTION OF THE LOWER CRUST BENEATH THE RIO GRANDE RIFT, E.R. Padovani and S. R. Hart, Dept. Earth & Planetary Sciences, Massachusetts Inst. of Technology, Cambridge, MA 02139

As part of a long-range objective to characterize the lower continental crust, petrologic and geochemical studies have been undertaken on representative suites of lower crustal xenolith samples from Kilbourne Hole maar and Potrillo maar in south central New Mexico. Major element analyses completed on about 50 samples indicate a wide range of compositions among the orthogneisses and paragneisses, with SiO_2 contents ranging from 43% to 70%, Na_2O contents ranging from less than 0.5% to 6% and K_2O contents ranging from 0.2% to 6%. The data do not suggest any dramatic depletion of alkalies in these granulite facies rocks. Rb/Sr and Sm/Nd systematics reveal mineralogic and isotopic disequilibria over a 1-3 cm scale defined by compositional layering within xenoliths. Although disequilibrium exists between layers, mineral pairs (such as plagioclase-garnet, plagioclase-clinopyroxene and K feldspar-plagioclase) are commonly in perfect equilibrium which must have occurred within the past 10-20 m.y. Monotonic Sr isotopic gradients within paragneisses may hold the key to understanding a much larger scale diffusion gradient (larger than individual xenoliths) at depth which may explain the difference in behavior between the Rb/Sr and Sm/Nd systems. The "errorchron" defined by the xenolith suite is consistent with an age of 1.7 b.y. (see Fig. 1) for the basement beneath the southern Rio Grande Rift. The combination of mineral geothermometers-geobarometers and isotopic results allows construction of a tentative time-temperature history for the lower crust beneath the rift and distance-scales of isotopic exchange.

Time-temperature history. The original age of cratonization in this area was about 1.7 b.y. Granulite conditions probably prevailed in the lower crust during this orogenic event. Following orogenesis, the crust cooled to perhaps stable shield geothermal gradients (implying lower crust temperatures of less than or equal to 500°C). Based on diffusion models, we believe the interlayer isotopic gradients would not survive continuous granulite conditions for the whole period 1.7 b.y. to present. Other intrusive events have been recognized in nearby regions of New Mexico, Texas and Mexico, with ages of 1.6, 1.2-1.7 and 0.5 b.y. (Muehleberger and Denison, 1964; Silver *et al.*, 1977; Loring and Armstrong, 1980)--their effect on Kilbourne Hole crust is yet unknown. No significant vertical motion (and erosion) has effected Kilbourne Hole crust during the Precambrian as suggested by the presence (Franklin Mts.) of a shallow granite-rhyolite terrain, perhaps 1 b.y. old. During the cooler, orogenically quiescent Precambrian times, mineral geothermometers would be reset to sub-granulite temperatures. Starting about 30 m.y. ago, with the beginning of extension of the Rio Grande Rift, magmatic activity and crustal thinning increased temperatures again into the granulite range. Peak temperatures of 1000-1100°C were reached, as evidenced by 2-pyroxene thermometry, and "bulk" K-feldspar-plagioclase thermometry. The present granulite textures were probably formed at this stage, along with mobilization of Rb and some Nd isotopic exchange between layers. This peak temperature was followed by some cooling as rifting slowed (about 5 m.y. ago), to bring the geotherm to its present value (Lachenbruch and Sass, 1977; Cook *et al.*, 1978); heat flow models predict present lower crustal temperatures of 800-900°C. K-feldspar "host"-plagioclase thermometry consistently records temperatures of 800-900°C, in agreement with the heat flow models. These thermal conditions were sufficient to keep adjacent minerals in continuing local isotopic equilibrium for Sr and Nd (see Fig. 2). Prior to eruption, probably by heating of the erupting magma, the xenolithic material was brought to >1000°C, such that subsequent decompression during eruption produced local "decompression meltting", especially of garnet (Padovani and Carter, 1977b). This heating did not have any significant effect on the isotopic systems, or on mineral chemistry (as witnessed by only small 20-30μ diffusion gradients in plagioclase adjacent to the decompression melt, and the very heterogeneous composition of the melts).

Chemistry of the lower crust. At least under Kilbourne Hole, the lower crust has not been massively depleted in alkalies, and paragneisses retain typically sedimentary isotopic signatures for Sr, Nd and $\delta^{18}O$ (James et al., 1980). Compositional heterogeneity is marked, with a whole spectrum of rock types ranging from very basic orthogneisses to highly siliceous peraluminous paragneisses.

Distance-scales of isotopic exchange. The recent granulite-facies event under Kilbourne Hole, though admittedly not particularly long-lived (≤30 m.y.), has been insufficient to bring about Sr and Nd isotopic homogenization on anything but a rather local (0.1-1 cm) scale. Further thinking is needed to establish the relevance of this result to the question of isotopic heterogeneities in the mantle source-regions of basalts (see Hofmann and Hart, 1978).

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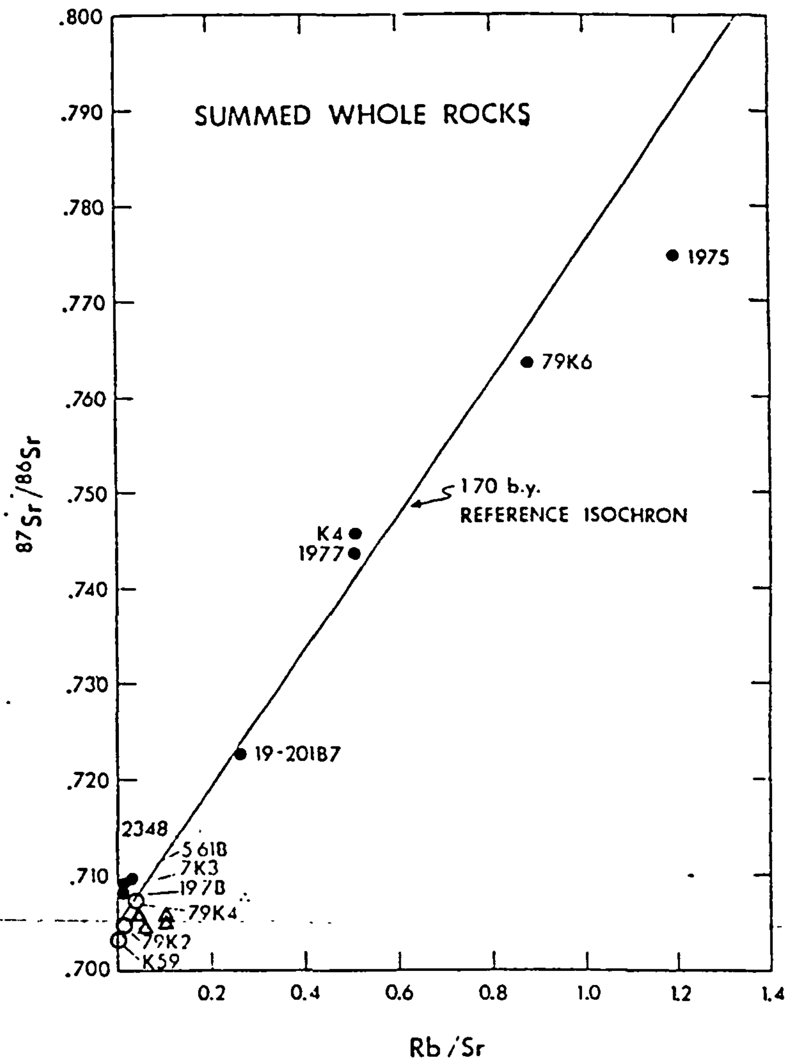


Figure 1. Rb/Sr systematics of "whole rock" xenoliths, obtained either by whole rock analysis of single xenoliths or by "summing" the layers of those xenoliths for which multi-layer Rb/Sr studies were performed (e.g. Fig. 2). Only xenolith 1975 falls significantly away from the 1.7 b.y. reference isochron. This data shows that the "original" age of cratonization of Kilbourne Hole lower crust was ~1.7 b.y. (though this point clearly needs further documentation). Furthermore, though the inter-layer data (such as in Fig. 2) suggests significant relative mobility of Rb versus Sr, the overall effect is not consistent with any dramatic Rb depletion for the lower crust, and the paragneiss samples (closed circles) in particular still show relatively high Rb/Sr ratios. The orthogneiss xenoliths (open circles) are characterized by uniformly low Rb/Sr ratios, but this is probably an original characteristic inherited from their igneous protolith, as opposed to an effect due to large-scale Rb depletion during granulite metamorphism. Note the data for five amphibolite-facies xenoliths from nearby Potrillo Maar (triangles).

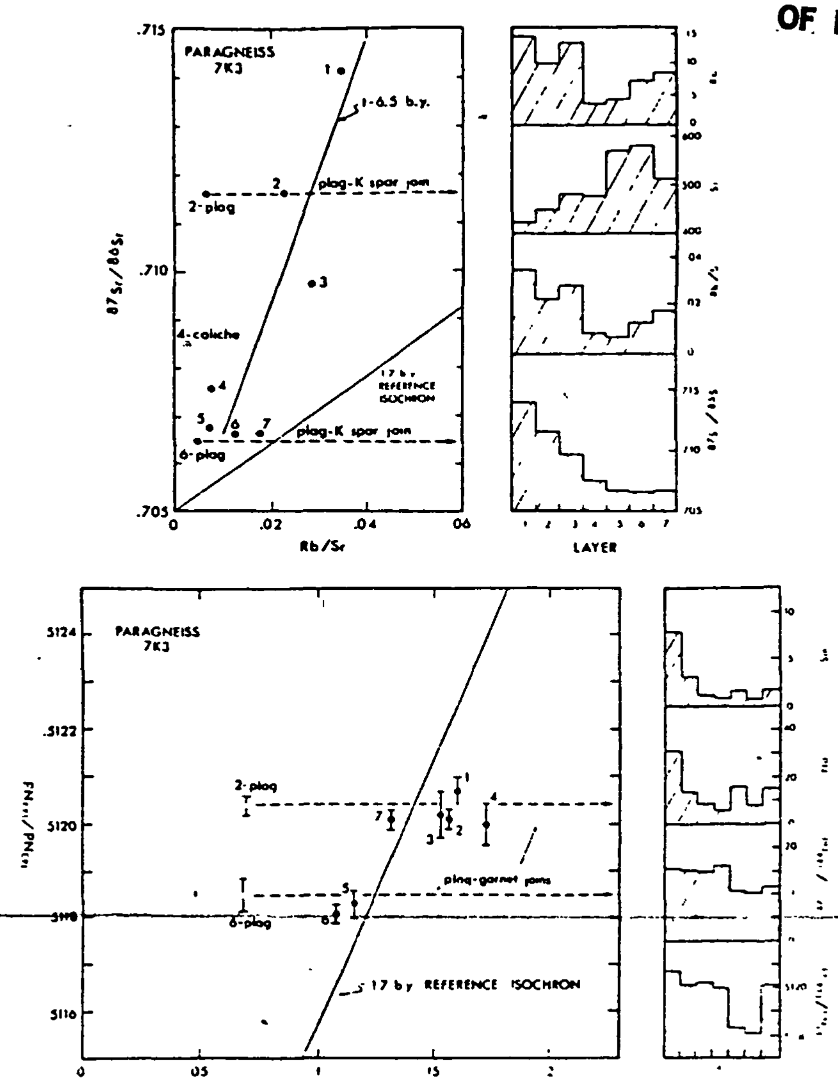


Figure 2. Rb/Sr (top figure) and Sm/Nd (bottom figure) isotopic relationships in minerals and layers of paragneiss 7K3. Minerals from within a given layer are essentially perfectly equilibrated with respect to Sr (plagioclase-K-feldspar pairs from layers 2 and 6) and Nd (plagioclase-garnet pairs from layers 2 and 6); allowing for the observed analytical errors, the <u>maximum</u> ages indicated for these mineral pairs are in the range 10-20 m.y. for both the Sr and Nd systems. In contrast to this small-scale intra-layer isotopic homogeneity, both Sr and Nd show significant isotopic disequilibria between layers. However, with respect to the presumed original age of metamorphism of this paragneiss (~1.7 b.y.), both the Sr and Nd systematics appear to show open-system behavior. The location of layers 1-4 to the left of the reference Sr isochron suggest loss of up to 80% of Rb from these layers at a relatively recent time; this Rb loss has produced a crude linear array of data points with an obviously meaningless slope age of ~6.5 b.y. In contrast, the Nd data suggests some inter-layer isotopic equilibration, as layers 5 and 6 and layers 1-4 and 7 are essentially in isotopic equilibrium. Note the regular monotonic change in $^{87}Sr/^{86}Sr$ across the layers; this is a feature which has been noted in all of the paragneiss samples studied thus far.

CRUSTAL MAGNETIZATION BENEATH THE RIO GRANDE RIFT BASED ON XENOLITHS FROM KILBOURNE HOLE AND POTRILLO MAAR; P. J. Wasilewski, NASA/Goddard Space Flight Center, Laboratory for Extraterrestrial Physics, Greenbelt, Maryland 20771; E. R. Padovani, Dept. Earth and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA 02139

Results of magnetic studies on xenoliths from the Colorado plateau and Rio Grande Rift support the concept of the continental Moho as a magnetic boundary (Wasilewski et al., 1979; Wasilewski and Padovani, 1981). Upper mantle peridotites contain chromites which are nonmagnetic at Moho depths. The xenolith results indicate that regional magnetic anomalies in the crust are related to both the topology of the Curie isotherm and to petrologic variations. These results combined with detailed petrologic and geochemical studies on lower crustal xenoliths have revealed that in an area of steep geothermal gradient, the magnetic bottom is at considerably more shallow depths (10-15 km) than is the case in an area with moderate geothermal gradient such as the Colorado plateau where the magnetic bottom is deeper (30-40 km). This is due to the steeper geothermal gradient as well as a different magnetic mineralogy. Though the rift is of limited areal extent it can be recognized in both POGO and Magsat magnetic anomaly maps due to the contrast with surrounding regions.

Beneath the southern Rio Grande rift, the crust appears to be more reducing with increasing depth as reflected by the ilmenite dominated anhydrous lower crustal xenoliths at Kilbourne Hole which have Curie points less than 300°C and characteristically small saturation magnetization and remanence. In contrast some of the xenoliths from Potrillo maar which are considered to represent intermediate crustal depths between those defined by exposed outcrop and wells drilled to basement and those defined by the granulite facies xenoliths have 550°C Curie points and large values of saturation magnetization and remanence. Granulite xenoliths from Elephant Butte and the Lucero Volcanic field (Wasilewski and Baldrich - unpublished research) have magnetic characteristics that differ from both the Colorado plateau and Kilbourne Hole and Potrillo maar granulites suggesting different conditions of equilibration may exist at lower crustal depths along the rift. It appears that active regions with high heat flow such as rifts may be anomalous with respect to their magnetic properties.

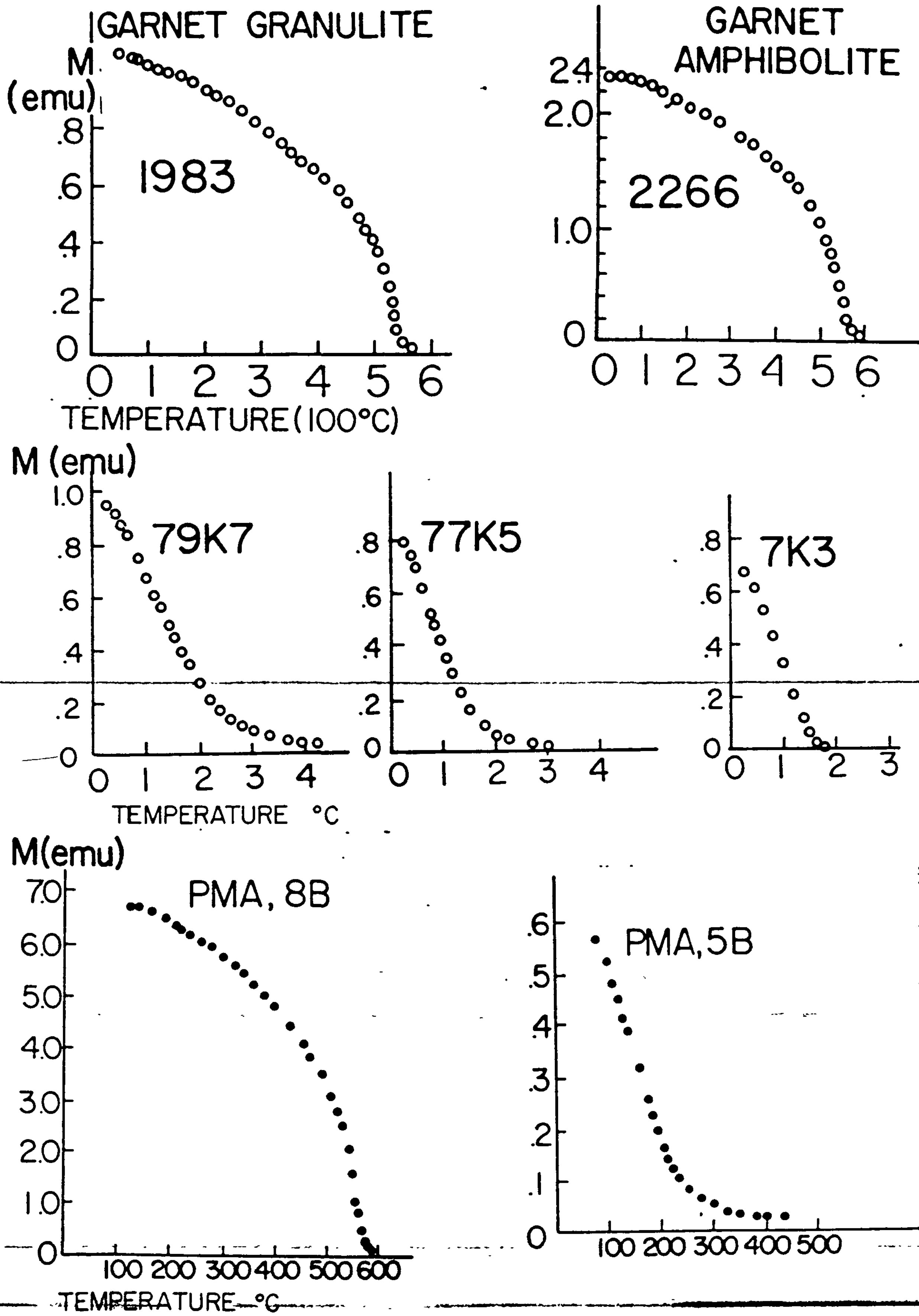
Shown in Figure 1 are Curie point curves for garnet granulite (1983) and garnet amphibolite (2266) from the Colorado plateau; pyroene granulties (79K7, 77K5, and 7K3) from Kilbourne Hole; and, an amphibolite grade rock from mid-crustal depth (PMA, 8B) and a lower crust granulite (PMA, 5B) from Potrillo maar.

All Colorado Plateau xenoliths have 550°C Curie points no matter what lithologies were evaluated. Kilbourne granulites have Curie points <300°C and Potrillo maar rocks have either 550°C Curie points (mid-crustal levels) or < 300°C Curie points (lower crust). The magnetic bottom beneath the Southern part of the rift should be no deeper than about 15 km as indicated by point A in Figure 2, which is the depth of the 550°C Curie point on a reasonable geotherm for the rift. If ilmenite dominates as is the case for Kilbourne Hole xenoliths then the magnetic bottom may be as shallow as 8-10 km (point B on Figure 2). Therefore, at best we may have only half the crustal thickness beneath the southern part of the rift made up of magnetic rocks.

Away from the central part of the rift where the geothermal gradient becomes more shallow, and the magnetic mineralogy may be developed in a more oxidizing environment, the effective magnetic crustal thickness should increase.

CRUSTAL MAGNETIZATION BENEATH THE RIO GRANDE RIFT

Wasilewski, P. J. and Padovani, E. R.



CRUSTAL MAGNETIZATION BENEATH THE RIO GRANDE RIFT

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