WORKSHOP ON
THE ARCHEAN MANTLE

January 11-13, 1989

Lunar and Planetary Institute
Houston, Texas

Sponsored by

Lunar and Planetary Institute
NASA Johnson Space Center

Papers Presented to the

Workshop on

The Archean Mantle

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Preface

This volume contains abstracts that have been accepted by the Program Committee for presentation at the Workshop on the Archean Mantle, held in Houston, Texas, January 11-13, 1989. Program Committee members are L. D. Ashwal (Lunar and Planetary Institute), I. D. MacGregor (National Science Foundation), T. J. Naldrett (Univ. of Toronto), W. C. Phinney (NASA Johnson Space Center), F. Richter (Univ. of Chicago), and S. B. Shirey (Carnegie Institution).

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TABLE OF CONTENTS

KOLAR AMPHIBOLITES -ARCHEAN ANALOGUES OF MODERN BASALTIC VOLCANISM?

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The geochemistry of komatiitic and tholeiitic amphibolites of the ca. 2700 Ma old Kolar Schist Belt places constraints on depth of melting and composition and long term evolution of their mantle sources. The komatiites and tholeiites are the predominant rock type in the N-S trending, less than 4 km wide belt. Because the amphibolites have pillow structures and are interbanded with ferruginous cherts and graphitic schists it is thought they were originally formed in submarine environment. The rocks of the belt underwent extensive folding and shearing. Krogstad et al (1) suggested that to west and east of the belt lie two disparate gneissic terranes mostly made up of granitoids derived from sources with mantle-like geochemical characteristics between 2630 to 2530 Ma ago. The komatiitic amphibolites are relatively minor and occur as thin units inter-bedded with the tholeiitic amphibolites. Relative to chondrites the western komatiites have lower Ce/Nd ratios while the eastern komatiites have higher Ce/Nd ratios (Fig. 1). The Ce enrichment in the eastern komatiites is not a result of crustal contamination of Ce depleted magmas (Fig. 1).

The Ce/Al_2O_3 ratios in the komatiite samples indicate their parental melts left varying proportion of garnet in their residue (Fig. 2) and this is consistent with low extents of melting at pressures greater than 50 kb. The western komatiites have a wide range in Sm/Nd ratios due to varying proportion of garnet left in the residue. The Sm-Nd age of the western komatiites is 2694 $\pm$ 136 Ma with epsilon$_{Nd}$ of +5$\pm$3.5. Thus the western komatiites were derived from sources depleted in light REE for a significant period of time.

The eastern komatiites have a restricted range in Sm/Nd ratios so that no age is calculable. They have an epsilon$_{Nd}$ of 3$\pm$1 at 2700 Ma suggesting that their sources were depleted for a shorter period of time or less depleted relative to that of western komatiites. Their sources were enriched in light REE some time before melting.

The eastern komatiites, eastern tholeiites, western komatiites and western tholeiites all have quite different Pb isotopic compositions (Fig. 2). The scatter in the Pb isotope whole-rock data for each type of amphibolite suggests that some of the amphibolites may have been contaminated by extraneous Pb perhaps represented by galena found in gold quartz veins within the amphibolites. The Pb isotope data on one tholeiite outcrop has little scatter and gives a Pb-Pb age of 2733$\pm$155 Ma., similar to Sm-Nd isochron age for the western komatiites. Surprisingly the Pb data for komatiites and tholeiites are quite different suggesting the interlayered komatiites and tholeiites have separate sources. Less surprisingly, the eastern komatiites have Pb isotopic characteristics quite different from those of either the western komatiites or tholeiites. The eastern komatiites may be Archean analogues of modern oceanic island or island arc basalts while the western komatiites may be Archean analogues of modern mid ocean ridge basalts. The occurrence of ca. 2.7 Ga old komatiitic and tholeiitic amphibolites derived from different sources in a narrow belt between two disparate younger late Archean terranes suggests that accretionary processes were important in the evolution of the eastern Dharwar craton.

KOLAR AMPHIBOLITES -ARCHEAN ANALOGUES OF MODERN BASALTS?

Balakrishnan, S. et al.

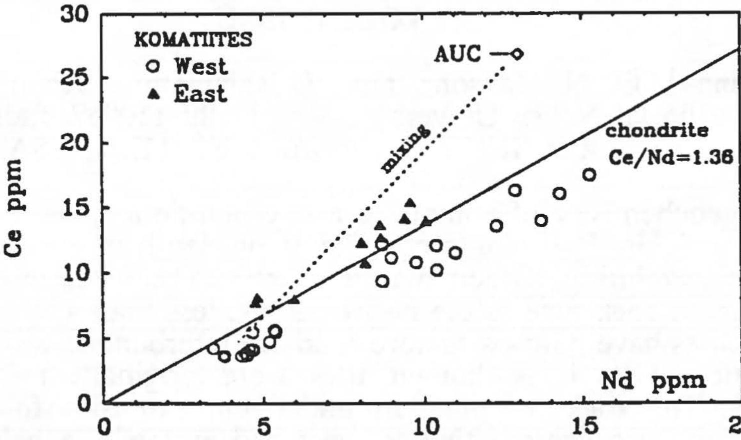

Fig. 1. Ce versus Nd concentrations of the western and eastern komatiitic amphibolites compared to a line with chondritic Ce/Nd ratio and to a mixing line between light REE depleted komatiite and Archean upper crust (AUC) after Taylor and McLennen (2). The granitoids in the Kolar area plot on the extension of the mixing line. Essentially all of the western komatiites have a Ce/Nd ratio less than that of chondrites, whereas the eastern komatiites have Ce/Nd ratios greater than that of chondrites. Note that the eastern komatiites plot sub-parallel to the chondrite line and not along the mixing line. This consistent difference in ratio over a range in composition implies that the mantle sources for the two komatiitic suites had the same Ce/Nd characteristics as the amphibolites.

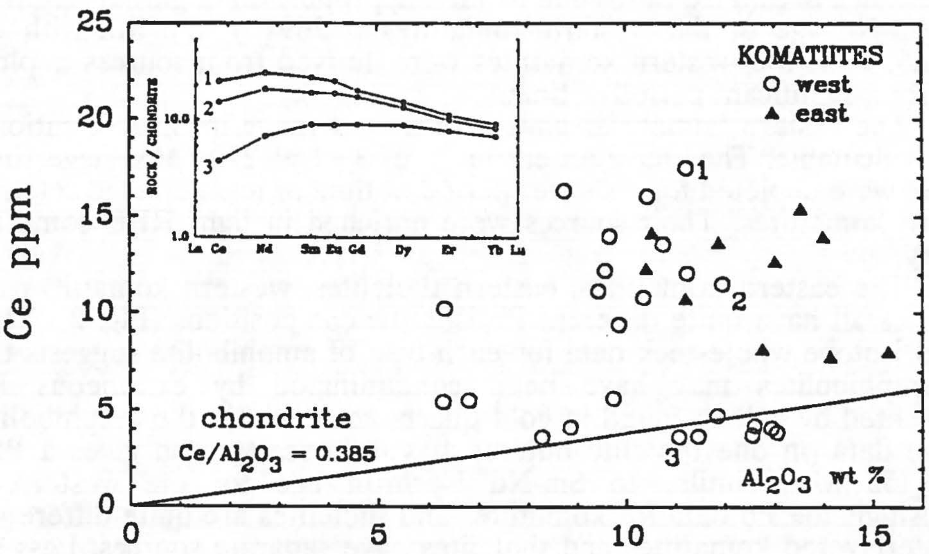

Fig 2. Ce versus Al_2O_3 concentrations of western and eastern komatiitic amphibolites compared to a line with chondritic Ce/Al_2O_3 ratio. Ce and Al are essentially incompatible in olivine and pyroxenes, whereas Al is an essential structural constituent of garnet. The melts leaving garnet in the residue would have Ce/Al_2O_3 ratios much higher than their source. The western komatiites that plot below the chondrite line were derived from melts leaving no garnet in residue and those with higher Ce/Al_2O_3 ratios were derived from melts that had left garnet in the residue. The komatiites with chondritic Ce/Al_2O_3 ratios have higher Sm/Nd ratios and less fractionated heavy REE (sample 3). Whereas ones with high Ce/Al_2O_3 ratios have lower Sm/Nd ratios and more fractionated heavy REE (sample 1 & 2) suggesting the spread in Sm/Nd ratios is due to different extents of melting of mantle sources leaving varying fractions of garnet in the residue. The Sm-Nd isochron age of 2694±136 would thus represent the time of melting.

KOLAR AMPHIBOLITES -ARCHEAN ANALOGUES OF MODERN BASALTS?

Balakrishnan, S. et al.

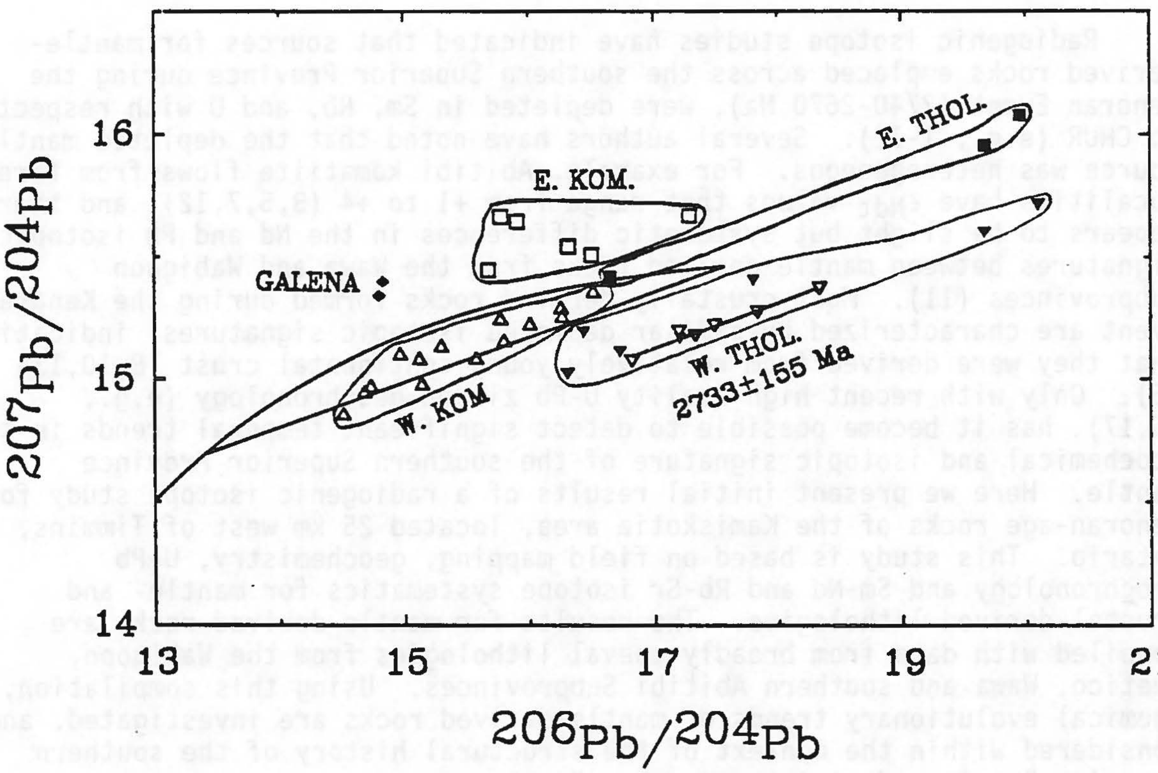

Fig. 3. Pb isotope data on eastern and western komatiitic and tholeiitic amphibolites compared to the Pb isotope data for galena from within the belt (3). Whereas the Pb data for the western tholeiites from a number of outcrops show a scatter, the data for samples from one outcrop lie closely about a line and give an age of 2733±155 Ma.

1. Krogstad et al., 1988, LPI Technical Rep., 88-06, 84-86.
2. Taylor and Mc.Lennen, 1981, Phil. Trans. Roy. Soc. Lond., **A301**, 381-399.
3. Chernyshev et al., 1980, J. Geol. Soc. India, **21**, 107-116

GEOCHEMISTRY AND Nd-Sr ISOTOPE SYSTEMATICS OF THE KAMISKOTIA AREA, WESTERN ABITIBI SUBPROVINCE, CANADA: IMPLICATIONS FOR MANTLE PROCESSES DURING THE FORMATION OF THE SOUTHERN SUPERIOR CRATON

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Radiogenic isotope studies have indicated that sources for mantle-derived rocks emplaced across the southern Superior Province during the Kenoran Event (2740-2670 Ma), were depleted in Sm, Rb, and U with respect to CHUR (e.g., 1-12). Several authors have noted that the depleted mantle source was heterogeneous. For example, Abitibi komatiite flows from three localities have ϵ_{Ndt} values that range from +1 to +4 (3,5,7,12), and there appears to be slight but systematic differences in the Nd and Pb isotopic signatures between mantle-derived rocks from the Wawa and Wabigoon Subprovinces (11). Most crustally-derived rocks formed during the Kenoran Event are characterized by similar depleted isotopic signatures, indicating that they were derived from relatively young continental crust (8,10,13-15). Only with recent high quality U-Pb zircon geochronology (e.g., 16,17), has it become possible to detect significant temporal trends in the geochemical and isotopic signature of the southern Superior Province mantle. Here we present initial results of a radiogenic isotope study for Kenoran-age rocks of the Kamiskotia area, located 25 km west of Timmins, Ontario. This study is based on field mapping, geochemistry, U-Pb geochronology and Sm-Nd and Rb-Sr isotope systematics for mantle- and crustal-derived lithologies. The results for mantle-derived rocks are compiled with data from broadly coeval lithologies from the Wabigoon, Quetico, Wawa and southern Abitibi Subprovinces. Using this compilation, chemical evolutionary trends of mantle-derived rocks are investigated, and considered within the context of the structural history of the southern Superior Province during the Kenoran Event.

The Kamiskotia area straddles a major granitoid-greenstone terrane boundary, and includes the westernmost extent of the Destor-Porcupine Fault Zone (DPFZ) of the Porcupine Gold District (largest lode gold district in the world, with 1530 tonnes Au produced, (18)). Central to the area is the Kamiskotia gabbroic complex (KGC), a large (170 km^2) tholeiitic intrusion overlain by a genetically-related, massive sulfide-hosting, bimodal volcanic suite. This stratigraphic package has been deformed by the diapiric emplacement of three granitoids, and then by late N-S compression which was possibly synchronous with deformation along the westernmost DPFZ (19). From U-Pb geochronology, the KGC and related volcanic rocks are 2707-2705 Ma, and two of the granitoids are 2695 and 2694 Ma (20). Late movement along the westernmost extent of the DPFZ is older than 2686 Ma, from U-Pb garnet and sphene analyses on a late- to post-tectonic alkalic metasomatic dike, spatially and temporally associated with gold mineralization (21).

For Kamiskotia lithologies, whole rock ϵ_{Ndt} and I_{Srt} values are calculated using U-Pb ages and range from -0.37 to +3.84 and 0.70084 to 0.71828, respectively. A KGC plag-cpx-whole rock Sm-Nd isochron from a fresh ferroan gabbro has an age of 2712 +/- 30 Ma, in close agreement with the U-Pb age, and an ϵ_{Ndt} of +2.53 +/-0.78. This is close to an estimate of the Abitibi depleted mantle source of ϵ_{Ndt} = +2.49 +/-0.27 determined from leached clinopyroxene separates from mafic - ultramafic sills (7). The majority of Kamiskotia lithologies have similar depleted ϵ_{Ndt} values from +2.0 - +3.0 and depleted mantle model (t_{DM}) ages of 2.7 Ga to 2.8 Ga, implying a recent extraction from a depleted mantle reservoir. Two late granitoids have ϵ_{Ndt} of -0.37 and +0.60, respectively, suggesting that they were derived from a slightly older, enriched crustal reservoir.

REE and Sm-Nd data for Kenoran-aged, mantle-derived lithologies with (or well-constrained by) high precision U-Pb ages (3-10,12,16-25) have been compiled for comparison with Kamiskotia rocks (Fig. 1). Voluminous tholeiitic basalts and komatiites, and large, supracrustal tholeiitic intrusions, characterized by low REE contents and low Ce/Yb)$_{CN}$ ratios were emplaced from >2740-2697 Ma. They were followed by LREE-enriched intrusive and extrusive alkalic rocks from 2700-2673 Ma. In the southern Abitibi Subprovince, tholeiitic and komatiitic suites from 2714 Ma to 2697 Ma have more depleted average ϵ_{Ndt} values from +2.5 - +2.8, similar to tholeiites from the Wawa Subprovince (11). Their high ϵ_{Ndt} values are consistent with minimal interaction with an enriched crustal component, typical of extensional regimes. Southern Abitibi alkalic rocks were emplaced coincident with or shortly after a regional transpression event (21,26). The younger alkalic rocks have an enriched ϵ_{Ndt} signature, with lower ϵ_{Ndt} values of +1.0 - +1.5 for a Kamiskotia area alkalic metasomatic dike and the Timiskaming volcanics. Southern Abitibi alkalic rocks exhibit a consistent enrichment in ϵ_{Ndt} outside of error (typically +/- 0.5 at 2-sigma level) with respect to uncontaminated Abitibi and Wawa tholeiites and komatiites. In the Wabigoon and Quetico Subprovinces, both tholeiitic rocks (2740-2720 Ma) and intermediate to felsic rocks with an alkalic affinity (2690-2685 Ma) have average ϵ_{Ndt} values from +1 - +2.5 (10).

At 2695 +/-10 Ma, there was a dramatic shift from the production of predominantly primitive, depleted tholeiitic - komatiitic melts, to predominantly enriched, locally volatile-rich alkalic melts across the southern Superior Province. This was coincident with a shift from predominantly island arc - back arc-like tectonics (16,21,27) to a transpressional, wrench fault tectonic setting (28-30), and with gold mineralization (17,21). The regional extent of nearly contemporaneous alkalic magmatism (extending >600 km E-W) may be due to a major mantle metasomatic event involving an extensive portion of the Archean mantle. By comparison with modern volcanic arc settings, subduction of a slightly older, isotopically enriched crustal (sedimentary?) component could account for the change in ϵ_{Ndt} values in the Abitibi (31-35), although alternatives (e.g.,36-39) should be considered. The role of subducted crustal material in Kenoran mantle enrichment processes needs to be properly addressed through more detailed trace element geochemistry and Pb-Sr-Nd isotope studies of mantle-derived rocks, and of potential sources for mantle enrichment such as LIL- and LREE-enriched sedimentary rocks.

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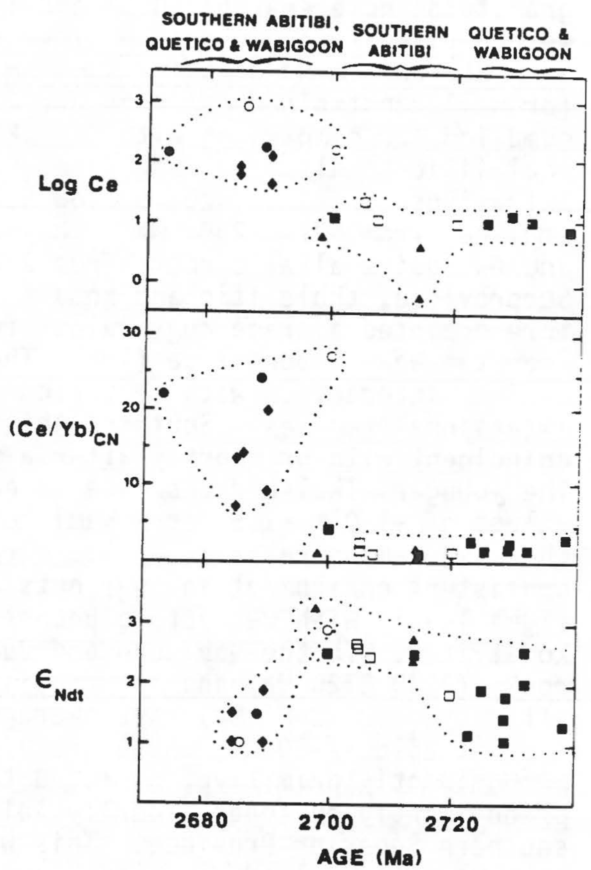
FIGURE 1.



■ - Tholeiitic
▲ - Komatiitic
● - Alkalic: includes albitite, lamprophyre, trachyte
◆ - Alkalic / Calc-alkalic: includes trachyandesite, monzodiorite, hornblendite

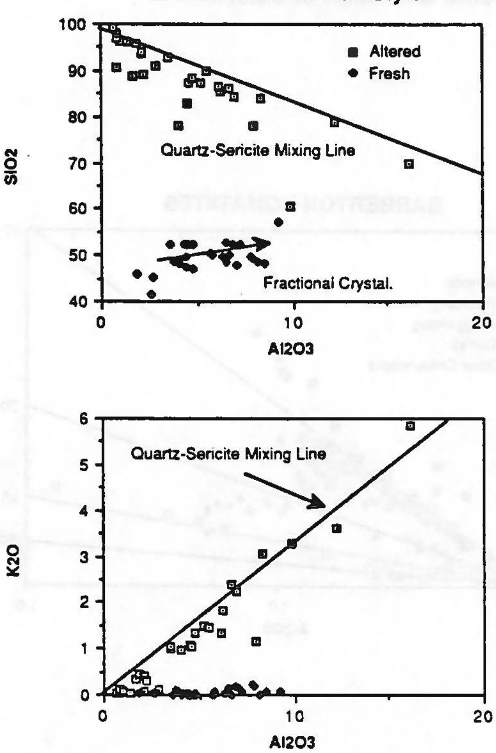
SYMBOLS REPRESENT AVERAGE OF 1 TO 15 ANALYSES.
OPEN SYMBOLS: THIS STUDY

MENDON FORMATION KOMATIITES: EXTREME AL2O3/TIO2 VARIATION IN THE UPPERMOST ONVERVACHT GROUP OF THE BARBERTON GREENSTONE BELT, **Gary R. Byerly, Department of Geology and Geophysics, Louisiana State University, Baton Rouge, LA 70803**

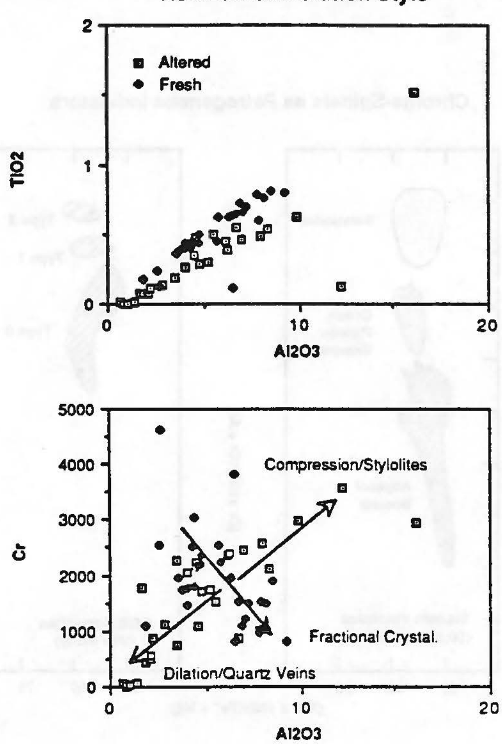
A revised stratigraphy for the central Barberton greenstone belt recognizes a new uppermost formation in the Onverwacht Group that is composed of interbedded sediments and komatiitic lavas (10; Lowe and Byerly, in review). These rocks have for many years been interpreted as Lower Onverwacht units faulted into place in the sequence. Indeed many low-angle faults do occur in this part of the greenstone belt, but several distinctive marker beds have been used to correlate units in isolated structural units. The Mendon Formation differs significantly from the other komatiitic formations of the Onverwacht Group in several aspects. In some Mendon sections sedimentary interbeds are volumetrically more important than lavas; Mendon sediments are all shallow-marine though they may be correlated to deep-water sediments in the northern greenstone belt; and, komatiitic flowtops are frequently extremely altered. These komatiitic alteration zones are interpreted as products of weathering at the rock-water interface (9). Interbedded sediments and altered flow-tops suggest that significant intervals of time elapsed between eruptions that formed the five komatiitic members of the Mendon Formation.

Alteration of some of the Mendon komatiites presents a major problem to understanding their magmatic petrogenesis. This alteration is characterized by replacement of primary minerals by fine-grained quartz and sericite, but often with remarkable preservation of original textures. SiO2 and K2O have been added to these rocks; and FeO, MgO, CaO, Na2O removed. Al2O3 and TiO2 are variable, but A/T (= Al2O3/TiO2) is constant within a single flow or sequence of flows. Variable Al2O3 and TiO2 at a nearly constant A/T is due to olivine fractionation but also to two distinctive alteration processes. The altered rocks in places developed styolites that have concentrated sericite and rutile; elsewhere quartz veins were emplaced, diluting the other rock components. In these altered rocks ratios of the relatively immoble elements, including Al, Ti, Cr, V, Zr, Y, and Sc, are nearly constant and probably reflect original magmatic ratios. Because these altered komatiites represent important end-components of volcanic episodes they have been carefully studied and compared to the less abundant, relatively fresh komatiites of the Mendon Formation.

Komatiitic Alteration Style



Komatiitic Alteration Style



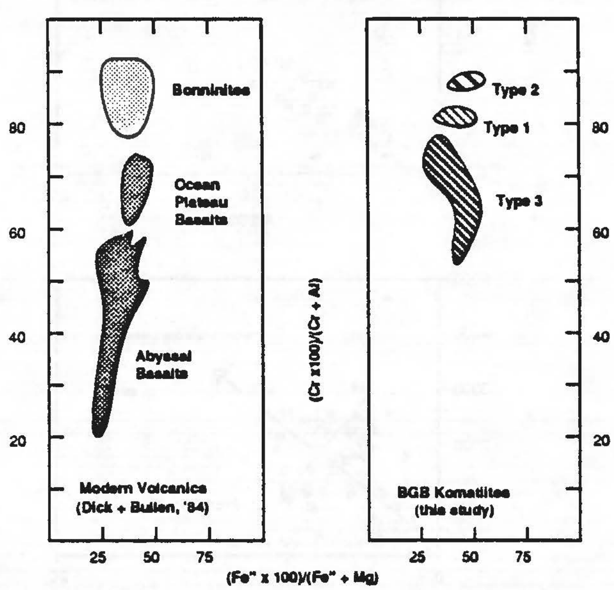
Mendon Formation Komatiites: Al2O3/TiO2 Variation

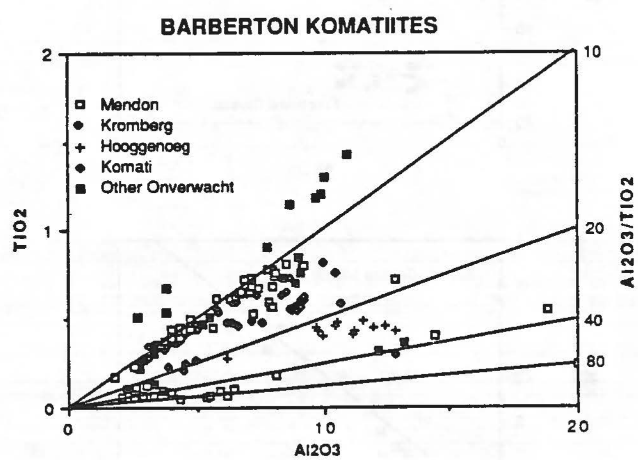
Gary R. Byerly

Chrome-spinels are commonly the only magmatic phase preserved in the Barberton komatiites. All Barberton komatiites contain very chrome-rich spinels. Spinel zoning trends in all but the two Type 3 komatiites display little variation in chromium, but major variation in magnesium and iron. The outer margins commonly display enrichment in titanium and manganese, and typically have a discrete overgrowth of magnetite. The cores of these spinels seem to have unmodified magmatic compositions whereas the magnetite overgrowths are probably of low-grade metamorphic origin. Compositional zoning in the outer margins of the grains is probably magmatic. Barberton komatiitic spinels are unlike modern abyssal basalts (MORB) but rather more like the unusual spinels found in the basalts of oceanic platforms, the boninites of island arcs, or the rare "ultramafic" lavas of some ophiolites (4,5). Cr# = Cr/(Cr+Al) is plotted against Fe# = Fe"/(Fe"+Mg), for modern volcanics, and the Mendon komatiites of this study. The groupings for Barberton lavas are based on rock A/T ratios: Type 2 < 15, 15 < Type 1 < 30, and Type 3 > 30. Since Cr is favored in solid phases and Al in liquids during partial melting a first order interpretation would be that all these rocks with high Cr# spinels formed by unusually high degrees of partial melting. Cr# changes dramatically with variation in degree of partial melting while Fe# changes little. Conversely, during fractional crystallization Fe# changes radically while Cr# changes only slightly. Indeed, for low-Al melts the spinel Cr# may remain nearly constant with increasing Fe# (7). In more typical compositions of MORB the zoning in single spinels may be extreme and show either increases or decreases in Cr# with slight to moderate increases in Fe#. A close correlation exists between rock and spinel Al2O3 contents (12). Barberton Al2O3-depleted komatiites, Type 2, are high rock Si/Al, and Cr-rich (Al-poor) spinels, whereas Al2O3-enriched komatiites, Type 3, have low Si/Al rocks and have relatively Cr-poor (Al-rich) spinels. Type 1 komatiites have chondritic A/T in the rocks and intermediate Al in the spinels.

Much of the major and trace element variation found in the Type 2 Mendon Formation komatiites can be ascribed to simple partial melting leaving a mantle residue of olivine, followed by lower pressure olivine fractionation and finally olivine plus clinopyroxene fractionation. Fractionation of melts from 26% to16% MgO require about 35% removal of olivine. The maximum range of fractional crystallization is about 50% to include the komatiites down to 10-12 % MgO. A nearly continuous variation exists from the high MgO to the low MgO lavas. The Sc and V contents of the lavas suggest a substantial amount of late augite fractional crystallization as seen in deflections in the Sc and V from constant ratios with Ti. Incompatible, immobile element ratios in Mendon Formation komatiites are consistent with those found in the Type 2 lavas that predominate in the lower Onverwacht (13). These are distinctly non-chondritic and nearly unique to early Archean greenstone belts. Aluminium, vanadium, and, to a lesser extent, scandium are especially depleted in these lavas as seen in their nonchondritic ratios with other incompatible elements. Petrogenesis of the Type 1 and Type 3 komatiites in the Mendon Formation has been more difficult to evaluate since these are largely represented by flows with extreme alteration effects.

Chrome-Spinels as Petrogenetic Indicators





Mendon Formation Komatiites: Al2O3/TiO2 Variation

Gary R. Byerly

Komatiites and komatiitic basalts occur throughout the Onverwacht Group. The stratigraphically lowest formation in the coherent block of the southern Barberton greenstone belt is the Komati formation, which is composed of predominant Type 2 lavas and minor Type 1 lavas (13). A single example of Type 3 lava is reported (8). Units H3 and H4 of the Hooggenoeg are exclusively Type 1 lavas (16; unpublished data, Byerly). The Kromberg Formation contains minor Type 2 komatiitic lavas interbedded with tholeiites throughout (Vennemann and Smith, in review), with one major unit, the Mafic Lapilli Tuff, KR2, Type 2 komatiitic basalt (Ransom, Byerly, and Lowe, in review). Stratigraphic units of unknown correlation to these Onverwacht formations include the Theespruit with abundant Type 2 komatiites and a single Type 3 komatiitic basalt (8); the Sandspruit with abundant Type 2 komatiites (8); the Weltevreden with abundant Type 1 komatiite and minor Type 2 and 3 komatiite (unpublished data, Byerly); the Schapenburg, with abundant Type 2 komatiites and komatiitic basalts (2); and the Jamestown, with four analyses of Type 2 komatiite (1). Several of the Onverwacht formations are quite distinctive based on major element analyses available in the literature. The Sandspruit Formation has a very low A/T of 8. These compositions do not overlap with any other Barberton komatiites. It is possible that in some way the higher grade of metamorphism typically found in the Sandspruit might affect the A/T, but Schapenburg rocks and some Theespruit rocks are metamorphosed to similar higher grade mineralogies without an apparent decrease in this ratio. The Hooggenoeg Formation basaltic komatiites produce a distinct trend at a moderately high A/T of 25. Other Type 1 komatiites and komatiitic basalts have A/T close to 16. Most Mendon Formation samples, and all samples from M2 and M3, display very little variation from the most common Barberton A/T of about 10. The widespread distribution of Type 1 and Type 3 lavas in the Mendon Formation is seen in both rock and spinel compositions. M1 is everywhere composed of Type 3 komatiites with A/T of about 80. The lower flows in M4 are Type 3 komatiites with A/T of about 40. Several flows in M4 and M5 are Type 1 komatiites with A/T near 25.

The importance of variable A/T in komatiite petrogenesis has long been recognized (11; see 14 for review). Several possible mechanisms seem likely responsible for the variation. A) <u>Fractional depletion or enrichment of garnet in an initially chondritic mantle source</u>. This could have taken place early in Earth history but should have resulted in a radiogenic isotopic signiture apparently not found in Archean komatiites, thus garnet redistribution immediately prior to, or during, partial melting is necessary (8). B) <u>Assimilation of crustal rocks with very high A/T</u>. This could take place in the lower crust or on the surface (3). Geologically the correlation of high A/T komatiites with sedimentary interbeds and perhaps prolonged time intervals between eruptions favors a contamination model. The relatively constant A/T along strike within single flows of the Mendon Formation suggests that if contamination took place it was more likely in the subvolcanic environment. A contamination model does not explain the coexisting Type 2 komatiites. C) <u>Mantle metasomatism of a depleted mantle source</u>. The intimate coexistence of this extreme range of A/T komatiites in the Mendon Formation suggests a model like that proposed for the upper sections of Troodos (15), except with a mantle with low initial A/T. A/T remains constant within limited groups of flows but ranges from 20 to over 65 for the upper Troodos group. This is attributed to variable degrees of melting, at least in part due to variable metasomatism of the local mantle, with progressive melt extraction. At Troodos the A/T does seem to change systematically with stratigraphic height suggesting progressively higher degrees of partial fusion with time. Although individual stratigraphic units in the Mendon Formation have distinctive A/T, there is no obvious temporal variation within this formation or the Barberton sequence as a whole.

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GEOCHEMISTRY AND GEOCHRONOLOGY OF LATE ARCHEAN MAFIC-ULTRAMAFIC SUPRACRUSTAL AMPHIBOLITES FROM THE NORTHEASTERN SINO-KOREAN CRATON, CHINA;
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Isotope data published by previous workers document the presence of Early Archean metabasaltic inclusions in the tonalitic gneisses west of Bohai Bay, eastern Hebei Province, P.R.C. Somewhat similar metakomatiitic amphibolites crop out as basal(?) supracrustal members of the Archean section northeast of Bohai Bay in southern Jilin/eastern Liaoning Provinces. Six analyzed specimens of the latter unit are more magnesian (averaging approximately 13 vs 7 weight percent MgO) and, although exhibiting a wider range of REE concentrations, on the average display the same degree

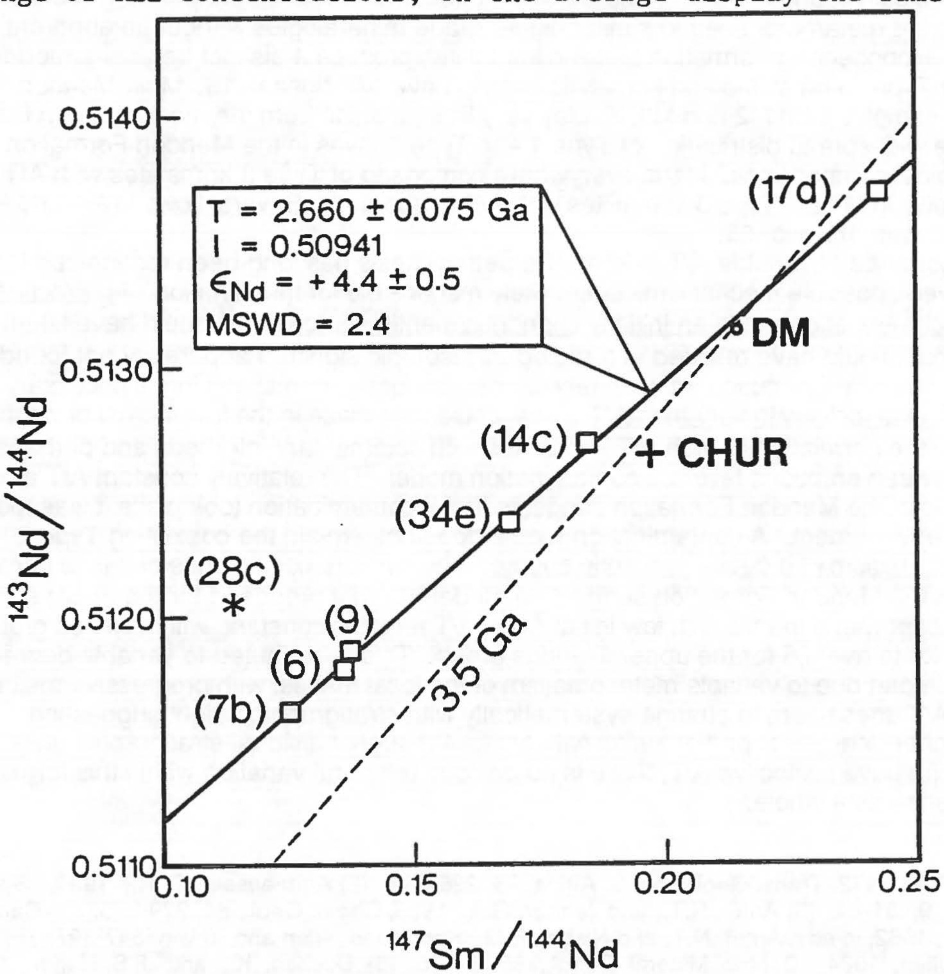

Fig. 1. Nd-Sm bulk-rock isochron diagram for seven analyzed mafic-ultramafic metamorphic rocks from the southern Jilin/eastern Liaoning basement series. The six supracrustal amphibolites of komatiitic chemical affinities define an isochron of Late Archean age. The mafic xenolith in tonalitic gneiss (no. 28c) lies well off this aray, and cannot be consanguineous with these other mafic-ultramafic melts. A 3.5 Ga isochron (as appropriate for the most ancient rocks in China, mafic inclusions from eastern Hebei Province) is illustrated for reference.

of fractionation in REE contents (La-Lu = 24-7X) compared to the former (24-9X). In terms of bulk-rock chemistry, metakomatiitic supracrustals from southern Jilin/eastern Liaoning Provinces are at least as primitive, and, therefore, could be as ancient as the 3.5 Ga old mafic inclusions in Hebei tonalites. However, new Nd-Sm and REE analyses for the six bulk rocks, combined with available petrologic/geologic information, indicate that metakomatiitic amphibolites from the Sino-Korean shield northeast of Bohai Bay are Late Archean in emplacement age. As shown in the Nd-Sm isochron of Fig. 1, this widely distributed igneous suite apparently separated from the mantle at about 2.66±0.075 Ga. ε_{Nd} values of +4.4±0.5 are illustrated in the Nd evolution diagram of Fig. 2. The data suggest a prior long-continued history (> 1.0 Ga) of depletion for this portion of the Late Archean Sino-Korean subcontinental lithosphere.

A seventh analyzed sample (no. 28c), a mafic inclusion of unknown origin in tonalitic gneiss, is strongly enriched in LREE, and possess disturbed major element proportions. Judging from isotopic data, which yield a depleted mantle model age of 1.67 Ga, it could represent a cognate xenolith in a mid Proterozoic tonalitic intrusion (shown on present maps as Archean in age).

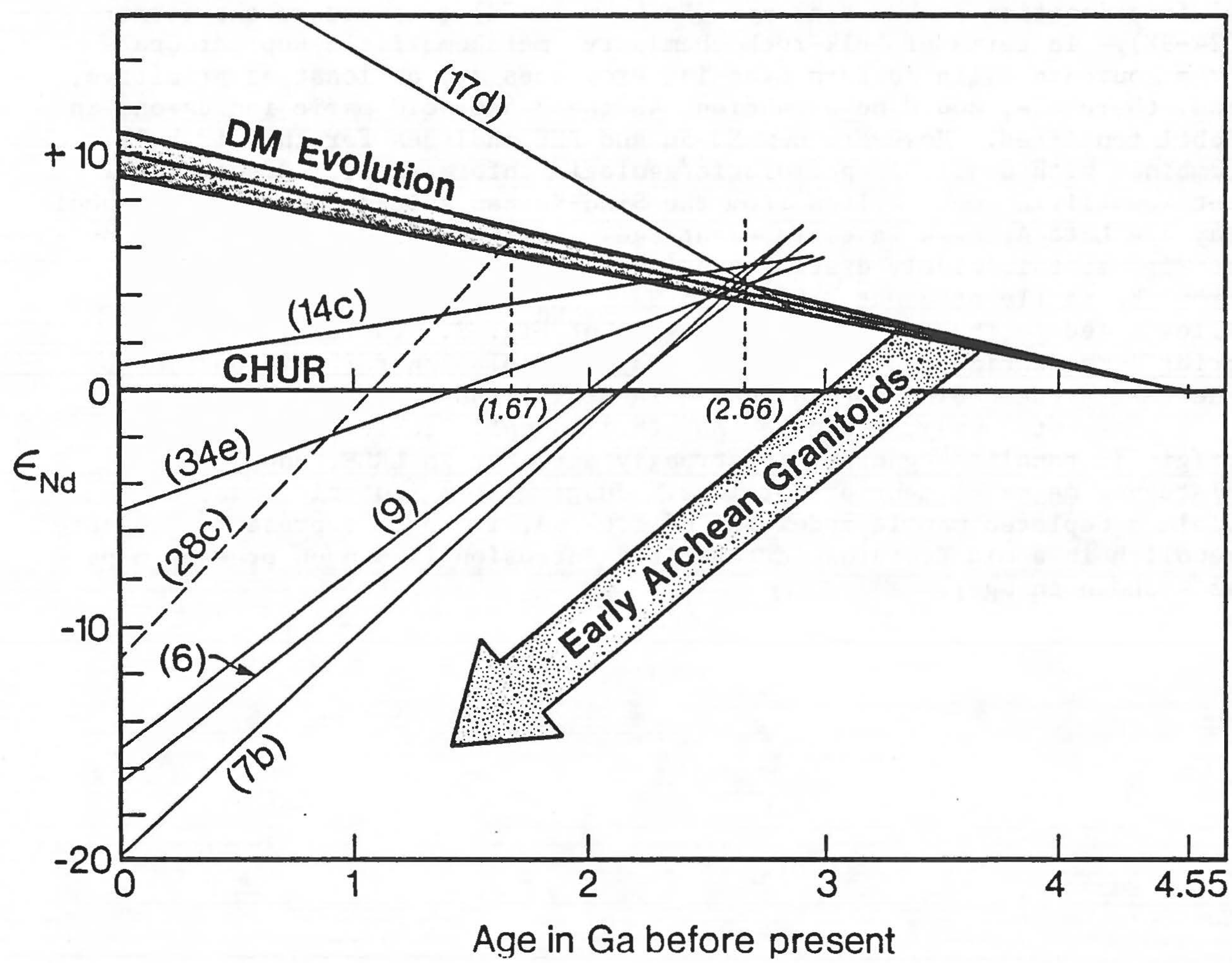

Fig. 2. ε_{Nd} evolution diagram for the analyzed mafic-ultramafic metamorphic rocks from southern Jilin/eastern Liaoning Provinces. The six supracrustal metakomatiitic amphibolites possess Nd isotopic curves which intersect the depleted mantle ε_{Nd} line in the vicinity of 4.4±0.5 in Late Archean time. In contrast, the isotopic evolution line for the mafic xenolith in tonalitic gneiss (no. 28c) intersects the depleted mantle curve line at about +6.5 in mid Proterozoic time. The isotopic evolution of sialic crust which separated from depleting mantle in Early Archean time (as appropriate for Early Archean enclaves in eastern Hebei tonalitic gneisses) is shown for reference.

THE GEOLOGY AND TECTONICS OF VENUS AND SOME POSSIBLE IMPLICATIONS FOR THE ARCHEAN EARTH; James W. Head, Dept. of Geological Sciences, Brown Univ., Providence, R.I. 02912

On the basis of thermal models and the high eruption temperatures implied by komatiitic lavas, the Earth's Archean upper mantle is thought by most workers to have been several hundreds of degrees hotter than at the present time, and yet there is evidence for Archean continental lithosphere P-T conditions being similar to those today (1). The implications of higher temperatures in the upper mantle include the possibility of greater advective heat loss, and an increase in the thickness of oceanic crust created at spreading centers, and these factors and the evidence for more normal thermal gradients in the continents, raise the question of the style and form of mantle convection and how it might be manifested in local, regional, and global heat-loss mechanisms. A variety of lithospheric heat-loss mechanisms (e.g., conduction, convection, advection, plate recycling, hot-spots) are observed on the planets (2) and these provide a basis for considering the range of styles that might have existed in space and time in the Earth's Archean.

In addition, if crustal spreading and plate tectonics were a typical and significant mechanism of heat-loss in the Archean, then the implied higher global average heat loss, and evidence for regional variations in heat loss, raise questions about the nature of these processes in terms of: 1) divergence- the style of crustal accretion at spreading centers, potential variations along and across ridges, and more precise estimates of heat loss per unit ridge length, 2) intraplate regions- the thermal structure, buoyancy, rigidity, deformation, and thermal and structural evolution of lithospheric plates, 3) convergence- environments of crustal/lithospheric loss at convergent boundaries and variation in styles related to crustal thickness, lithospheric buoyancy, and the thermal and mechanical structure of the lithosphere; if most Archean oceanic crust has been recycled, what is the evidence at convergent boundaries that would permit the identification and establishment of the presence of converging oceanic lithosphere in the Archean?, 4) global patterns- the total inventory of ridge lengths and spreading rates on the planet required for specific heat loss scenarios (3), the implications of these length/rate scenarios for the homogeneity and heterogeneity of heat loss (and the implications for the nature of convergent boundaries), 5) balance of forces- the distribution and relationship of forces in a recycling lithosphere system, and 6) links between crustal spreading/plate recycling and mantle convection- how closely are styles and patterns of mantle convection (e.g., whole-mantle, layered, hot spot, etc) related to observed and predicted patterns of plate recycling?

The terrestrial planets, and in particular Venus, the most Earth-like of the terrestrial planets, may offer clues to the answers to some of these questions. Venus, because of its very high surface temperature (735K), may have many similarities to the Archean in terms of higher upper mantle temperature, thinner lithosphere, thicker 'oceanic' crust at any spreading centers, lithospheric buoyancy, geometry, tectonic style, and balance of forces at convergent zones, and styles and patterns of regional and global heat loss. The purpose of this contribution is to review aspects of the current knowledge of the tectonics of Venus to identify potential areas that might have implications for the Archean Earth.

On the basis of data obtained for Venus to date (4), the tectonic style of Venus is characterized by extensive linear zones of deformation, in some places extensional and in others compressional, suggesting the possibility of large-scale lateral movement, as well as distinctive regions of broad topographic rises and associated volcanism, suggesting the possibility of localized thermal rises and hot-spot volcanism. These characterisitcs are in general contrast to the stable lithospheres, vertical tectonics, and the conduction-dominated heat loss typical of the smaller terrestrial planets (2, 5). Volcanic plains deposits are widespread, making up over 50% of the surface of the areas observed, although the detailed origin of the plains is not known. The average age of the surface so far observed at high resolution is less than one billion years, and perhaps as young as several hundred million years(6), comparable to the average age of the Earth, and much less than that of the smaller terrestrial planets. These observations argue that although conduction must be a factor, other mechanisms of heat transfer, such as advective/hot spot (7), and plate recycling (8), may be significant on Venus (2,9).

Crustal Spreading- Evidence for divergent plate boundary characteristics and crustal spreading in Aphrodite Terra has recently been presented (8), including linear rise crests, bilaterally symmetrical topography, central troughs, fracture zone-like features, offset rise crests at fracture zones, split and separated topography, Icelandic-like plateau regions, and thermal boundary layer-like topographic signatures suggesting spreading rates of mm to a few cm per year. Terrestrial spreading centers have been modeled under Venus conditions (10): a typical spreading center mapped to Venus would produce an average crustal thickness of 15 km due to enhanced upper mantle temperatures. The topography and gravity of Aphrodite are consistent with a plateau-like central region with crustal thickness of about 30 km spreading at about 0.5 cm/yr for the past 200 My, flanked by a zone of more normal crustal thickness (15-20 km). These observations, as well as other characterisitcs of Aphrodite Terra, suggest that changes in upper mantle temperature of the order of 100^{o}C may be common along the strike of the rise crest in both space and time. In addition, large, localized volcanoes are often seen along the rise crest, suggesting that effusion and construction may be more common in this environment than on Earth at present.

Hot spots- Regional areas of Venus (2000 x 3000 km scale) such as Beta and Atla are characterized by broad domes and superposed volcanism (11) and it has been proposed that there are a sufficient number of these areas to account for the majority of heat loss (7,12). These areas are linked to zones of rifting and crustal spreading by a predominantly equatorial pattern of linear rises. They also mark the convergence of a number of these tectonic trends, usually three as in the case of Beta Regio (11). Therefore they may represent part of a larger system of heat loss linked to extension and convergence.

Convergent Boundaries- The distinctive orogenic belts (13) in Ishtar Terra show evidence of extensive shortening and crustal thickening, as well as a variety of tectonic architectures (14). These data suggest that crustal/lithospheric underthrusting and loss are taking place even in an environment that would favor positively buoyant lithosphere (15). For example, Freyja Montes (14) show evidence of outboard flexure, a foredeep, and underthrusting, and segments of outboard brittle upper crust appear to have been delaminated and imbricated onto the mountain range in a manner similar to that outlined for flake tectonics (16).

Global Boundaries and Total Ridge Length- The incomplete high resolution data coverage for Venus precludes documentation of total ridge length and determination of the geologic characteristics and rates of geologic activity along all of the observed rises. The upcoming Magellan mission will provide global high-resolution coverage and permit a better assessment of the global nature of boundaries.

Regional and Global Variations in Heat Loss- There is evidence of regional variations in tectonic style (equatorial divergence, high northern latitude convergence (17)), and evidence that portions of the surface are slightly older and more stable than others. For example, although crater densities are insufficient to determine ages of small areas in the northern hemisphere covered by the Venera 15/16 missions, there is nonetheless evidence for a systematic decrease in crater density from high numbers toward the North pole, to low numbers toward the equator (18), where zones of crustal spreading appear to be active today. The Equatorial Highlands, a band of positive topography oriented about 21 degrees to the equator(19), visibly dominate the near-equatorial region and a plot of global average elevation as a function of latitude show a strong bilateral symmetry centered on these highlands (20). This suggests that the equatorial highlands may represent fundamental aspects of deeper convection in the Venus interior.

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Geochemistry and Isotopic Characteristics of Archean Basalts and Komatiites and Their Inference on Early Crust-Mantle Differentiation

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Chemical composition and evolution of the upper mantle are commonly inferred from geochemical and isotopic study of basalts, komatiites, peridotite nodules, ophiolite slabs and even continental rocks. Several important questions relevant to the Archean mantle evolution include: (1) Possible early Archean mantle stratification through crystallisation of terrestrial magma ocean, (2) Significance of highly depleted domains in the Archean mantle- were they resulted from extraction of continental crust or from intra-mantle differentiation processes? (3) Archean basalts and komatiites often show LREE-enriched characteristics, yet the available Nd isotopic data invariably suggest that the Archean mantle was generally depleted. Could this apparent contradiction be due to the role of recycling of continental crust? (4) Significance of negative Eu anomalies in komatiitic rocks- any connection with an early formation of anorthositic crust? These questions may partially be answered with Nd isotopic information and geochemical study of certain useful trace elements, particularly REE and Nb-Ta, in Archean basalts and komatiites.

A review of REE geochemistry and Nd isotopic compositions in Archean basic-ultrabasic rocks leads to the following conclusions: (a) For Archean komatiites, the classification based on heavy REE typology or (Gd/Yb)N ratios is well correlated with Al2O3/TiO2 or CaO/Al2O3 ratios. Such chemical variation is best explained by garnet fractionation process, though it is still debatable whether the fractionation took place during magma genesis or as a result of garnet precipitation in early terrestrial magma ocean(s) leading to stratified mantle layers from which different types of komatiites were generated. (b) Light REE distributions in basalts and komatiites are highly variable. LREE-depleted signature, i.e., $(La/Sm)N < 1$, is evident for the majority of Archean basic-ultrabasic rocks, suggesting that their mantle sources were depleted in LIL and other incompatible elements. This depletion is most likely caused by extraction of continental material. However, except for some PK, Archean rocks appear to be "less depleted" than the modern N-MORB, and many are in fact even "enriched" in LREE. This in turn suggests that (1) less volume of continental material had been extracted in the Archean, (2) previously highly depleted mantle had been refertilised by reinjection of early continental material (= recycling of continental crust), or (3) mantle-derived basic and ultrabasic melts have been contaminated by older crustal material. Nd isotopic arguments and commonly observed high La/Nb ratios favor (2) or (3) above, but cannot distinguish them easily.

Initial ϵNd values for most Archean rocks range from +2 to +4, almost irrespective of their ages. It first implies that the upper mantle has been significantly depleted, likely by removal of continental material, since at least 4 Ga ago. Moreover, the survival time for highly depleted mantle sources, as evidenced by the occurrence of very LREE-depleted PK, could not have lasted for long; otherwise the depleted sources would have increased their ϵNd value rapidly, up to +10 by 2.5 Ga. The lack of very high ϵNd value in late Archean rocks could be due to the re-enrichment effect by continental recycling or re-equilibration with upward input of chondritic(?) lower mantle material. Alternatively, the Nd isotopic data may be interpreted as resulting from contamination of mantle-derived melts by continental rocks during magma intrusion/extrusion episodes.

In many Archean terranes, komatiitic rocks often show very persistent negative Eu anomalies in their REE patterns. This leads us to reconsider the possibility of early anorthositic extraction as a possible cause of such anomalies. However, in order to produce such high degrees of negative Eu anomalies, massive quantity of plagioclase (20 to 30% of mantle source region in some cases) would be required to separate to form anorthositic crust. Yet no vestige of such an important crust has ever survived. It is hence concluded that Eu anomalies (both + and -) in Archean basic-ultrabasic rocks impose no petrogenetic significance and are likely due to post-magmatic alteration processes, in which Eu geochemical behavior may be decoupled from the rest of REE. Furthermore, there have been suggestions that terrestrial magmas are probably water rich, and unlike lunar basalts, they are not dense enough to float plagioclase. If garnet precipitation is taken into account as envisaged in the magma ocean concept, much of the Al budget would be consumed and there would be little Al left for crystallisation of plagioclase at shallow depths.

BOUNDARY CONDITIONS FOR THE ARCHEAN MANTLE. John H. Jones, SN2, NASA Johnson Space Center, Houston, TX 77058.

Presently, there is little agreement between geophysicists as to whether the Earth's upper and lower mantles are chemically similar [e.g., 1,2]. However, there is evidence that the upper mantle was chemically homogenized in pre-Archean times. There is also strong evidence that the upper mantle has not chemically equilibrated with the core or participated in core-forming processes during the last 3-3.5 billion years [3]. There remains some question concerning the ability of the mantle to mix and disperse heterogeneities such as the "Dupal" anomaly [4]. However, this observation is compromised by the possibility that old continental materials have been subducted recently. On balance, therefore, it seems most reasonable to assume that the Archean mantle looked quite like the mantle we observe today. In particular, it appears that there may have been mantle that looked very much like the present-day sources of mid-ocean ridge basalts (MORB mantle). Also, even though radioactive heat sources were more vigorous in the Archean than today, it is quite possible that rates of convection in the Earth have been similar over most of geologic time [5]. Thus, it is possible to paint a picture, describing the Archean mantle as being rather similar to the present mantle.

Equilibration with the Core. A popular model for the origin of the unexpectedly high abundances of noble siderophile elements in mantle xenoliths is that of inhomogeneous accretion [6]. In this model, the Earth began as a very reduced planet and formed a core that efficiently removed Fe and elements more siderophile than Fe into the core. Later accreted material, which constitutes ~10-15% of the final mass of the Earth, is more oxidized. Metal may still separate from this later mass of material but much less readily, so that only the very most siderophile elements are extracted into the core. Finally, the Earth accretes its last ~1% of material, which is so oxidized that further core formation is not possible. In this model noble siderophile elements in the Earth's mantle should exist at about 1% of CI, while moderately siderophile elements exist at ~10% of CI. This is approximately what is observed, although deviations from this simple scenario can be found [7]. In any event, the rather high f_{O_2}'s observed in present-day mantle-derived materials and the high abundances of noble siderophiles are inconsistent with the presence of (Fe,Ni) metal. Thus, it is inferred that the upper mantle of the Earth is not presently in equilibrium with the core and that the f_{O_2} of the mantle has increased over time [7]. The timing of the last metal-silicate equilibration event will be evaluated below. However, it appears difficult for the upper mantle to have participated in any core-forming events in post-Archean times, since Co/Mg ratios of mantle-derived basaltic liquids have remained essentially unchanged since the beginning of the Archean [8].

Homogenization of the Upper Mantle and its Timing. If the inhomogeneous accretion model discussed above is correct, then certain elements that were added late in the accretion of the Earth were effectively homogenized throughout the upper mantle very rapidly. Elements such as Ni, Co and Ir, that behave compatibly during silicate partial melting, are rather uniform in their abundances in mantle xenoliths. If only spinel lherzolites are considered, there are no apparent differences in the Ni, Co and Ir concentrations of lherzolites from the SW United States, Hawaii, Alaska and Australia [9], at the hand-specimen scale. Garnet lherzolites show more variability in Ir contents but, on average, have either the same mean Ir abundances as spinel lherzolites or somewhat higher ones (~2X) [9]. Nickel abundances in garnet lherzolites are very similar to those in spinel lherzolites [9]. In any event, the data from the spinel lherzolite suite seems to imply that the latest accreting materials were efficiently mixed into the upper mantle prior to incorporation into continental lithospheres and, consequently, isolated from mantle mixing processes. If the ages of silicate inclusions from South African diamonds may be taken to approximate the timing of the separation of continental lithosphere from the rest of the mantle, then homogenization must have occurred prior to 3.0-3.5 Æ [3]. Thus, it is probable that the upper mantle was homogenized in pre-Archean times. Note that fine-scale mixing of late-accreted material need not occur if incomplete core formation was responsible for the high siderophile element concentrations [7], but, regardless of the exact mechanisms for adding/extracting siderophiles to/from the mantle, the upper mantle appears to have once been effectively homogenized.

Can the timing of the last core-mantle equilibration event be specified? Possibly not. However, several model-dependent scenarios can be discussed. Firstly, the $^{238}U/^{204}Pb$ ratio (i.e., μ) of 8-10 in the silicate portion of the Earth is not the chondritic value of 0.15 and the timing of the fractionation event that enriched U relative to Pb in the bulk silicate Earth may yield the time of core formation. This is because Pb is chalcophile and is expected to enter the Earth's core with S at the time of core formation [7]. If so then, in two-stage U-Pb models, either the Earth accreted later than meteorites (~4.45 Æ) and core formation occurred with little change in μ as late as ~1 Æ later <u>or</u> the age of the accreted materials that made the Earth was the same as that of meteorites (~4.55 Æ) and core formation occurred at 4.45, causing a large change in μ [10]. The latter scenario seems more reasonable geochemically [e.g., 7], but other solutions are mathematically possible. Additionally, if the inhomogeneous accretion model discussed above is correct, then materials that possibly possessed very low μ values (i.e., chondritic material) were added to the upper mantle after core formation had ceased. In this case, either a three stage model must be advocated or the time interval between the initiation of core formation and the end of accretion was so short (<< 100 m.y.?) that two-stage models are good approximations to more "rigorous" three-stage models. Again, the latter possibility seems more likely, given the short (<100 m.y.) accretion timescales that are currently in vogue [11].

Summarizing, it seems most likely that the U-Pb age of the Earth dates the time of core formation and that accretion of any "late-stage veneers" occurred immediately following the last core-forming event. The possibility of core formation in Archean or post-Archean times seems unlikely. Again, if a late-stage veneer was added to the upper mantle it must have been effectively homogenized. Homogenization of the last ~1% of accreted material into the upper mantle must have occurred within ~1 Æ of core formation, if it occurred at all.

Global Chemical Differentiation?. It is expected, from our experience with chondritic meteorites and basaltic achondrites, that certain "refractory" elements should exist in the bulk Earth in chondritic relative proportions. If there have been large-scale differentiation events, such as terrestrial magma oceans [12], these refractory elements can fractionate from one another [e.g., 13]. On the other hand, if mantle samples can be found that show minimal fractionations between refractory elements, then we may postulate either that differentiation events have only occurred on relatively small scales or that mixing processes have efficiently erased the traces of earlier global fractionations. In fact, there are mantle xenoliths that possess relatively unfractionated heavy REE (HREE) [9]. The HREE are refractory and are compatible enough at low degrees of partial melting that they can remain relatively undepleted. Further, the HREE also exist in approximately the correct abundances. Relative to CI chondrites, devolatilization and core formation processes are expected to enrich the REE in the mantle by ~2.25X, and the observed abundances of HREE in "fertile" xenoliths are ~2-3X CI [9].

Thus, on the basis of mantle xenoliths, a global differentiation event (such as that associated with the postulated "giant-impact" hypothesis for the origin of the Moon) seems unlikely. On the other hand, it is as yet unclear that any terrestrial basalt has been derived from a previously undifferentiated source region. Thus, inferences from the two types of mantle-derived samples contrast with each other, but it is possible that these discrepant views may be rationalized by consideration of sampling scales. Basalts, which sample much larger volumes than do individual xenoliths, may have had some pristine mantle in their source regions, but the sources must have, *on average*, been differentiated. For example, no known basalt has a chondritic U/Nb ratio [e.g., 14]. These two refractory elements (Nb and U) apparently fractionate very little during ordinary igneous processes, but they are fractionated from the chondritic ratio in all mantle source regions sampled by basalts. The complementary U/Nb reservoir is apparently the continental crust [14]. However, model calculations based on Sm-Nd systematics indicate that ~0-40% of the mantle *could* be pristine [15] and undifferentiated. If pristine mantle exists, however, no known basaltic magmas have been tapped from these sources.

As was alluded to earlier, it is surmised that the continental crust was removed from the mantle reservoir that we now regard as the MORB source. Inasmuch as Archean mantle-derived magmas typically have slightly positive ε(Nd) values, it is also surmised that a great deal of the mantle was depleted very early [5]. What is unknown is the scale and degree of this depletion event. The general lack of basalts older than ~3 Æ with negative initial ε(Nd) values [5] appears to indicate that enriched or metasomatized mantle was rare.

Summary. The Earth's mantle began in a more reduced form than is observed today and core formation depleted the mantle in siderophile elements to varying degrees. By the beginning of the Archean, the mantle was probably much more oxidized than its initial state. Subsequent to core formation at ~4.45 Æ there was a homogenization event whose intensity is model-dependent. Finally, there was a differentiation event (most probably between 4.4-3.9 Æ) that produced continental crust and MORB-like mantle, but which was not so spatially extensive that nearly pristine samples of the mantle cannot be found today.

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ARCHEAN SEDIMENTARY ROCKS AND THE ARCHEAN MANTLE; Scott M. McLennan, Dept. Earth and Space Sciences, SUNY at Stony Brook, Stony Brook, NY, 11794-2100, U.S.A.

Most of our understanding of the composition of the Archean mantle is derived from examining the geochemistry of mantle-derived magmatic rocks. It is generally recognized that sedimentary rocks, if carefully selected, can reveal considerable information about the exposed continental crust of the earth; the special utility of sedimentary rocks being that they provide large scale averaging of the provenance [1]. For the most part, such compositions are dominated by intracrustal fractionation processes which obscure most information about the ultimate mantle sources. However, during the Archean, and especially in Archean greenstone belts, sedimentary rocks commonly lack the signatures of intracrustal differentiation (notably negative Eu-anomalies) [2] and accordingly may provide some useful information about the mantle sources contributing to the crust. The hallmark of Archean sedimentation in greenstone belts is turbidite deposition and such sediments are likely to have been deposited under a variety of tectonic conditions, including both active and passive settings. Phanerozoic deep sea turbidites similarly are characteristic of deposition at both active and passive continental margins. It is at active margins where evidence suggests that the processes of intracrustal differentiation are less severe, or can be accounted for, and thus allow us to examine and characterize the nature of mantle sources [3]. Some data are now available for modern turbidites from continental margins and comparison of such data to Archean turbidites would appear to be pertinent.

Archean sedimentary rocks are preserved both in high grade and low grade metamorphic terranes. In high grade terranes, sedimentary lithologies and facies relationships indicate that deposition, in at least some cases, was in a cratonic environment. In these cases, trace element geochemistry generally mimics that of typical post-Archean sediments, with distinctive negative Eu-anomlies; processes of intracrustal differentiation dominate the sedimentary geochemistry [4,5]. On the other hand, in the sedimentary cycles of Archean low grade terranes, relatively immature greywacke-mudstone turbidite deposits are abundant. The exact tectonic setting of such deposits is a matter of some dispute and it is likely that a variety of settings is preserved. Volcanic components to these sediments suggest that they were deposited in orogenically active settings. It has long been observed that REE patterns for Archean greenstone belt sediments typically lack the negative Eu-anomalies that are so characteristic of the post-Archean [1,2]. This lack of evidence for significant intracrustal differentiation of the igneous sources may provide a window through which we can examine characteristics of the ultimate mantle sources.

A distinctive feature of Archean sedimentary rocks is that HREE-depletion is commonly observed, suggesting that the end member compositions of the Archean bimodal suite are major components of the provenance[1,2]. Such HREE-depletion is uncommon for igneous rocks from arc environments [6], however, there has been a dearth of geochemical data for comparable Phanerozoic sediments and so direct comparisons have not been possible. In Fig. 1, a piot of Eu/Eu* vs. Gd_N/Yb_N is shown for Archean and Recent turbidites. Although there is overlap, Archean turbidite sequences display considerably less Eu-depletion in comparison to Recent sequences, thus confirming the suggestion that intracrustal processes were of less importance during the Archean. Archean turbidites also commonly display HREE depletion ($Gd_N/Yb_N>2.0$), but such characteristics are entirely absent from Recent turbidites ($Gd_N/Yb_N<2.0$).

The origin of HREE-depletion in Archean igneous suites has long been a matter of concern. A commonly cited origin is through melting of tholeiitic basalt or ultramafic compositions at P-T conditions of eclogite stability [7]. The diversity of major element and other trace element data for Archean HREE-depleted igneous rocks suggests that this may not be an appropriate general model and that in many cases a direct mantle origin may be indicated [8]. In the case of the sanukitoid suite, a LIL-enriched mantle source is strongly indicated [9, 10]. Regardless of whether HREE-depleted Archean felsic igneous rocks are derived by direct melting of the mantle or by melting of recycled basaltic/ultramafic material at mantle depths or both, it is possible that Archean crust was derived from a mantle that differed from that generating present continental crust. The nature of this difference is not entirely clear and could have been as simple as differing P-T conditions of melting or as fundamental as differing bulk compositions. It is worth noting that HREE depletion in Archean turbidites is accompanied by low Yb/Hf ratios, suggesting that detailed study of Hf isotope systematics could provide some important constraints.

A second difference between Archean and Recent turbidites, that may have some implications for understanding the Archean mantle, comes from the Th and U data. The Th/U ratio of the upper continental crust is about 3.8 [1]; the ratio in the primitive mantle is also thought to be 3.8 (recent data suggests that it may be as high as 4.2 [11]). During sedimentary processes, the Th/U ratio tends to rise due to oxidation and mobility of uranium. Conditions leading to low Th/U ratios during sedimentary processing are also generally well understood and typically involve rather reduced conditions (e.g.- black shales). Accordingly, some caution is warranted in interpreting such data in terms of provenance. If we examine the Th/U ratio of modern turbidites, many samples with ratios above 4.0 are observed, likely a result of sedimentary processing. It is apparent, however, that samples with low Th/U ratios, significantly less than 3.0, are also common (Fig.2). These low ratios, generally associated with chemically immature samples, are more difficult to explain in terms of sedimentary processes and likely reflect the provenance composition. Other geochemical and isotopic data indicate that this provenance consists of two dominant components of old recycled upper crust and young arc-derived crust. It is the arc-derived component that is characterised by the low Th/U ratios. Low Th/U ratios are commonly observed in arc-derived igneous rocks and there is considerable evidence that low ratios are characteristic features of the mantle sources [12], indicating that the mantle is depleted in LIL-enriched components, most likely due to the generation of the continental crust.

The Archean data display very different characteristics. Many of the samples show quite high Th/U ratios that can be related to relatively severe weathering effects of source rocks. On the other hand, the very low Th/U ratios, of less than 3.0, are absent. Such data can be interpreted in several ways. One possiblity is that weathering conditions were different in the Archean and that many of these samples originally had low Th/U ratios similar to modern turbidites. This is not considered especially likely because samples with clear evidence for severe weathering of the source (e.g.- Pilbara Block [13]) do not show particularly high ratios when compared to similar modern sediments. A second interpretation is that the provenance consists dominantly of differentiated 'upper crust' and does not possess a significant component of more direct mantle derivation. The lack of evidence, in the REE data, for significant intracrustal differentiation of the provenance also renders this option less likely. A final possibility is that the Archean mantle sources to the crust had higher Th/U ratios than presently seen. Such differences would be consistent with either sampling fundamentally different mantle than is sampled at present or that the mantle had seen less effects of crust extraction. There are few high quality Th and U data for Archean igneous rocks and these rather intriguing observations from sedimentary rocks indicate that acquisition of such data should be given some priority.

The basic conclusion of this study is that there are some fundamental differences in the composition of Archean and Recent turbidite sediments. Many of the Recent samples are derived from tectonically active continental margins and a significant component of the provenance consists of mantle-derived material which has not undergone significant intracrustal differentiation. It is likely that Archean sediments had generally similar origins; in fact, the influence of intracrustal differentiation appears even less severe. Accordingly, differences seen in Gd/Yb and Th/U ratios may indicate that the composition of the mantle or the mantle processes that gave rise to the continental crust differed.

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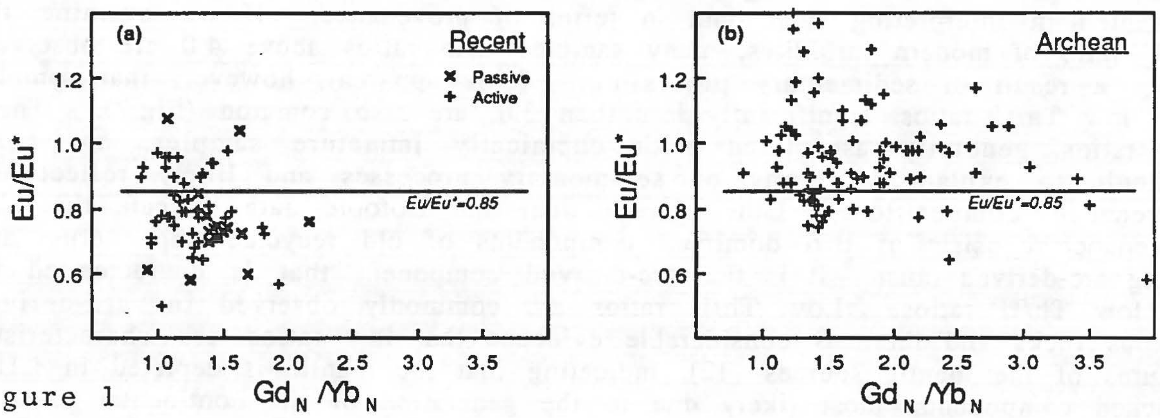

Figure 1

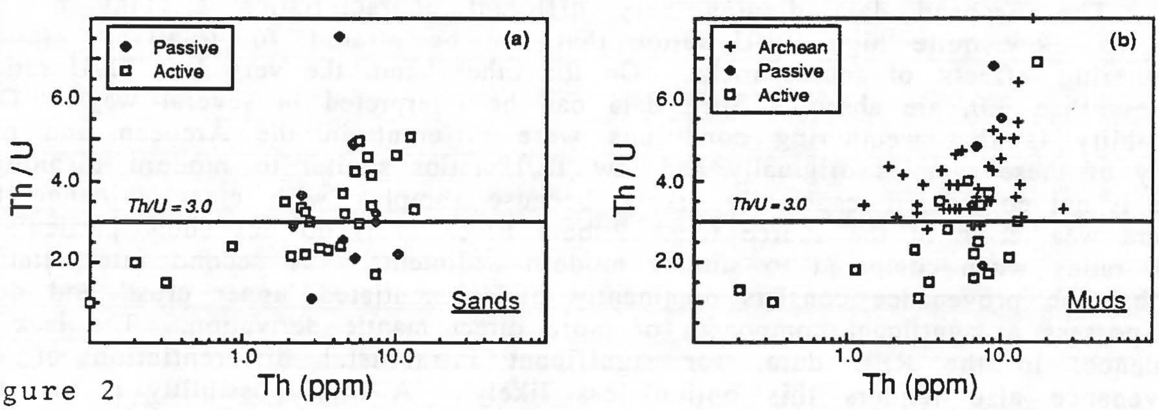

Figure 2

ARCHEAN CRUSTAL RECYCLING: IMPLICATIONS FOR ISOTOPIC HETEROGENEITY IN THE MANTLE; P.A. Mueller, Dept. of Geology, Univ. of Florida, Gainesville, FL 32611, and J.L. Wooden, U.S. Geological Survey, Menlo Park, CA 94025.

INTRODUCTION. Geochemical models for the growth of the continental crust and its impact upon mantle evolution are predicated upon elemental transfer from the mantle to the crust via melts that are enriched in incompatible (low D) elements (e.g., O'Nions et al 1979). In general, the crust produced is of low enough density that it is not readily remixed with the mantle in bulk, but may be partly recycled as subducted sediment (e.g., Kay 1985). Because trace elements, particularly incompatible ones, can be greatly affected by the degree of partial melting and crystal fractionation as well as recycling, they are not as useful indicators of the extent of recycling and mixing as are radiogenic isotopes (e.g., Davidson 1987). This is particularly true for the U-Pb system because of the low abundance of Pb in the mantle (<1 ppm) relative to the crust (>10 ppm), and even more so in the Archean when the 235U-207Pb system offers enhanced temporal resolution relative to Rb-Sr, Sm-Nd, or Lu-Hf systems.

The potential impact of recycling crustal components into the mantle during the Archean (and later) must be evaluated in regard to both the mechanisms of recycling and the nature of the materials available for recycling. Various workers have discussed the probability that plate tectonics operated in Archean time (e.g., Sleep and Windley, 1982; Hargraves, 1986) and the geochemical importance of crustal recycling (e.g., Armstrong 1981). Others have used diamond inclusions (e.g., Boyd et al., 1985) and younger volcanic rocks (e.g., Hawkesworth et al., 1983) to clearly show that isotopically old sub-continental lithosphere resides below some Archean cratons. With the increased reliance upon old, sub-continental lithosphere as a potential reservoir involved in the generation of modern volcanic rocks (e.g., Hart et al., 1986; Hawkesworth et al., 1983; Shirey et al., 1986), it is instructive to examine the role that Archean crustal recycling may have played in influencing the development of the range of isotopic compositions currently observed in modern mantle-derived rocks from continental and oceanic terranes.

THE ARCHEAN. If the arguments in favor of Archean plate tectonics and, consequently subduction, are accepted (e.g., Hargraves 1986 and references therein), then it would seem inevitable that recycling of sialic crust occurred. The critical issues then become 1) the nature of the recycled material and 2) the mechanism(s) by which this recycled material interacted with the mantle.

With regard to the nature of the material subducted, it is clear from a variety of studies that various Archean cratons had markedly different geologic histories that led to very different paths of isotopic evolution (e.g., Moorbath et al., 1975; Oversby, 1978; Tilton, 1983; Gariepy and Allegre, 1985; Thorpe et al., 1984; Wooden and Mueller, 1988). Mueller and Wooden (1988) recognized three different cratonal types based primarily on their isotopic evolution in the U-Pb system. These types are described below and depicted in Figure 1.

Type I. The Superior Province of the Canadian Shield and other areas that grew rapidly without incorporating older crust as would be the case for many modern intraoceanic arcs are examples of Type I cratons. Initial isotopic values will lie along or close to mantle growth curves.

Type II. The high grade gneiss terranes of southwestern Greenland and Labrador represent areas that underwent high-grade metamorphic events early in their history and, despite their extent of differentiation, have evolved with depleted characteristics such that they now exhibit Pb isotopic ratios below the mantle growth curve.

Type III. The Wyoming Province of the western United States is an example of a craton that was well differentiated early in its history and evolved for at least several hundred million years without suffering significant depletion via high grade metamorphism. Such cratons will probably have the most markedly enriched isotopic compositions and lie well above average mantle growth curves.

NATURE OF MIXING. Although it is clear that materials of widely different isotopic and elemental compositions were being shed from various Archean continents and that these materials were likely to have been subducted, their actual impact on mantle evolution is controlled by the nature of their interaction with the mantle. Although this interaction may be very complicated in detail (e.g., Kay, 1985, Davidson, 1987), we are concerned only with large scale consequences. Even at the largest scales, however, it is important to separate the effects of isotopic exchange from those produced by changes in elemental abundances. Though this dichotomy is important to a greater or lesser extent for all isotopic systems, it is particularly important in the U-Pb system because of the large disparity in the crustal and mantle abundances of U and, particularly, Pb.

In general, modern concepts of petrogenesis in subduction zones call upon subduction of a lithospheric slab with a veneer of altered (hydrated) oceanic crust and sediment (e.g., Davidson, 1987). The subduction of the slab leads to dehydration of its upper portions. The emitted fluids (and/or melts) then interact with the mantle wedge, and perhaps lower crust in continental regions, to stimulate melting. In reality, an infinite number of possible crust-mantle mixing schemes are then possible.

For example, Figure 2 depicts three possible scenarios of crust-mantle interactions that would likely be associated with recycling of each of the three cratonal types. Although the heavier lines represent the most likely patterns, the actual range of possibilities is essentially infinite. These models take into account two different aspects of mixing, changes in elemental abundances (change in slope of isotopic evolution lines) and isotopic equilibration (vertical lines representing essentially instantaneous changes in isotopic composition). Although elemental transfer associated with partial melting will generally lead to the lowering of ratios such as Rb/Sr or U/Pb in the residue, it cannot be taken for granted that the final ratios in the mantle wedge above a dehydrating slab will be lower than the pre-subduction values of the wedge. If the net transfer of incompatible elements from the slab to the crust is not complete, residual fluids trapped in the wedge (metasomatism) may lead to local, if not bulk, increases in elemental ratios such as U/Pb. Regardless of the extent to which elemental abundances are changed by the fluids emanating from the slab, these fluids are also likely to be out of isotopic equilibrium with the host rock of the wedge. This disequilibrium will be partially alleviated by isotopic exchange between the fluids and the wedge as has been suggested for oxygen isotopes (e.g., Carlson, 1984). The extent of equilibration is difficult to evaluate and the vertical lines in Figures 2B and 2C are not intended to be quantitatively representative.

With regard to the three scenarios depicted in Figure 2, it is important to point out that the isotopic composition of modern volcanic rocks derived from reservoirs which evolved along any of these paths could be the same. Only in case A, however, could any reliable estimate of the age of the heterogeneity be made utilizing the present day isotopic (e.g., 207Pb/204Pb) and elemental (e.g., 235U/204Pb) ratios. This situation is simply one of the spectrum of possibilities that also includes recent intramantle elemental redistributions. In either case, it is impossible to calculate the "age" of a mantle reservoir.

AN EXAMPLE. Recognition of portions of the mantle that may have been affected by Archean crustal recycling as described above will be problematic for all cratonal types, but particularly so for Types I and II. In the southern Superior Provice for example, Tilton and co-workers (e.g., Tilton, 1983) have shown that the mantle associated with this Type I craton probably experienced net reductions in ratios such as U/Pb during craton formation and that the mantle in this area evolved and retained a depleted signature. Recycling of Type II materials also will lead to the development of a depleted isotopic signature that would be particularly difficult to recognize. Low 206Pb/204Pb and 207Pb/204Pb from the Rockall Plateau in the North Atlantic (Morton and

Taylor, 1987), however, might be an example. Because the overall extraction of sialic crust has led to an overall depletion in the mantle currently sampled by mafic volcanism (e.g., MORB), the signatures imparted by recycling associated with the formation of Type I and Type II cratons will be difficult to distinguish as having been uniquely and separately preserved. In the case of Type III cratons, however, recycling is much more likely to produce an enriched signature that will be distinctive and relatively easy to recognize.

One area in which recycling associated with the growth of a Type III craton may be recognized is in the northwestern United States. Discussions by Leeman (1982), Carlson (1984), Hart (1985), Church (1985), and Wooden and Mueller (1988) have drawn attention to the fact that Pb, Sr, and Nd isotopic data for young volcanic rocks from the Yellowstone Plateau, Snake River Plain, and Columbia River Plateau show strong indications of either contamination by Late Archean crust or derivation in part from sub-continental lithosphere that last underwent isotopic equilibration during the Late Archean.

Figure 3 depicts the array of U-Th-Pb data for both young volcanic rocks from this region and of Archean basement from the Beartooth Mountains that is composed of a variety of crustally and mantle-derived rocks, including the mafic Stillwater Complex (Wooden and Mueller, 1988; Czamanske et al., 1986). As is clear from this diagram, U-Pb systematics for the late Archean basement and the younger volcanic rocks are very similar. There is considerable disparity, however, between the cohesive pattern of the young volcanic rocks and the scatter seen in the data from the Archean crust in the U-Th-Pb system. This contrast in thorogenic Pb patterns strongly argues against a model of crustal contamination to explain the secondary U-Pb and Th-Pb relations exhibited by the younger volcanic rocks. In addition, older crustal components (>3.0 Ga, Henry et al., 1982; Leeman et al., 1985) exist in this terrane and have isotopic systematics very different from the Late Archean rocks. Assimilation of these rocks would also likely lead to increased scatter in both 207/204 and 208/204 vs 206/204 plots.

If the isotopic systematics of the younger mantle-derived volcanic rocks were not produced by contamination with older crust, then they must reflect their source. As pointed out by the authors noted above, a reasonable explanation involves the existence of enriched, sub-continental lithosphere beneath this region that is part of the source of the younger volcanic rocks. The Pb isotopic data discussed above and in Wooden and Mueller (1988) strongly suggests that this portion of sub-continental lithosphere was enriched by interaction with older crustal detritus carried to mantle depths by processes akin to modern subduction. This suggestion is strengthened by noting that the Late Archean andesitic rocks of the Beartooth and Bighorn Mountains, which fall along the Pb isotopic array for the Late Archean rocks of Figure 3, exhibit the depletion in high field strength (HFS) elements characteristic of modern subduction related volcanism (Mueller et al., 1983; Mueller and Wooden, 1988). These data lend support to the argument that at least some of the Late Archean rocks were produced in an environment where processes similar to those of modern subduction zone magmatism were operative. Consequently, it would appear likely that subduction of old Wyoming detritus during an episode of Late Archean plate convergence led to the development of a zone of at least partially enriched mantle that remained largely intact until the present.

CONCLUSION. Isotopic reequilibration and changes in elemental abundance ratios associated with recycling of Archean and younger crust are capable of producing significant changes in the isotopic composition of the mantle. These changes may give the appearance of either depletion or enrichment, and the time at which these heterogeneities were initiated is not readily susceptible to calculation. Growth of continents via subduction-related volcanism leads to the development of enriched or depleted mantle wedges that may remain for long periods of time as keels of sub-continental lithosphere. Delamination of these zones during later times allows these heterogeneities to be distributed through the mantle and contribute to the isotopic signature of even modern mid-ocean ridge volcanism.

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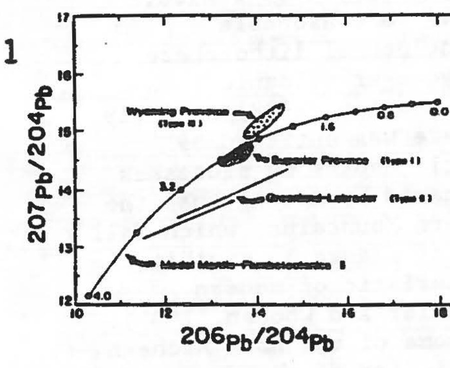
F.1



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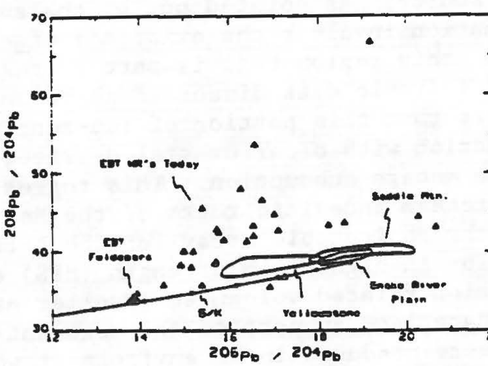

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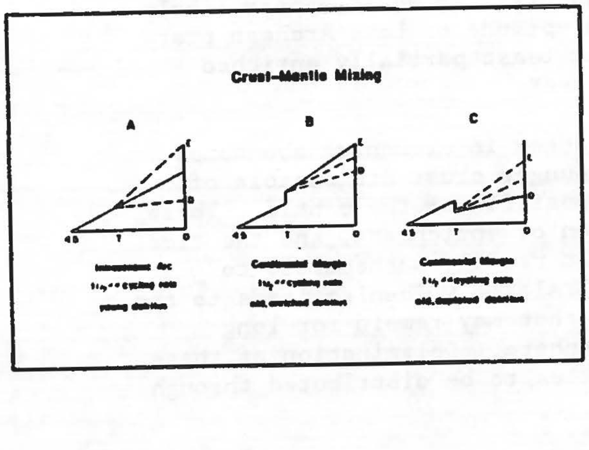

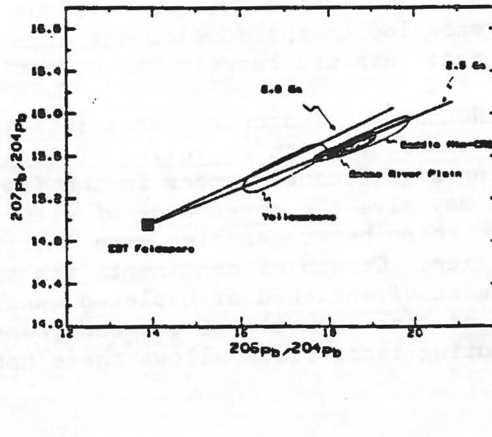

EVIDENCE FOR A DIFFERENTIATED MANTLE AND PLATE TECTONICS DURING THE LATE ARCHEAN DEDUCED FROM ECLOGITE XENOLITHS IN THE BELLSBANK KIMBERLITE.

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The origin of eclogite xenoliths in kimberlites and alkali basalts is the subject of much controversy. Eclogites are garnet + cpx rocks generally with basaltic bulk compositions that crystallized (or re-crystallized) at relatively high pressures in the lower crust/upper mantle. Kyanite, rutile, opx, olivine, plagioclase, phlogopite, and amphibole are common accessory phases [1]. Eclogites with omphacitic cpx and Ca-, Fe-rich garnet found in blueschist terranes, are considered to represent metamorphosed oceanic crust [1]. In fact, basaltic material is converted to eclogite at pressures >10kb (e.g., [2-4]).

In contrast, most eclogite xenoliths in kimberlites and alkali basalts are more magnesian and vary greatly in texture, mineral compositions, and isotopic characteristics. There are three contrasting petrogeneses proposed for these "mantle-derived" eclogites: **1)** as high-pressure igneous cumulates (garnet pyroxenites) that formed as dikes within the upper mantle [5-9]; and **2)** as the metamorphic products of a subducted oceanic crustal protolith [10-17]; and **3)** as relicts of the Earth's primary differentiation shortly after accretion [18-21]. Basically, it is the differences in the progenitors (i.e., crustal versus mantle) which can impart these rocks with various distinguishing characteristics.

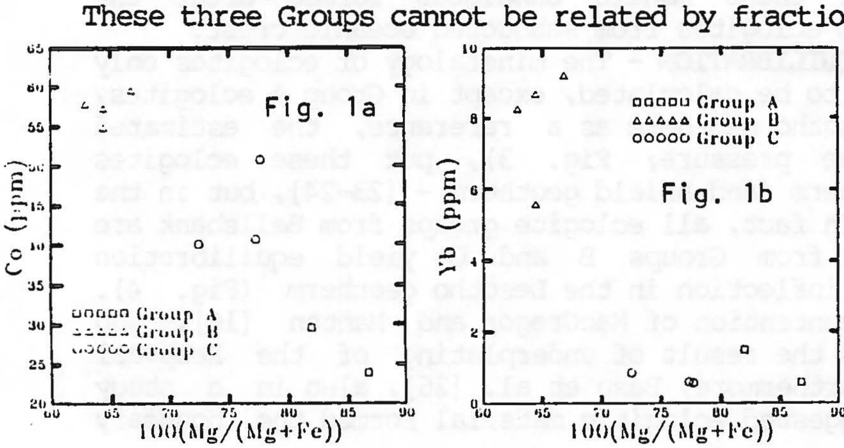
A suite of eclogites from the Bellsbank kimberlite (DeBruyn and Martin Mine) were studied in order to determine their petrogenesis. Three groups have been defined on the basis of major and trace elements, isotopes, and mineral chemistry. Ultrapure mineral separates were prepared for isotope and REE analyses.

<u>Group A</u>: low jadeite moles in cpx; Mg- and Cr-rich garnets; Cr-rich clinopyroxene; high whole-rock MG#'s; mantle type δ^{18}O (4.8 to 5.1 ^{o}/oo) and ^{87}Sr/^{86}Sr (0.70375-0.70420).

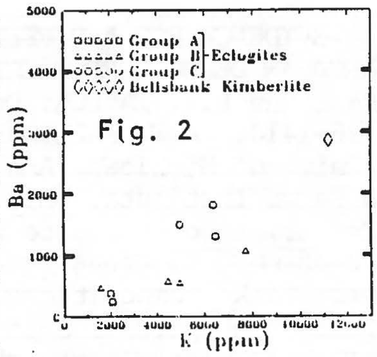
<u>Group B</u>: moderate jadeite moles in cpx; Fe-rich garnets; extremely high ϵ Nd (+120 to 235), LREE-depleted cpxs; low δ^{18}O (3.0 to 3.3 ^{o}/oo); highly radiogenic ^{87}Sr/^{86}Sr ratios (0.70907-0.71106); extreme LREE-depleted/HREE-enriched garnets; low concentrations of incompatible trace elements in the whole-rocks.

<u>Group C</u>: high jadeite moles in cpx; CaO-rich garnets; positive Eu anomaly in both garnet and cpx REE; Al_2O_3-rich whole-rock composition; low δ^{18}O (4.3 to 4.9 ^{o}/oo); radiogenic ^{87}Sr/^{86}Sr (0.70617-0.71032); low REE abundances.

These three Groups cannot be related by fractional crystallization, as Co and Yb abundances increase as MG# decreases (abundances calculated as reconstructed whole rock values from ultrapure mineral separates and modal abundances: Fig. 1). These should decrease if garnet and cpx are the main fractionating phases. Furthermore, the range in Sr (0.7042 - 0.7100), Nd



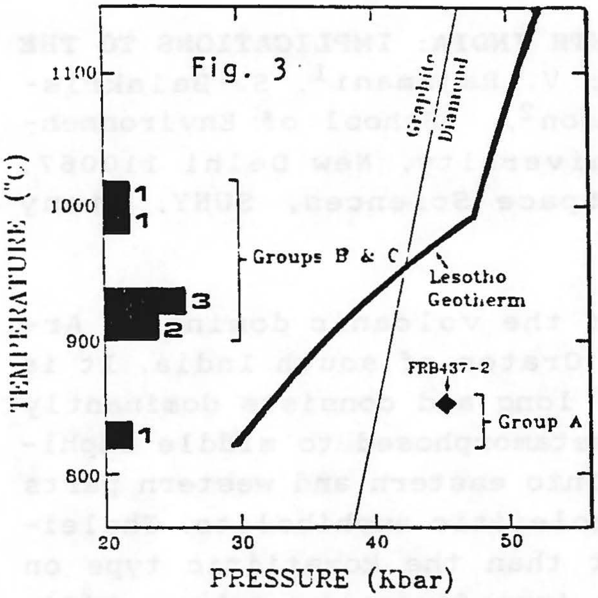
(0.5116-0.5254), and O (3.0-5.1°/oo) isotopes also negate a petrogenesis of all three eclogite groups by fractional crystallization from the same parental magma. Metasomatic enrichment of these xenoliths, witnessed in interstitial phlogopite and amphibole, and is a result of kimberlite infiltration [22]. This demonstrated in Fig. 2, where measured whole-rock abundances of K and Ba from the Bellsbank eclogites form a positive correlation culminating in the kimberlite itself.



Group A eclogites are defined as mantle cumulates because of: their high MG#; minor amounts of orthopyroxene and olivine are present; mantle oxygen and Sr isotope values; and the fact that Group A eclogites are the only group which exhibit garnet/cpx mineral Kd's consistent with fractionation from a basaltic magma (e.g., [17]). Group B eclogites have compositions consistent with the seawater-altered basaltic portion of oceanic crust (LREE-depleted signature; low $\delta^{18}O$; radiogenic $^{87}Sr/^{86}Sr$). Group C eclogites have compositions consistent with the plagioclase-dominated cumulate portion of oceanic crust, which has also witnessed some seawater alteration (low $\delta^{18}O$; radiogenic $^{87}Sr/^{86}Sr$; positive Eu anomaly in whole rock; low REE abundances; low $\delta^{18}O$; Al_2O_3-rich whole-rock composition). The preservation of a positive Eu anomaly in Group C eclogites demonstrates plagioclase involvement at some point during their petrogenesis. Such plagioclase involvement must have occurred prior to their emplacement into the garnet stability field of the mantle [22].

AGE OF THE ECLOGITES - Using ultrapure garnet and cpx mineral separates, two point mineral isochrons yield the age of eruption of the Bellsbank kimberlite (≅ 90m.y.). This indicates that garnet and cpx were in isotopic equilibrium until they were brought to the surface in the kimberlite. The age of the eclogite xenoliths can be estimated from the Sm-Nd isotopes. Rb-Sr isotopes cannot be used because of the decoupled nature of the Rb/Sr and $^{87}Sr/^{86}Sr$ ratios, indicating either an influx of radiogenic Sr or a decrease in the Rb/Sr ratio since (re)crystallization. As such, the calculated whole rock Rb/Sr ratios yield model ages greater than the age of the Earth. This is not the case for Sm-Nd which exhibit coupled isotopic ratios. We have calculated the model ages for the Bellsbank eclogites relative to Bulk Earth evolution (present day $^{143}Nd/^{144}Nd = 0.51264$; $^{147}Sm/^{144}Nd = 0.1954$). These yield ages of 2.30 Ga and 2.52Ga for Group B eclogites and 1.12 Ga for Group A. The high $^{143}Nd/^{144}Nd$ ratios for Group B eclogites (0.51880-0.52459) indicate that an ancient depletion affected these eclogites. The Sm-Nd model age for Group A eclogites demonstrates that the these mantle cumulates formed after the recrystallization of the Group B eclogites from subducted oceanic crust.

PRESSURES AND TEMPERATURES OF EQUILIBRATION - The mineralogy of eclogites only allows equilibrium temperatures to be calculated, except in Group A eclogites, where opx occurs. Using the Lesotho geotherm as a reference, the estimated equilibrium temperatures (and one pressure; Fig. 3), put these eclogites slightly below the Lesotho geotherm (and shield geotherm - [23-24], but in the diamond stability field [25]. In fact, all eclogite groups from Bellsbank are sources of diamond. Eclogites from Groups B and C yield equilibration temperatures which straddle the inflection in the Lesotho geotherm (Fig. 4). This would tend to support the contention of MacGregor and Manton [16], who suggested that the inflection is the result of underplating of the Kaapvaal craton by eclogitic material. Furthermore, Basu et al. [26], also in a study of Roberts Victor eclogites, suggested eclogitic material formed the boundary



layer between lithosphere and convecting asthenosphere, as these eclogites yield equilibrium temperatures which also straddle the point of inflection on the Lesotho geotherm.

IMPLICATIONS - the highly depleted Nd isotope signature of Group B eclogites indicates that an ancient depletion affected these xenoliths. We do not support the idea that these eclogites may be products of the Earths primary differentiation, because of this isotopic evidence for an already differentiated Earth. Furthermore, petrological evidence supports an oceanic crustal origin [17, 22]. The model ages indicate that such depletions occurred during the late Archean. Preservation of these extremely depleted and ancient isotopic signatures suggests that the Earth was highly differentiated at the end of the Archean. This is witnessed in the high ∈ Nd's of Group B eclogites, indicating that the source of the basaltic progenitor (ancient MORB source) was already LREE-depleted. We conclude that subduction was active at the end of the Archean and that late Archean basaltic oceanic crust recrystallized to an eclogite assemblage as subduction conveyed it into the mantle beneath the Kaapvaal craton. Portions of this subducted Archean oceanic crust underplated the Kaapvaal craton and were effectively isolated from mantle processes until entrainment in the Bellsbank kimberlite.

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THE KOLAR SCHIST BELT, SOUTH INDIA: IMPLICATIONS TO THE NATURE OF THE LATE ARCHEAN MANTLE; V. Rajamani[1], S. Balakrishnan[1], E. J. Krogstad[2] and G. N. Hanson[2], [1]School of Environmental Sciences, Jawaharlal Nehru University, New Delhi 110067, India; [2]Department of Earth and Space Sciences, SUNY, Stony Brook, NY 11794, USA

The Kolar Schist Belt is one of the volcanic dominated Archean belts in the eastern Dharwar Craton of south India. It is N-S trending, 3-4 km wide and 80 km long and consists dominantly of tholeiitic and komatiitic rocks metamorphosed to middle amphibolite facies. The belt is divided into eastern and western parts with respect to a central massive tholeiitic amphibolite. Tholeiitic amphibolites are more abundant than the komatiitic type on both parts. The belt includes minor iron formation and graphitic slate. It is surrounded on all sides by granitoid gneisses. In the central part of the 80 km long belt the contacts between the belt and the gneisses are tectonic on both sides. The rocks in the contact zones are highly sheared and altered. The shearing is considered to be a late event (1), that affected first two generation of folds (2). Based on structural evidences Mukhopadhyay (2) suggested that the rocks of the belt and the surrounding gneisses were subjected to E-W sub-horizontal compression over a protracted period of time.

The amphibolites of the belt, dated by whole-rock Sm-Nd and Pb-Pb methods, are considered to have formed ca. 2700 Ma ago (3,4). There are at least two suites of intercalated komatiitic and tholeiitic amphibolites: those occurring on the western part of the belt were formed from long term LREE depleted mantle sources (Table 1), whereas those on the eastern part were formed from long term LREE depleted and short term LREE enriched sources (3,5). In their Pb isotopic characteristics each of the four amphibolite types seems to have evolved from distinct sources (3,4). Balakrishnan et al. (4,6) suggested that the mantle sources for the western and eastern amphibolites were similar to those of the present day mid-ocean ridge and ocean-island or island-arc basalts, respectively.

The magmas for the komatiitic amphibolites are considered to have been derived from depths greater than 100 km (as much as 200 km), by low, but variable, extents of melting (5). The mantle sources at these depths had variable Fe/Mg ratios which were higher than that of pyrolite. The tholeiites associated with komatiitic rocks on the western part of the belt were shown to have derived from depths much less than 75 km by melting of sources with Fe/Mg ratios which were quite variable and much higher than those for the komatiitic rocks (7). Thus, their geochemical features suggest that the tholeiites and komatiites were generated from from lithospheric and asthenospheric mantle sources respectively. The intrusion of komatiitic melts into the lithosphere probably raised Fe/Mg ratios and caused melting (7).

Surprisingly, the sources for the tholeiites and the komatiites had different long term U-Pb evolutionary histories. The sources for the tholeiites evolved with lower U/Pb ratios prior to 2700 Ma relative to those of western komatiitic rocks. We wonder whether the processes resposible for increase in Fe/Mg ratios also caused a lowering of U/Pb ratios.

Mantle-derived monzodioritic to granodioritic rocks ranging in age from 2633 to 2553 Ma occur to west of the belt (8,9). Mantle sources for these gneisses, which must have been shallow (8), also had a long term LREE depleted history, but were enriched in LREE before magma generation. A similar, long term depletion and a short term enrichment in LREE in mantle sources is required for 2530 Ma granodioritic gneisses occurring to east of the belt (1). Based on igneous and metamorphic age data and on Sr, Nd, and Pb isotopic characteristics of the gneisses, Krogstad et al. (1,9) inferred distinct tectonic settings for the mantle-derived granitoid gneisses occurring on either side of the belt.

Within a 6 km cross section across the Kolar Schist Belt, komatiitic to granodioritic rocks of late Archean age derived from laterally and vertically distinct parts of the mantle now occur in juxtaposition. These rocks were formed in a time span of about 200 Ma. Their geochemical characteristics suggest that by the late Archean: (1) a large part of the mantle-source was depleted in LREE with magnitude of depletion tending to increase with depth; (2) certain parts of the mantle were variably enriched in LREE and/or in Fe/Mg ratios before melting by the addition of high pressure melts and/or by fluids; (3) the mantle had regions which were evolving separately for long periods of time with different U/Pb ratios during the Archean and (4) excepting for a hotter asthenosphere the late Archean mantle was as heterogenous as the present day mantle.

KOLAR SCHIST BELT
Rajamani et al.

Table 1. Age and isotopic features of Kolar rocks

	Amphibolites			Gneisses	
	W. Kom.	W. Tho.	E. Kom.	W. Gn.(Dod)	E. Gn.
Age Ma	2700	2700	2700	2630	2530
Eps.Nd	+2 to +8	+4	+1.7 to +4.5	-1 to +1.7*	0to +4.5
mu_1	8	7.5	8.3	8.7 to 9.2*	8 to 8.2

* contamination by older crust inferred (1)

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ARCHAEAN FLOOD BASALTS FROM SOUTH AFRICA: IMPLICATIONS FOR LOCAL HETEROGENEITY IN THE ARCHAEAN MANTLE

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The Dominion Group (DG) of South Africa represents one of the earliest cover sequences overlying the granite greenstone belts of the Archaean Kapvaal Craton. It is laterally extensive, being preserved over an area of ~15 000 km^2, with a maximum thickness of 2.7 km, and while the preferred stratigraphic age is 2.7-2.8 Ga, preliminary ion-probe zircon results suggest an age of 3.0 Ga. The volcanic suite within the Dominion Group is dominant over sedimentary rocks and tends to be bimodal with minor quartz feldspar porphyries interbedded with variously differentiated basic lavas. Metamorphism, which is restricted to lower greenschist facies, has mobilised the alkali elements, Ba, Sr and to a lesser extent Ca, but has not obscured the original igneous textures which show that the basalts were largely aphyric. In comparison, the high field strength elements (Ti, Zr, Hf, Nb, Ta, Y), Th, the REE and the transition elements appear to have been little affected by metamorphism and reflect original magmatic variations.

Two suites of lavas have been distinguished on the basis of Ti, V, Zr and Fe abundances, one characterised by high Ti/V and Zr/V ratios and the second by low Ti/V and Zr/V and while these differences are subtle, particularly for the more primitive samples, they are significant and suggest at least two parental magma types. Both groups are characterised by $SiO_2 > 52\%$, increasing with fractionation to 60%, and large variations in MgO, Cr and Ni, all of which can be accounted for by fractionation of olivine, pyroxenes, plagioclase and spinel. The lack of iron enrichment distinguishes these rocks from modern continental tholeiite suites, being more comparable with calc-alkaline trends. The most primitive basalts belong to the low Ti/V group and have Mg # greater than 0.6, Ni > 200 and Cr > 300 ppm, values appropriate for primary mantle-derived magmas.

Incompatible elements show enrichment styles similar to modern arc volcanics(1) and continental flood basalts(2) in that the LREE are enriched over both the HREE and the HFS elements, Nb and Ta. In modern basalts with similar major element compositions, these trace element features would be interpreted as reflecting mantle processes. However, the preferred model for Archaean basalts is that they were derived from contamination of komatiite by the thermal erosion of the continental crust followed by mixing of the two melts to form a hybrid magma that mimics a basaltic composition(3,4). Thus it is essential to compare the basalts with compositions expected from such mixing models before they can be used to infer the nature of their mantle source regions. However, this is rendered more difficult in the Archaean because of the mobility of the LIL and some major elements during even low grade metamorphism. Hence petrogenetic interpretations rely heavily on the more immobile elements and Nd isotope variations.

Superficially, the DG basalts appear to conform to the contamination model, being depleted in the HFSE but light REE enriched. However, subtle differences in trace element abundances suggest that this is not the case for the most primitive of the low Ti/V basalts. For example both Ti and V are more abundant in the DG basalts than in either the Archaean crust or komatiites. Moreover, their Ti/V ratios are very similar to komatiitic values but markedly distinct from those in the Archaean crust, observations that are difficult to reconcile with a contamination model. In addition, the enrichment of the LREE over the HREE and Ta and Nb is greater than that expected from contamination. On a diagram of La/Yb vs. La/Ta, the DG basalts do not lie on simple mixing curves between primitive or depleted mantle and either bulk crust or crustal melts as typified by the local prophryries. Rather the basalts lie close to the chondritic Ta/Yb value of 0.09, which is again difficult to reconcile with contamination. Al_2O_3/TiO_2 ratios in there more primitive rocks are also close to or less than chondritic and are thus similar to komatiitic values.

Nd isotope ratios corrected to 3.0 Ga give ε_{Nd} values of 0 ± 0.5,with one sample at + 1.2, suggesting either a chondritic or slightly depleted mantle source. This is distinct from the diamond inclusion data(5) which at 3.0 Ga lie between -2 to -3.8. Thus although the DG lavas occur on the Kapvaal craton, there is no indication that their source region was related to the lithospheric mantle keel thought to have been established beneath this region at ~3.5 Ga. Rather, major and trace element and Nd isotope evidence indicate a chondritic source. LREE and probably LILE abundances in the primary magmas reflect source enrichment concomitant with or slightly prior to melting, similar to that inferred for the mantle wedge above modern subduction zones. However this is not to imply that the Dominion Group lavas are subduction related but that trace element enrichment resulted from the migration of hydrous fluids or melts within the mantle, a conclusion supported by their silica rich nature.

The evidence from the DG basalts thus implies that the mantle beneath the Kapvaal craton at 3.0 Ga was markedly heterogeneous. Their fertile and in part chondritic source contrasts with the evidence from peridotite xenoliths and diamond inclusion data which suggest that much of the sub cratonic mantle was highly infertile, having suffered either komatiite extraction(6) or majorite fractionation(7) prior to 3.0 Ga. Such material is clearly incapable of producing basaltic melts, particularly in the volumes apparent in the Dominion Group and the later Ventersdorp sequences. The presence of these volcanic rocks implies that either komatiite extraction was not a regional event or that after extraction the mantle was still tectonically active and was partly replaced by more fertile asthenospheric material. Lithospheric thinning in an extensional environment is one mechanism whereby asthenospheric mantle can rise to lithospheric levels(8) and it is perhaps significant that volcanism in both the Dominion and Ventersdorp sequences is related to the development of the Witwatersrand sedimentary basin.

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ABUNDANCES OF AS, SB, W, AND MO IN EARLY ARCHEAN AND PHANEROZOIC MANTLE-DERIVED AND CONTINENTAL CRUSTAL ROCKS; K.W. Sims*#, H.E. Newsom#, and E.S. Gladney*; # Dept. of Geology and Institute of Meteoritics, Univ. of New Mexico, Albuquerque, NM 87131, U.S.A.; * Los Alamos National Laboratory, Health and Environmental Chemistry MS K484, Los Alamos, NM 87545.

INTRODUCTION We are using a radiochemical epithermal neutron activation analysis technique [1] to determine the abundances of As, Sb, W, and Mo in Archean and Phanerozoic mantle-derived and crustal rocks. We have analyzed metasediments of the Isua-Akilia and Malene suites of West Greenland [2], shales from early Archean greenstone belts [2], komatiites from Onverwacht [3], post Archean shales from Australia [4] and loess from several different continents [5]. As a current mantle baseline we are using analyses from a suite of mid-ocean ridge basalts and ocean island basalts which were analyzed by a different radiochemical technique involving metal separation. Some of the Mo and W data from this suite have previously been published [6]. Preliminary analysis of this data indicates that several questions pertaining to the composition and differentiation of the earth can be addressed, including: core formation through time and the involvement of non-igneous processes in the formation of the continental crust. Furthermore, the depletion of these moderately siderophile elements can be used to test the models of incomplete core formation [7] and heterogeneous accretion [8], which have been proposed to account for the abundances of siderophile elements in the earth.

RESULTS The abundances in the primitive mantle of compatible siderophile elements, such as Ni and Co, are well known from mantle nodules, because they are retained in olivine during partial melting. The abundances of incompatible elements such as Mo, W, Sb and As, must be determined by normalizing these elements to lithophile elements of similar geochemical behavior in both mantle and crustal reservoirs.

Mo is correlated with the light rare earth element Ce in mantle derived oceanic rocks [6] (Fig. 1). Our new data on Archean and Phanerozoic crustal and mantle rocks cluster around the Mo/Ce ratio of the oceanic rocks, suggesting that this Mo/Ce ratio represents the primitive mantle.

W is highly incompatible and correlates with the element Ba in the mantle-derived oceanic rocks [6] (Fig. 2). Our new crustal data are skewed toward the high side of the W/Ba ratio of the oceanic rocks, indicating that W/Ba ratio of the primitive mantle is somewhat greater than indicated by the W/Ba ratio of the oceanic rocks.

Sb is similar in geochemical behavior to Pb, Mo and Ce during igneous fractionation (Fig. 3). The data are more scattered than for Mo, W or As, however it appears that the continental crust is enriched in Sb relative to Ce by a factor of 7. This enrichment is possibly due to hydrothermal processes during crustal formation. Our data indicate that the Sb/Ce ratio of the crust is similar to the estimate of Taylor and McLennan [2]. Compared to previous estimates of the depletion of Sb in the primitive mantle [9], our data suggests that the primitive mantle is more depleted perhaps by a factor of 5.

As is correlated with the light rare earth element Nd (Fig 4). Compared to the mantle-derived oceanic rocks, the continental crust appears to be enriched in As relative to Nd, by a factor of 15. Once again, this enrichment is possibly due to the involvement of hydrothermal processes during crustal formation. Our data indicates that the As/Nd ratio in the crust is a factor of 4 greater than previous estimates [2]. The primitive mantle abundance of As may be similar to the estimate of Sun [9], or as much as a factor of two lower.

DISCUSSION This study has shown that the Mo/Ce and W/Ba ratio are almost the same for Archean and Phanerozoic mantle-derived and continental crustal rocks. This suggests that these ratios probably represent the Mo/Ce and W/Ba ratios of the primitive mantle. Sb and As are more volatile than Mo and W, and their depletion in the earth's mantle is due to both volatility and core formation. The depletion due to core formation is estimated by assuming that their original abundance was similar to lithophile elements of similar volatility. It is our intention to use the determined depletions of Sb and As to test the models which have been proposed to account for the abundances of siderophile elements in the earth. However, this will require the (planned) experimental determination of the metal/silicate partition coefficients for these elements.

Newsom et al. [6] has shown that the depletion of Mo in the earth was independent of the Pb isotope variations that had been interpreted as resulting from continual core formation [10]. This work confirms their earlier conclusions [6] which were based only on data from oceanic rocks.

This new data for Sb and As indicate that crustal formation has enriched the abundances of Sb and As in the continental crust relative to the mantle-derived oceanic rocks. This is similar to the observed enrichment of Pb and U in the continental crust [11]. Processes which may have caused Sb and As to behave in a more incompatible manner than their respective normalizing elements, Ce and Nd, include hydrothermal alteration and inorganic complexing (halogen and oxy-anion).

Archean chemical sediments from the banded iron-formation of Isua [12] have an As/Nd ratio similar to the continental crust while most of our data for the West Greenland suites show an As/Nd ratio similar to the mantle-derived oceanic rocks. Dymek and Klein [12] have suggested that the Isua banded iron-formations are a result of hydrothermal processes. The observed bimodal distribution of the As/Nd ratio in the early Archean rocks from West Greenland suggests that both igneous and hydrothermal processes were active in early crustal formation.

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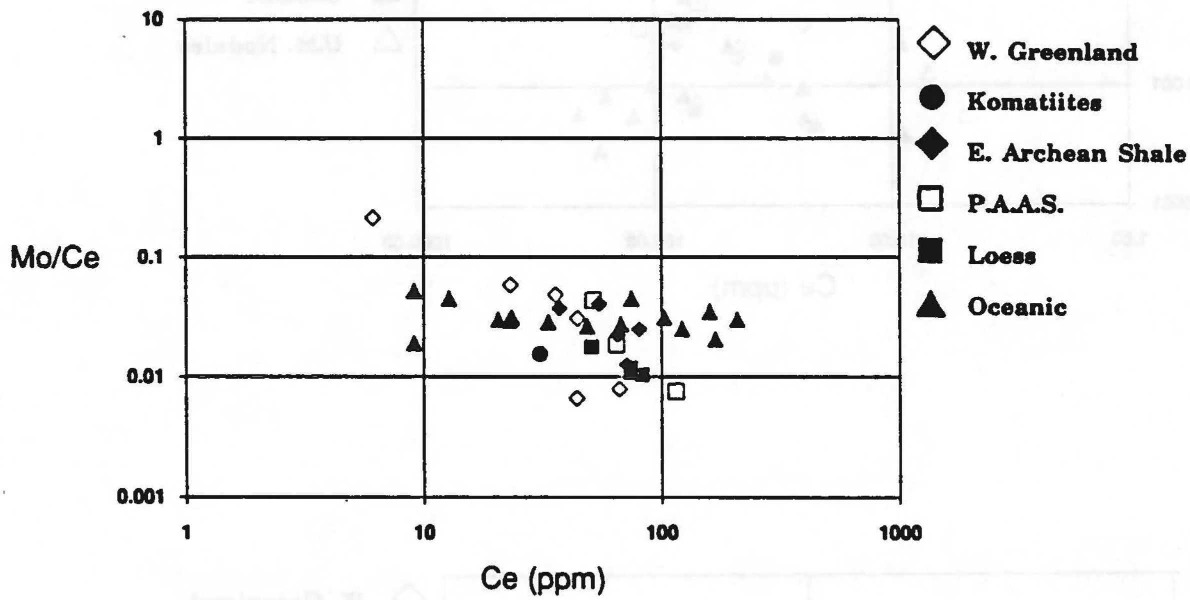
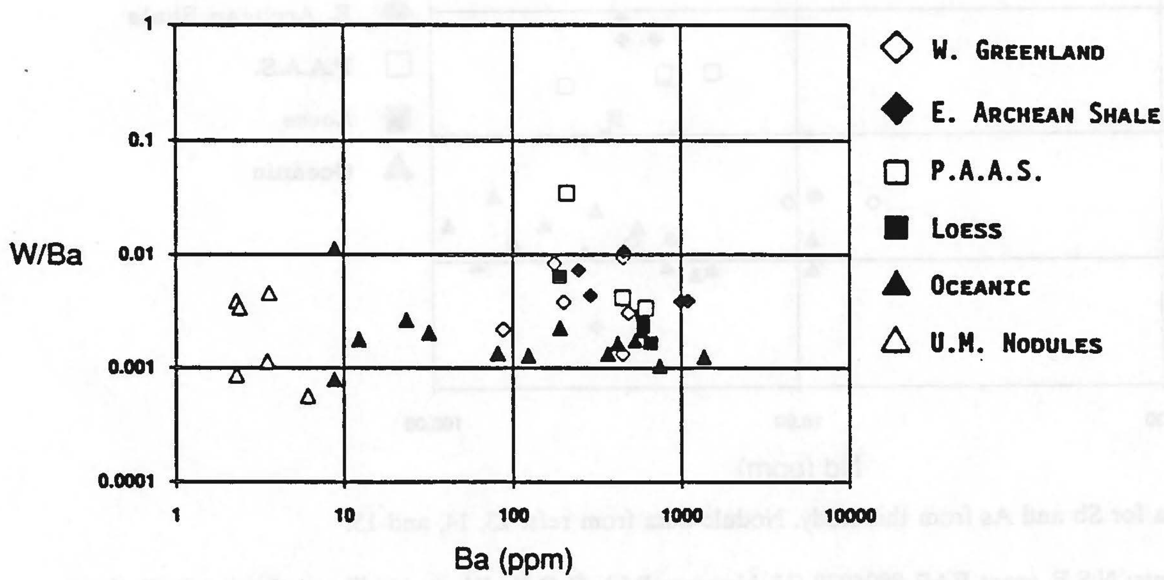
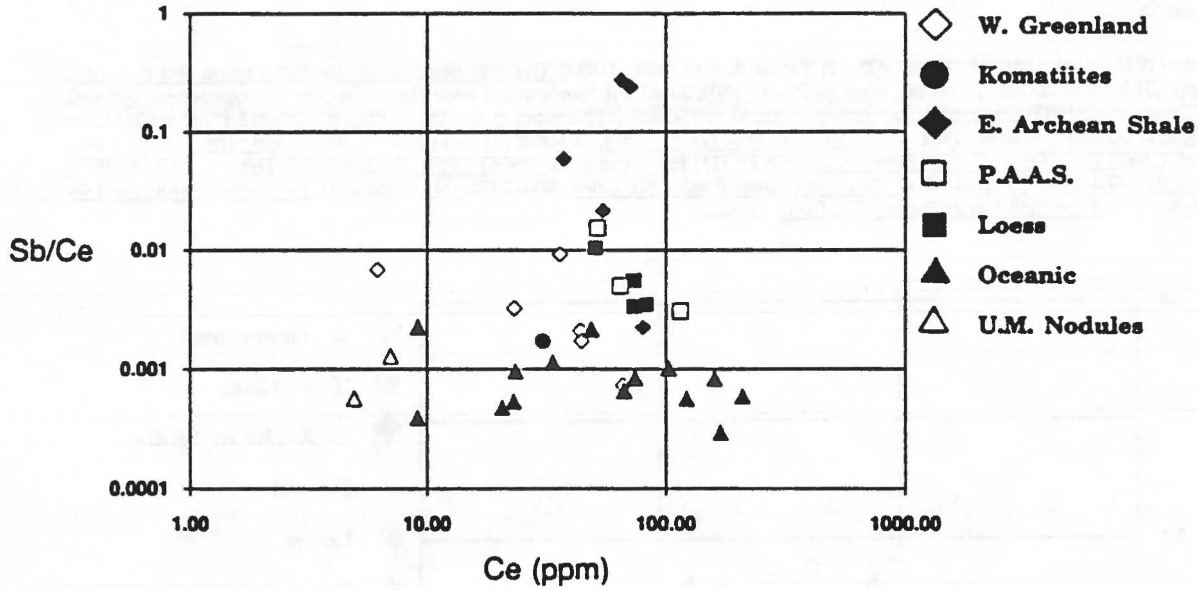
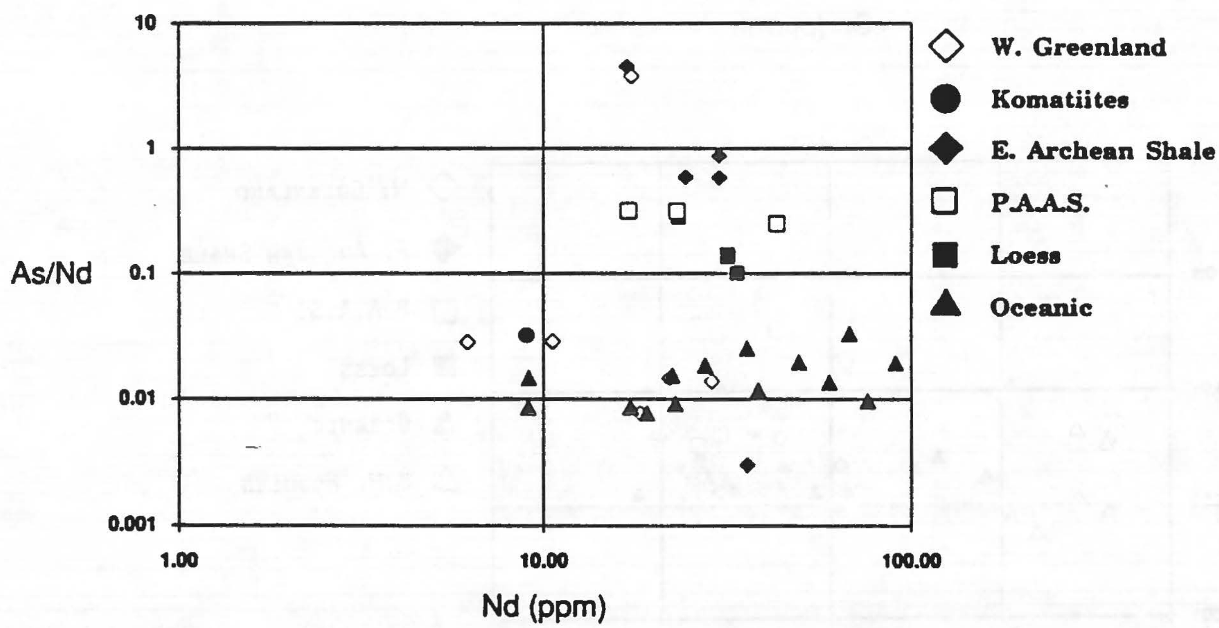




Figs. 1 & 2. Data for Mo and W from this study. Nodule data from refs. 13, 14 and 15.





Figs. 3 & 4. Data for Sb and As from this study. Nodule data from refs. 13, 14, and 15.

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ISOTOPIC EVOLUTION OF THE ARCHAEAN DEPLETED MANTLE

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For most Archaean greenstone belts, Sm-Nd ages are significantly older than those given by the Pb-Pb or U-Pb zircon methods (1). This feature largely reflects the construction of the Sm-Nd isochrons from a wide range of rock types and results in the isochrons representing mixing lines between different mantle, or mantle and crustal reservoirs (2). Recalculation of the Sm-Nd data to the most reasonable Pb-Pb or U-Pb ages for the greenstone belts results in a significantly greater range of ε_{Nd} in the Archaean mantle (Fig. 1). Several Early Archaean mafic and ultramafic volcanics sequences then show higher $\varepsilon_{Nd}(T)$ values than their Late Archaean and Proterozoic counterparts. The existence of a depleted reservoir in the Early Archaean with ε_{Nd} as high as +4 is also indicated by the Nd isotopic composition of Early Archaean sediments (3). Such features contradict a regular increase in ε_{Nd} of the depleted mantle from 4.55Ga to the present and suggest that the depletion of the mantle has been at least a two- stage process.

Presumed uncontaminated Archaean tholeiites, mafic and ultramafic volcanics from Proterozoic greenstone belts, Phanerozoic ophiolites, and modern MORB record a constant rate of depletion of the mantle at a rate of 2.2 ε_{Nd} units per Ga. The increase in ε_{Nd} during this time may reflect the formation of continental crust in island arc environments. However, the average Sm/Nd value inferred for the depleted mantle from this growth rate is significantly lower than the values measured on mantle- derived basalts. This feature suggests suppression of the growth rate by the recycling of crust back into the mantle (5), and/or by mixing with an isotopically less- depleted mantle component (6). Such buffering results in the isotopic composition of the depleted mantle lying within a relatively narrow growth band of 4 to 5 ε_{Nd} units from 2.0Ga to the present.

Nd isotopic data for komatiites (1) suggests a correlation between isotopic composition and the division into Al-depleted (ADK) and Al-undepleted (AUK) komatiite types: the AUK, which characterise Late Archaean greenstone belts, fall within the extrapolated Proterozoic-Phanerozoic growth limits for the depleted mantle (Fig. 1). In contrast, the ADK which predominantly characterise Early Archaean greenstone belts, have more depleted isotopic compositions which suggest their source evolved at 2 to 4 times the rate of that of the tholeiites and AUK (Fig. 1). Limited Hf isotopic data (7) for the Barberton and Pilbara greenstone belts suggest complementary high $\varepsilon_{Hf}(T)$ values in the ADK. Comparable growth rates are inferred only for the source of some Lunar basalts which have ε_{Nd}(3200Ma) values of +12 (Fig. 1). The isotopic heterogeneity required for the lunar mantle has been generally ascribed to crystal accumulation during the solidification of an extensive magma ocean (4). Similarly, the isotopic heterogeneity noted for the Archaean volcanics coupled with petrological evidence for distinct source regions for tholeiites and komatiites, indicates some compositional layering of the terrestrial mantle during the Early Archaean. Partitioning data for high pressure mineral phases (8) precludes the formation of a terrestrial magma ocean of more than 200km depth. However, the mineralogical layering from a shallow (less than 120km deep) magma ocean would be sufficient to produce ε_{Nd} +12 after 1Ga of isolation (4). An alternative mechanism, the production of isotopic heterogeneities by melt extraction, possibly during the formation of an early basaltic crust (9), is considered more plausible.

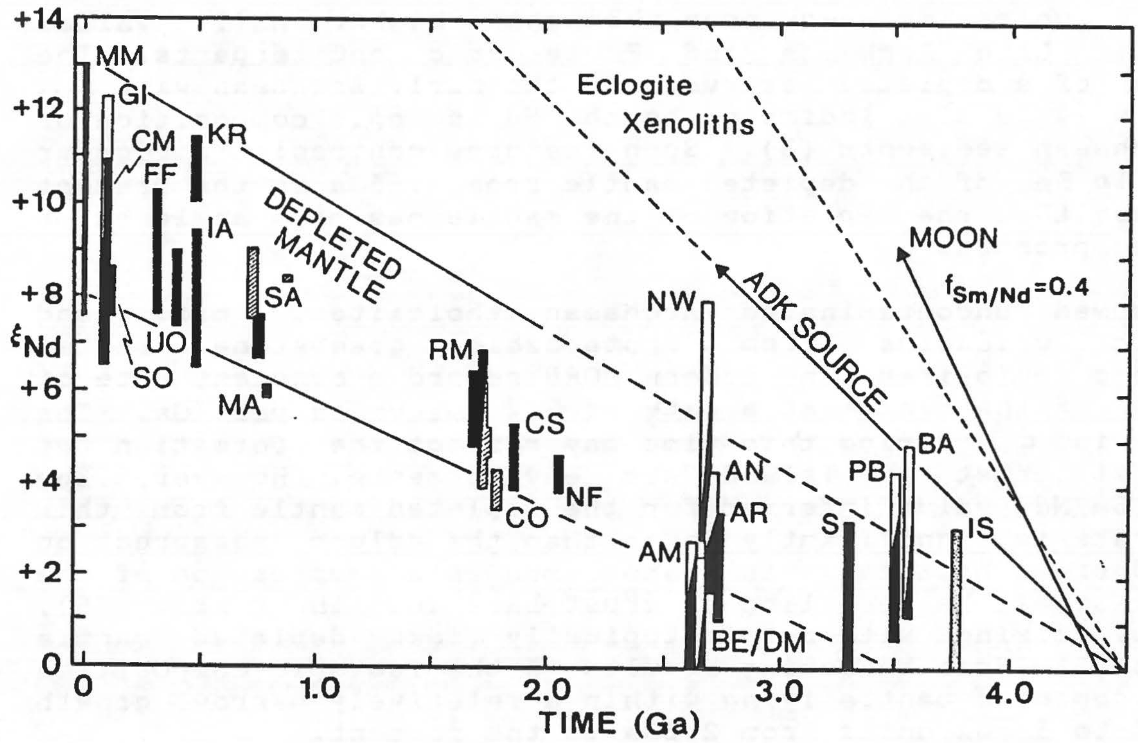

Figure 1. Variation in ε_{Nd} with time for mantle derived rocks (unshaded: komatiites; shaded: ocean ridge assemblages; hatched: primitive arcs) and sediments (stippled). In order of increasing age: MM modern MORB; GI Gorgona Island; CM Cretaceous MORB; SO Semail ophiolite; FF Fennel Formation; UO Urals ophiolite; KR Kings River ophiolite; IA Iapetus basalts; SA Saudia Arabian ophiolites; MA Matchless amphibolite; RM Rocky Mountain greenstones; CO Colorado greenstones; CS Circum-Superior belt; NF Jouttiaapa Formation; BE/DM Belingwe and Diemals-Marda; AM Abitibi, Munro; AN; Abitibi, Newton; AR Abitibi, Rainy Lake; NW Norseman-Wiluna; S Saglek; PB Pilbara; BA Barberton; IS Isua. Also shown are possible evolution curves for the depleted mantle, komatiite source (ADK), eclogite xenoliths, and lunar basalts. Data sources are given in Ref. 1.

The gradual decrease in the relative $\varepsilon_{Nd}(T)/\varepsilon_{Nd}(T)_{CHUR}$ ratios of the komatiites toward the late Archaean suggests gradual erosion of the heterogeneities, possibly by the inception of convection on a scale related to modern plate tectonic processes. Whether the tholeiite and komatiite sources were remixed to form the Proterozoic-Phanerozic depleted mantle is unknown. Several eclogite xenoliths found in kimberlites yield ancient Sm-Nd ages and have extremely high $\varepsilon_{Nd}(T)$ (10). Such xenoliths lie on the same evolution curves inferred for the ADK source (Fig. 1) suggesting that they may represent fragments of an ancient depleted reservoir which escaped remixing by isolation in the roots of early- formed cratons.

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Mantle-Crust Relationships in the Eastern Superior Province Inferred from Hf and Pb Isotope Studies

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Isotopic study of the Michipicoten-Gamitagama greenstone belts and surrounding area of the Superior Province, Ontario, provides insight on the nature of Archean crust-mantle relationships and the evolution of the mantle long after the greenstone belts were cratonized.

Pb isotope analyses of basalts from the belts indicate that the time integrated $^{238}U/^{204}Pb$ values of the sources of these volcanics (μ_1) were variable. The μ_1 value of the youngest basalt (2.70 Ga cycle III) is analytically identical to those of komatiites and basalts from the Abitibi belt (Tilton, 1983; Dupré *et al.*, 1984). The μ_1 value of these rocks is significantly lower than average earth estimates of this value (*e.g.*, Stacey and Kramers, 1975) and therefore indicates a source that was depleted with respect to large ion lithophile elements. In contrast, data for the earlier formed cycle I basalts (2.76 Ga), and felsic volcanic rocks from both of the cycles have higher μ_1 values indicating undepleted or crustally contaminated sources.

The variations in μ_1 of the rocks of the Michipicoten and Gamitagama belts are shown as relative displacements of the lower extrapolations of Pb isochrons on a plot of $^{207}Pb/^{204}Pb$ *versus* $^{206}Pb/^{204}Pb$ in Fig. 1. (cycle III= 2.71 Ga upper cycle felsic volcanics, cycle I= 2.75 Ga lower cycle felsic volcanics and HLGC = 2.89 Ga Hawk Lake Granitic Complex, from the granitic terrain immediately bordering the greenstone belt). The Pb isotopic variations of the rocks relate to the original sources from which the rocks were derived because the Pb isochron ages are in agreement with the U-Pb zircon ages for the same units. Furthermore, the apparent initial $^{207}Pb/^{204}Pb$ ratios are anticorrelated with initial $^{176}Hf/^{177}Hf$ isotope ratios (expressed as ϵ_{Hf} values) from the same rocks (Smith *et al.*, 1987). The anticorrelation is interpreted to reflect the derivation of the rocks from an old crust and a depleted mantle.

The enrichments of $^{207}Pb/^{204}Pb$ of the felsic volcanics relative to that of their associated basalts suggests analogies with Pb isotopic compositions from Cenozoic bimodal volcanic intercontinental rift areas. (Fig. 2) Both the felsic rocks and basalts show time progressive increases in their ϵ_{Hf} values and decreases in their apparent initial $^{207}Pb/^{204}Pb$ values over the 200 Ma life span of the belts. These secular variations also suggest a rifting type tectonic model where, as the evolution of the greenstone belt progressed, there was a systematic increase in the proportions of depleted mantle contributions over crustal contributions to the rocks.

Magmatic activity subsequent to the cessation of greenstone belt volcanism in the area took the form of diabasic and lamprophyric dykes and carbonatites. Prominent among these intrusions are the regionally widespead 2.45 Ga Matachewan dykes. Pb isotope data from dykes separated by over 200 km in distance indicates the source of the dykes is uniform with respect to the initial Pb isotope ratios suggesting that the Pb isotope signature reflects that of a mantle source. The μ_1 value of this source indicates an average-earth type source very similar to cycle I mafic volcanics produced over 300 Ma earlier. This contrasts with data from carbonatite complexes of the area which show the depleted type signature (Bell *et al.*, 1987). Therefore, it appears that both depleted and undepleted mantle sources were tapped during the time of greenstone belt formation and both of these sources were available for later magmatic activity. However, the times at which these sources were originally formed is still a major problem in geochronology (see Fig. 2).

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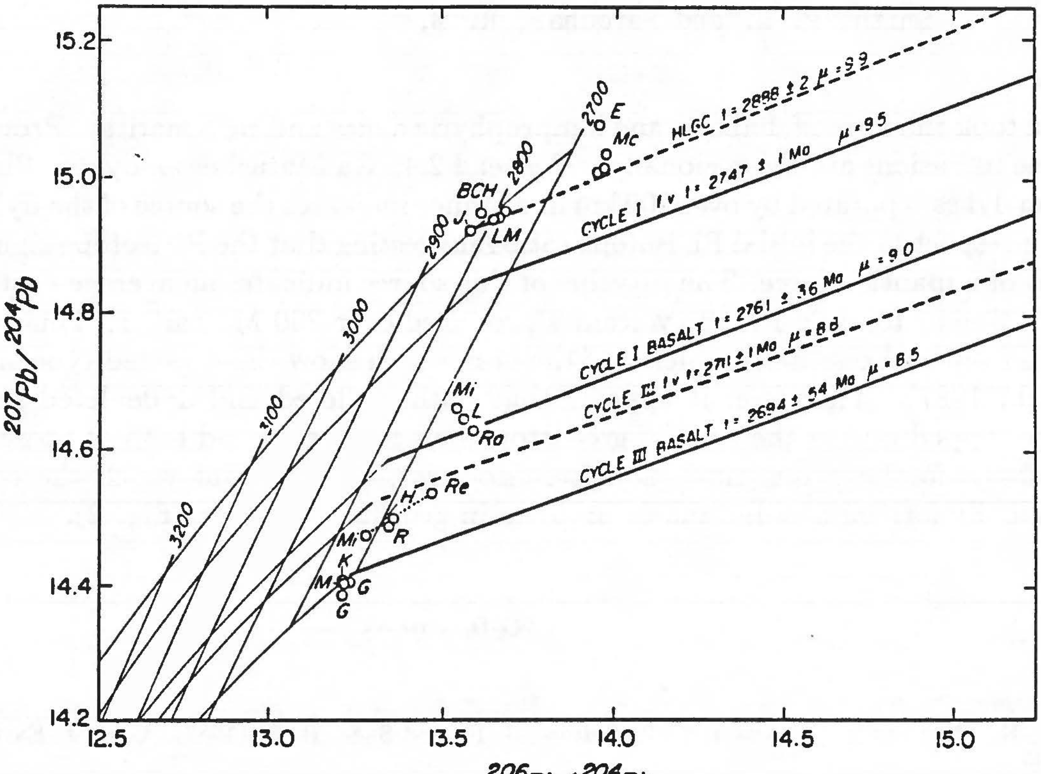
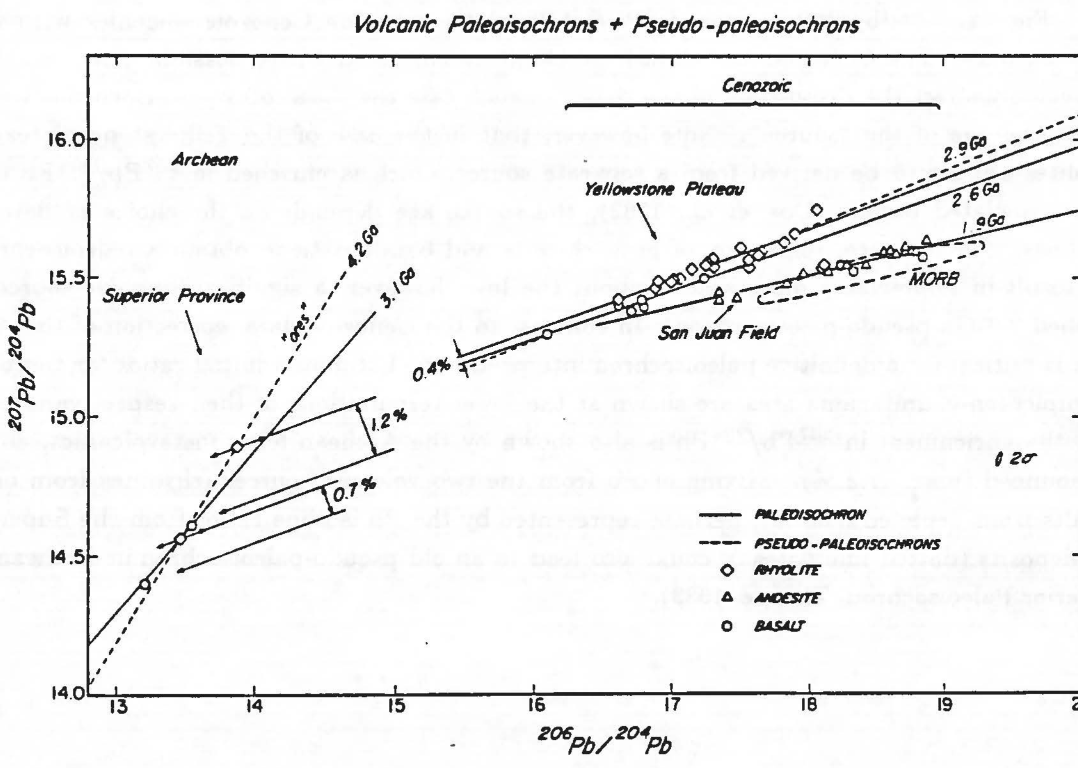
Fig. 2. $^{207}Pb/^{204}Pb$ *versus* $^{206}Pb/^{204}Pb$ plot comparing Cenozoic volcanics with the Archean metavolcanics. The Cenozoic rock data have been age corrected where possible; however, this does not appreciably affect the disposition of the data. In each case the data form paleoisochrons which possibly reflect the age of the "source". Note however, that in the case of the Yellowstone plateau where the rhyolites appear to be derived from a separate source which is enriched in $^{207}Pb/^{204}Pb$ compared to their associated basalts (Doe *et al.*, 1982), the source age depends on the choice of data used to fit the lines. For instance, regression of both rhyolite and basalt data to obtain a paleoisochron age does not result in appreciably more scatter about the line; however, a significantly older source age results (dashed 2.9 Ga pseudo-paleoisochron). In contrast to the Cenozoic data, correction of the Archean rock data is critical for a definitive paleoisochron interpretation. Estimated initial ratios for the basalts of the Michipicoten-Gamitagama area are shown at the lower terminations of their respective isochrons. Note that the enrichment in $^{207}Pb/^{204}Pb$ is also shown by the Archean felsic metavolcanics, although more pronounced (max. 1.2 %). Mixing of Pb from the two volcanic sources (rhyolites from old crust and basalts from depleted mantle), perhaps represented by the Pb isotope ratios from the Superior Province ore deposits (dotted line "ores"), could also lead to an old pseudo-paleoisochron in Archean rocks (*e.g.*, Superior Paleoisochron, Thorpe, 1983).



HLGC t = 2888 ± 2 μ = 9.9
CYCLE I f v t = 2747 ± 1 Ma μ = 9.5
CYCLE I BASALT t = 2761 ± 36 Ma μ = 9.0
CYCLE III f v t = 2711 ± 1 Ma μ = 8.8
CYCLE III BASALT t = 2694 ± 54 Ma μ = 8.5
2700
2800
2900
3000
3100
3200
E
Mc
BCH
J
LM
Mi
L
Ra
H
Re
R
Mi
K
M
G
G
15.2
15.0
14.8
14.6
14.4
14.2
12.5
13.0
13.5
14.0
14.5
15.0
$^{207}Pb/^{204}Pb$
$^{206}Pb/^{204}Pb$

Fig. 1



Volcanic Paleoisochrons + Pseudo-paleoisochrons
Cenozoic
Archean
Yellowstone Plateau
2.9 Ga
2.6 Ga
1.9 Ga
MORB
San Juan Field
Superior Province
"ores"
4.2 Ga
3.1 Ga
0.4%
1.2%
0.7%
2σ
PALEOISOCHRON
PSEUDO-PALEOISOCHRONS
RHYOLITE
ANDESITE
BASALT
16.0
15.5
15.0
14.5
14.0
13
14
15
16
17
18
19
20
$^{207}Pb/^{204}Pb$
$^{206}Pb/^{204}Pb$

Fig. 2

PETROGENESIS OF HIGH MG#, LILE-ENRICHED ARCHEAN MONZODIORITES AND TRACHYANDESITES (SANUKITOIDS) AND GRANODIORITIC DERIVATIVES IN SOUTHWEST SUPERIOR PROVINCE

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In southwestern Superior Province, diorite, monzodiorite, and trachyandesite occurring within syn- to post-tectonic intrusive complexes and within greenstone belts have very distinctive chemical characteristics. They have 55 to 60 wt. % SiO_2, greater than 6 wt. % MgO, Mg #'s greater than 0.60, greater than 100 ppm Ni and 200 ppm Cr, and very high alkali ($Na_2O + K_2O = 6$ wt. %), Sr and Ba (both 600 to 1800 ppm), and LREE abundances (Ce= 65-190 ppm). The Archean rocks share chemical similarities to relatively rare high-Mg andesites occurring within Phanerozoic arcs, among these, the Miocene "sanukitoids" of the Sanuki region of Japan (*1*, *2*). Recent experimental melting studies upon the Japanese sanukitoids have unequivocally demonstrated that such rocks may originate by partial melting of mantle peridotite at pressures between 10 and 15 kilobars under water-undersaturated to water-saturated conditions (*3*). The similarities in the abundances of SiO_2, FeO, MgO, Ni, and Cr between the Archean rocks and the Japanese sanukitoids led Shirey and Hanson (*4*) to propose that the Archean rocks could also have been derived by direct partial melting of the mantle, and that they be referred to as sanukitoids.

The Archean sanukitoids cannot be derived by melting, fractionation, or crustal contamination of typical basalts of the Superior Province. Such sources commonly have Mg #'s, and MgO, Ni and Cr abundances which are similar to, or lower than the sanukitoids, and thus are inconsistent with the expected source rocks. Furthermore, the extremely high LILE abundances of the sanukitoids cannot be explained by reasonable extents of melting of basaltic precursors. The Archean sanukitoids occur in close spatial and temporal association with LILE-enriched lamprophyric magmas, but, in general, such rocks cannot be parental to the sanukitoids due to their insufficient MgO, Ni, and Cr contents, and similar or lower Mg#'s. The sanukitoids cannot be created by simple crustal contamination of komatiitic melts (*5*) because crustal contaminants would have had lower LILE contents than the sanukitoids. Combined assimilation - fractional crystallization (AFC) modelling calculations by the methods of Nielson (*6*) yields melts of appropriate silica content with much lower Ni abundances and Mg#'s, and much lower Na, K, Sr, and Ba than the sanukitoids.

Geochemical modelling of the sanukitoid data set in southwestern Superior Province supports a mantle origin for these rocks. Such an origin is consistent with their primitive FeO-MgO systematics, their high transition metal contents, experimental melting studies upon high-Mg andesites and peridotite at low pressures, and by their primitive isotope characteristics. The sanukitoids in Ontario with crystallization ages of about 2700 Ma have $(^{87}Sr/^{86}Sr)_i$ of 0.701, epsilon Nd values of +1 to +2.5, and u_1 values near 7.8 (*7, 8, 9*).

We suggest that the sanukitoids resulted from partial melting of the mantle triggered by addition of aqueous fluids. The extremely high LILE contents and steep REE patterns of the sanukitoids relative to primitive mantle is consistent with addition of an LILE-enriched component to the source. The LILE-enriching component probably contained high contents of Na, K, Sr, Ba, P, and LREE's because these elements are notably high in the sanukitoids. Although low extents of melting of an unenriched source leaving garnet in the residue could explain the LREE-enrichment of some samples, the rather constant $(Ce/Nd)_n$ ratio of 1.5 over a three-fold variation in Ce (65 to 190 ppm) suggests that LREE and LILE enrichment was probably a characteristic of the source at the time of melting. If garnet was a residual mineral in the mantle source, the small variation in Ce/Nd ratios limit the degree of melting to 5% or greater, and requires the source to be LILE-enriched. The three-fold variation of both Ce and Sr suggests that there could have been a difference in the extent of melting by as much as 30%, assuming that the sanukitoids are unfractionated and were derived from a similarly LILE-enriched source. Thus, the sanukitoids could have formed by 5 to 35% melting of LILE-enriched peridotite. This would be consistent with the experimental data.

The incompatible behaviour of K_2O indicates that phlogopite was not in the residue. The more restricted range of Na_2O (3-5 wt. %) suggests that a Na-rich phase (e.g. amphibole or jadeite) may have been in the residue. Although the REE data permit the presence of garnet at low extents of melting, garnet may not be stable in peridotite at the low pressures necessary to form the sanukitoids.

Variation of about 2 cation mole % FeO in the most primitive sanukitoids suggest that the source may have been heterogeneous in major elements. Such variation in FeO is greater than would be expected by different extents of melting (+/- 0.5 mole %), and cannot be explained by differences in pressures of melting (>14 kilobars difference), because experimental criteria limit sanukitoid formation to +/- 5 kilobars (between 10 and 15 kilobars). A possible explanation is that, compared to pyrolite, the mantle source contained regions enriched in mafic components (komatiitic or basaltic?), resulting in a source with a higher Fe/Mg ratio which could yield sanukitoids with higher Fe/Mg ratios. The sanukitoids which are enriched in Fe/Mg also have the lowest LILE contents, suggesting that they resulted from greater extents of melting. This would be consistent with the larger mafic component in the source.

The monzodioritic sanukitoids are closely related to more siliceous and chemically evolved quartz monzodiorite to granodiorite. The evolved rocks have chemical characteristics, such as high Mg#'s, high Sr and Ba, which are consistent with an origin by derivation from sanukitoid parents. The rock association consisting of sanukitoids and their derivatives has been termed the "sanukitoid suite" (*4*). Our detailed investigations of the sanukitoid suite within the Roaring River Complex of the

Wabigoon subprovince suggest that granodiorite could have resulted from fractionation of sanukitoid parental magmas.

The sanukitoid suite is part of a larger rock association within the Superior Province which includes lamprophyres and syenites with similar LILE enrichments. One possibility is that they are all related to a similar process of melting initiated by the introduction of fluids into the mantle or lower crust. The source of the fluids is equivocal. Serious consideration should be given to the possibility that the fluids were derived from return of sediments to the mantle in subduction zones.

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GEOCHEMICAL AND ISOTOPIC CONSTRAINTS ON THE COMPOSITION OF THE ARCHEAN MANTLE

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Nd isotopic compositions of Archean komatiites and basalts reveal that their mantle source(s) beneath greenstone belts had the following characteristics:

(a) the source of the oldest preserved mafic rocks from Isua, Greenland, was isotopically depleted, with $\varepsilon_{Nd} = +2$. Depletion characterized the source of almost all Archean volcanics, with ε_{Nd} values reaching a maximum of about +5 (or even +8) in 2.7 Ga old komatiites from Kambalda, Western Australia. ε_{Nd} values in early to middle Proterozoic rocks are no higher than in Archean rocks: maximum ε_{Nd} values in 2.1 and 1.9 Ga volcanics are around +5.

(b) Most regions show a range of Nd isotopic compositions. 3.4 Ga old volcanics from the Pilbara block, Western Australia, have ε_{Nd} values from 0 to +5 (the lower value identical to that in the contemporaneous Barberton volcanics in South Africa); 2.7 Ga old volcanics in the Abitibi belt show a predominance of ε_{Nd} values around + 2.5 but also a range from +1 to +4; and 2.7 Ga Kambalda volcanics have a still larger range of values, from -2 to at least +5. At Kambalda, the lower values result from contamination of depleted komatiite magmas with older crustal rocks. Although the same process may be responsible for part of the variation in other regions, it can be demonstrated using trace element arguments that much of the variation results from differences in source compositions. The mantle sampled by volcanic rocks in greenstone belts was heterogeneous.

(c) Banded iron formations and other chemical sediments in greenstone belts have ε_{Nd} values as high, or higher than values in contemporaneous volcanic rocks and clastic sediments. It can be argued that the Nd in these sediments is derived from seawater whose isotopic composition is controlled by interaction with Archean oceanic basalts. If this is true, then the Archean oceanic mantle was as depleted or more depleted than the mantle beneath the greenstone belts.

The presence of widespread depleted mantle throughout the Archean creates a dilemma because the nature and location of a complementary enriched reservoir is uncertain. It is believed that the complement of today's depleted mantle is continental crust, but the absence of granitoid terranes older than 3.7-3.9 Ga, and the absence of an isotopic signature of older crustal material in the oldest granitoids, apparently argues against the existence of continental crust during the first 700 Ma of Earth history. On the other hand, the discovery of 4.0-4.3 Ga old zircons by the ANU group (Froude et al 1983) is best explained by the existence of granitoid rocks of this age.

We suggest that these disparate observations can be explained by a model for the early history of the Earth that takes into account two unusual features of this period. The first is the likely presence of thick, voluminous basaltic crust. High temperatures in the Archean mantle (evidenced by the presence of komatiites) cause melting beneath spreading centres to start at great depths. Large volumes of magnesian basalt thereby form and erupt to produce a thick crust. Estimates based on the compositions of komatiites and constrained by the siderophile element contents of Archean tholeiites suggest that melting may have started around 5 GPa (150 km) and produced a crust at least 40 km thick.

The second feature is effect of impacting by major planetesimals. It is now believed (e.g. Hartmann 1988) that the impacts that formed large (~1000 km diameter) basins on the lunar surface 3.9 Ga ago represent merely the end phase of a type of activity that was normal during the first 700 Ma, on both the Moon and the Earth. We argue that it is no coincidence that the age of the oldest terrestrial rocks corresponds to cessation of this activity.

Our model is as follows. The crust of the Earth for the first 700 Ma was a well-mixed regolith composed largely of basalt but also with a significant granitoid component. There was continuous input of incompatible element enriched basalt into this crust (a consequence of high mantle temperatures) and continual cycling of this basalt back into the mantle. Temperatures at the base of the crust were high enough to cause secondary melting and the formation of granitoid magmas. Impacting mixed the two components and prevented the formation of discrete granitoid terranes. The amount of granitoid material was high enough that its isolation in a surface layer was largely responsible for the depletion of the mantle. The basaltic crust was also moderately enriched in incompatible elements and its residence on the surface contributed to mantle depletion, but because it cycled from and to the mantle, its isotopic composition followed that of the mantle. The average composition of the surface layer never departed far from mantle compositions and when this material remelted 3.7 Ga ago to form the older preserved granitoids it left no discernable isotopic record of its earlier history. When major impacting ceased around 3.9 Ga the granitoid material began to accumulate to form continental terranes that became the nucleii of the present continents.

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EVIDENCE FOR SUBDUCTION AND SPREADING IN THE ARCHEAN ROCK RECORD: IMPLICATIONS FOR ARCHEAN TECTONIC STYLE AND THE EVOLUTION OF THE SUBCONTINENTAL LITHOSPHERE. H.H. Helmstaedt and D.J. Schulze, Department of Geological Sciences, Queen's University, Kingston, Ontario, Canada K7L 3N6

Two of the major arguments against Archean plate tectonics have been the apparent absence from the Archean rock record of ophiolites and eclogites, the presence of which in Phanerozoic orogenic belts is commonly accepted as evidence for sea-floor spreading and subduction, respectively. Although many students of Archean rocks have refused to view greenstone belts as Archean analogues of ophiolites (e.g., 1), others have proposed that the mafic sequences of some greenstone belts must have originated in proto-oceanic basin settings (e.g., 2,3). Evidence for the occurence of complete or partial ophiolite assemblages, including sheeted dykes, in Archean greenstone belts has been presented from South Africa (4,5), Wyoming (6), and northwestern Canada (7), and a well-preserved Proterozoic ophiolite (2Ga) was identified by St. Onge et al. (8) in the Cape Smith belt of northern Quebec. It has been found also that the oxygen isotope profile of Archean oceanic crust in the Barberton greenstone belt, South Africa, is indistinguishable from that of Phanerozoic ophiolites (9). We may conclude, therefore, that analogues of Phanerozoic ophiolites are present in the Archean rock record. If ophiolites constitute evidence for sea-floor spreading in the Phanerozoic, the existence of Archean and Proterozoic ophiolite analogues suggests that this process must have been active since early Precambrian times.

Opponents of Archean plate tectonics used the absence of eclogites from surface outcrops of undisputed Archean age to conclude that, without "eclogite sinkers", subduction would have been impossible during the Archean (e.g., 10). On the other hand, besides theoretical arguments for Archean subduction (e.g., 11, 12), evidence has been accumulating that a number of ultramafic xenolith types from diamondiferous kimberlites are possible remnants of subducted Archean oceanic lithosphere. Archean isotopic signatures in eclogites from the Robert Victor pipe, South Africa, were recognized since the early seventies (13,14), and the existence, at Robert Victor and other pipes, of mantle eclogites with ages in excess of 3 Ga was confirmed later by the Sm/Nd method (15). Early Archean ages were also determined on mineral inclusions in diamonds (16), confirming that at least some of the diamonds in kimberlites are of xenocrystic origin. The first suggestions that some eclogite and grospydite xenolith from kimberlites are fragments of subducted oceanic crust were also made in the seventies (17,18,19,20,21,22). Xenolith types now considered to be of subduction origin on the basis of textures, mineral assemblages, major and trace element compositions, and isotopic ratios include certain <u>eclogites and grospydites</u>, thought to be derived from subducted metabasites and metarodingites (23,24,25,26,27,28), <u>alkremites</u>, derived from Al-rich sediments (29) or black wall-chlorite alteration around metaserpentinites, <u>peraluminous garnet-kyanite rocks</u>, representing the refractory residue after melting of pelitic sediments (30,31), and <u>diamondiferous low-Ca garnet harzburgites and dunites</u>, interpreted as high-grade metamorphic equivalents of graphite-bearing metaserpentinites (32). As the most plausible protoliths to these xenoliths are typical members of ophiolite assemblages, we consider this part of the Archean xenolithic upper mantle sample as analogous to high-pressure metamorphic ophiolitic melanges that appear to be absent from Archean granite-greenstone and granulite-gneiss terrains but that, in the Phanerozoic record, are accepted as tangible evidence for subduction.

As theoretical models for Archean plate tectonics postulate very fast rates of spreading (e.g., 11,12,33), it can be assumed that Archean subduction zones were characterized by high convergence rates and the subduction of relatively young oceanic lithosphere. As a consequence of the relatively shallow or low-angle subduction resulting from these conditions, much of the Archean lithosphere under continental nuclei such as the southern African craton must have accreted and thickened by lateral tectonic underplating. Such underplating was accomplished by imbrication of the upper part of the subducting oceanic slab, while successive trench positions were overridden by the continental plate (26,27). The geometry resulting from the imbrication of slivers of successively younger rocks is analogous to that of duplexes at the base of major thrust sheets and must have resembled that detected by seismic profiling in oceanic slabs presently underplating the convergent parts of the northwestern margin of the North American plate (e.g., 34, 35).

Assuming that low-angle subduction was the rule during the Archean, entire cratons must have been underplated by oceanic lithosphere. The complexity within the Archean subcontinental upper mantle should thus be comparable to field relationships in a collage of accreted oceanic terranes bounded by highly deformed melange zones. Although it is probable that this collage was homogenized somewhat during high-grade metamorphism, partial melting, and later intrusions, the variety of mantle xenoliths recovered from young kimberlites on Archean cratons shows that the upper mantle has remained far too complex to be modelled in terms of traditional paleogeotherm-based upper mantle stratigraphy.

The post-Archean evolution of the continental lithosphere involves a gradual change from a regime of rapid spreading and low-angle subduction to more "normal" plate tectonics with steeper subduction angles. Low-angle subduction became an exception, restricted to episodes of rapid plate convergence and/or subduction of low-density crust. Such episodes have preceeded periods of intra-plate magmatism, including some of the major kimberlite events (36), and are held responsible for widespread modifications and metasomatic overprints of the Archean upper mantle.

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PRECAMBRIAN MANTLE BENEATH MONTANA: GEOCHEMICAL EVIDENCE FROM EOCENE VOLCANICS AND THEIR XENOLITHS; Irving, Anthony J., Hugh E. O'Brien and I. S. McCallum, Dept. of Geological Sciences, University of Washington, Seattle, WA 98195

Magmatic rocks from several of the Eocene-Oligocene potassic to sodic alkalic subprovinces of central Montana possess isotopic and trace element features clearly indicative of interaction of ascending melts with ancient mantle lithosphere related to the Wyoming craton. Outcrops of Archean crustal rocks in the Little Belt and Little Rocky Mountains indicate that the Wyoming craton extends into northern Montana (Figure 1), but the young magmatic rocks provide a more detailed geochemical map of the full extent of the craton. Furthermore, mantle xenoliths within several of the alkalic subprovinces appear to be samples of ancient depleted lithosphere. These xenoliths contain mineralogic and geochemical evidence for an ancient metasomatic enrichment event.

Sr-Nd isotopic systematics for alkalic rocks from Haystack Butte, Crazy Mountains, Leucite Hills (Wyoming) and Smoky Butte define an array extending from Bulk Earth to very large $-\epsilon_{Nd}$ (Figure 2). We interpret this trend as a mixing line between an asthenospheric component and ancient light-REE enriched mantle lithosphere. There is some correlation between $-\epsilon_{Nd}$ and enrichment in Ba for these rocks (Figure 3), which is consistent with the observed geochemical features of exposed Archean crustal rocks of the Wyoming craton (eg., Mueller and Wooden, 1988). Pb isotopic compositions for rocks from these same subprovinces are also consistent with this mantle source melting model (Figure 4).

Evidence for a third component, richer in radiogenic Sr, is apparent especially in the rocks from the Highwood and Bearpaw Mountains, and we believe by analogy with Recent potassic volcanics from Italy, Sunda-Banda and western Mexico that this component is related to subduction processes (Figure 2). An important observation for *all* of the Montana-Wyoming alkalic provinces is the notable lack of correlation of $^{87}Sr/^{86}Sr$ with Rb/Sr (Figure 5), which implies that the bulk of the radiogenic Sr is young and therefore not related to the ancient lithospheric component. We believe that this component may have been added to the asthenospheric wedge during the well-documented regional Eocene-Oligocene subduction event. Similarly we ascribe the relative depletions in HFS elements (Figure 3) largely to young subduction processes, although we cannot rule out a contribution from ancient lithosphere. These conclusions are consistent with tectonic models implying flat to very shallow subduction of the Farallon Plate beneath Washington, Idaho and Montana in the early Tertiary (eg., Bird, 1984).

Ultramafic xenoliths within the Highwood Mountains rocks comprise glimmerite-veined harzburgites and phlogopite dunites, which most likely represent ancient depleted residual mantle lithosphere that has undergone metasomatic enrichment by mica-saturated fluids. One glimmerite vein is relatively enriched in Ba and light REE (Figure 6). Pb-Pb pseudoisochron ages of 1.87 Ga for the Highwood rocks and 2.1 Ga for Smoky Butte thus may be indicative of the timing of Proterozoic enrichment events in the subcontinental lithosphere. We propose that these ancient geochemical signatures have been inherited by ascending asthenospheric melts through assimilative interaction with metasomatically-veined subcontinental lithospheric mantle.

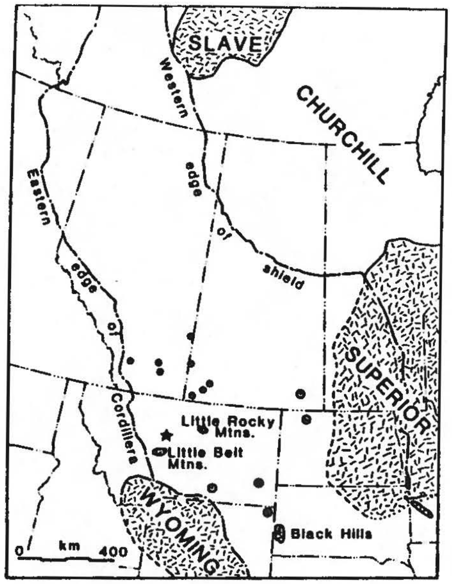

Figure 1. Map showing outcrop of Archean rocks in the Wyoming, Superior and Slave cratons. Asterisk indicates Highwood Mountains. Archean rocks (dots) and Proterozoic rocks (circles) encountered in drill cores are also indicated.

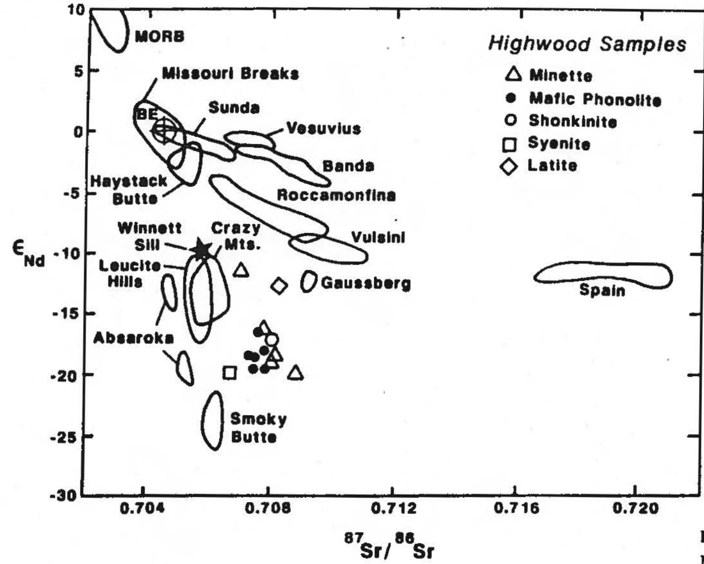

Figure 2. Plot of Nd and Sr isotopic compositions for potassic volcanics from Montana-Wyoming and elsewhere (data from Hawkesworth and Vollmer, 1979; Vollmer et al., 1984; Fraser et al., 1985; Nelson et al., 1986; Dudas et al., 1987; Meen and Eggler, 1987; O'Brien et al., 1988; Stolz et al., 1988; Scambos and Farmer, 1988)

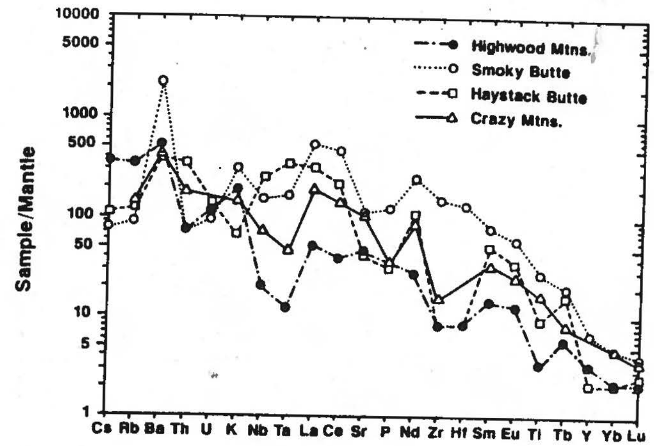

Figure 3. Primitive mantle-normalized trace element abundances for potassic mafic volcanics from Montana (O'Brien et al, 1987, 1989; Fraser et al., 1985; Dudas et al., 1987)

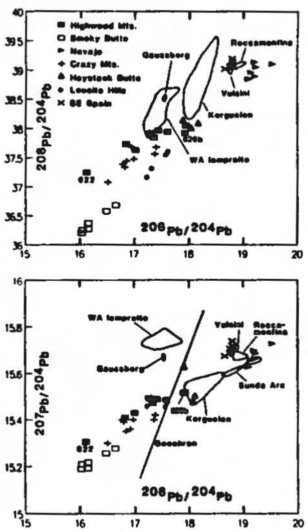

Figure 4. Pb isotopic compositions for potassic mafic rocks from Montana-Wyoming (data from O'Brien et al., 1988; O'Brien, 1988; Vollmer et al., 1984; Fraser et al., 1985; Dudas et al., 1987), Navajo province (Alibert et al., 1986) and elsewhere (after Nelson et al., 1986)

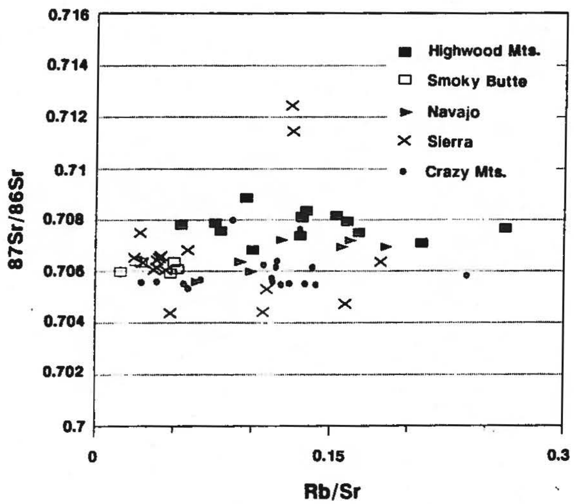

Figure 5. Variation of $^{87}Sr/^{86}Sr$ with Rb/Sr for potasic mafic rocks from the Highwood Mountains and elsewhere (data from O'Brien, 1988; Fraser et al., 1985; Alibert et al., 1986; Dudas et al., 1987)

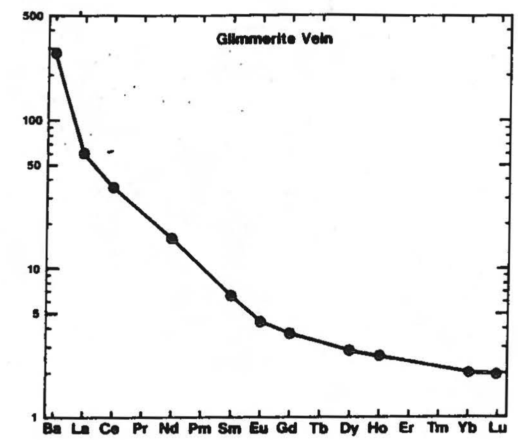

Figure 6. Chondrite-normalized rare earth element abundances and primitive mantle-normalized Ba abundance for a phlogopite glimmerite vein within a harzburgite xenolith from a primitive minette from the Highwood Mountains

MAGMA EVOLUTION IN THE STILLWATER COMPLEX, MONTANA: REE, Sr, AND Nd ISOTOPIC EVIDENCE FOR ARCHEAN LITHOSPHERIC INTERACTION; D.D. Lambert, R.J. Walker, S.B. Shirey, and R.W. Carlson, Department of Terrestrial Magnetism, Carnegie Institution of Washington, 5241 Broad Branch Road, N.W., Washington, D.C. 20015, and J.W. Morgan, U.S. Geological Survey, Reston, VA 22092.

Archean mafic layered intrusions emplaced within cratonic terrains (*e.g.* Stillwater, Bird River, Lac des Iles, Munni Munni) provide geochemical information regarding the evolution of the subcontinental mantle and the interaction of mantle-derived magmas with Archean continental crust. Mafic layered intrusions also are the world's major repositories for three strategic mineral resources: commonly Ni is associated with massive sulfide accumulations near the base of these intrusions [1]; Cr is found in discrete chromitite layers associated with ultramafic cumulates [2]; and the most important concentrations of the platinum-group elements (PGE) occur with disseminated sulfides in stratabound layers or "reefs" in plagioclase-rich cumulates which crystallized stratigraphically higher in the magma chamber [3]. Research which has focused on the genesis of these "reef-type" PGE deposits has emphasized mixing of geochemically-distinct magmas [4,5,6]. The lithosphere may have played an important role in the genesis of these deposits: contamination of mantle-derived magmas with sulfur-rich ***continental crust*** was an important process in the development of some Ni deposits [7] and magma mixing was important in the formation of both the Cr and PGE deposits [8,9]. ***Enriched mantle*** may have been a source for some of these magmas [6].

The Stillwater Complex is an Archean mafic layered intrusion which crops out in a belt approximately 45 km long in the Beartooth Mountains of south-central Montana. Magmas parental to the complex intruded Archean metamorphic rocks of the Wyoming craton which have ages of 3200 Ma to 2750 Ma [10]. The age of the Stillwater Complex is well constrained at 2700 Ma by several isotopic techniques [11]. Five major stratigraphic subdivisions of the complex have been recognized [12]: the Basal series (BS), the Ultramafic series (UMS), and the Lower, Middle, and Upper Banded series (LBS, MBS, and UBS, respectively). Five mineralogic zones of the LBS, MBS, and UBS mark the reappearance of Mg-rich olivine as a cumulus phase. These have been referred to as olivine-bearing subzones (OBZ's [13]) or troctolite-anorthosite zones (TAZ's [4]). The PGE-rich horizon of the Stillwater Complex, informally named the J-M Reef [4], occurs approximately 400 m above the top of the UMS within TAZ I. Magmas parental to TAZ I and the J-M Reef may have had anorthositic affinities (A-type magma [5]), unlike magmas parental to the BS, UMS, and gabbroic portions of the LBS, MBS, and UBS which may have had more ultramafic or boninitic major element affinities (U-type magma [5]). We have documented the nature, source, and mixing characteristics of these magmas at Stillwater by utilizing isotope dilution REE data for cumulus orthopyroxenes from the BS, UMS, and LBS and wholerock samples of fine-grained sills and dikes collected in footwall hornfels and Sr and Nd isotopic data for sulfide-bearing cumulates from all major zones of the Stillwater Complex.

REE results: Nine orthopyroxene separates (opx) from the BS, 18 opx from the UMS, and 7 opx from the LBS (including TAZ I) have (Nd/Sm)n ratios which range from 1.05 in the BS to 0.6 in TAZ I and (Dy/Yb)n ratios of 0.9 (BS) to 0.5 (TAZ I), well in excess of the ratios expected in opx which crystallized from magmas with chondritic proportions of the REE (ratios of 0.45 and 0.38, respectively). These opx therefore crystallized from magmas which were very light-REE enriched and heavy-REE depleted. The HREE depletion has been ascribed to the presence of residual garnet in the source region of these magmas [14,15]. The LREE enrichment is consistent with either contamination of Stillwater parental magmas with LREE-enriched Archean crustal rocks or to derivation from enriched Archean subcontinental mantle [15]. Very little overlap exists in REE data for opx from these three zones of the complex and there is a trend of decreasing LREE enrichment and decreasing HREE depletion with stratigraphic height. This trend cannot be modeled by simple closed-system crystal fractionation, suggesting a more complicated process involving coupled crystal fractionation, assimilation, and magma recharge, typical of large mafic magma chambers [16]. This trend, however, is consistent with decreasing amounts of crustal contamination higher in the stratigraphic section. Calculated REE abundances in magmas parental to the BS and UMS have (Ce/Yb)n ratios of 8-18 and (Dy/Yb)n ratios of 2, very similar to REE abundances in group 2 high-MgO gabbronorite sills of the Stillwater footwall [17]. These sills are very similar to high-MgO magmas which have a crystallization order appropriate for the U-type magma (olivine→orthopyroxene), including high-MgO andesites (boninites), basaltic komatiites, and mafic rocks of the Archean sanukitoid suite [18]. Calculated REE abundances in magmas parental to TAZ I and the J-M Reef have (Ce/Yb)n ratios of 4 and (Dy/Yb)n ratios near 1, very similar to REE abundances in group 1 gabbronorite sills of the Stillwater footwall [17]. These sills are similar to higher-Al_2O_3 magmas which have a crystallization order appropriate for the A-type magma (olivine→plagioclase), such as leuconorite dikes of the Nain Complex [19]. The presence of these two geochemically distinct magmas should be recorded isotopically in cumulates of the complex, assuming post-crystallization isotopic homogenization and *in situ* crustal contamination have not obscurred these differences.

Rb-Sr isotopic results: Isotopic data for wholerocks analyzed in this study do not define an isochron nor do they lie near a 2700 Ma reference isochron. ε_{Sr} varies from +1.0 to +34.0 in plagioclase-rich rocks of the LBS, MBS, and UBS and -260 to -13.1 in olivine and pyroxene-rich rocks of the UMS. These data demonstrate that the Rb-Sr isotopic system in these rocks has been disturbed during low-grade metamorphism or near-surface alteration, in agreement with previous Sr isotopic analyses of rocks and minerals from Stillwater [20,21,22]. An estimated initial Sr isotopic composition, based on unaltered plagioclase-rich rocks, is 0.70200 to 0.70235 (ε_{Sr} = +14 to +19) which is distinctly more radiogenic than primitive mantle at this time, consistent either with derivation of Stillwater parental magmas from an enriched mantle source or contamination with older continental crust.

Sm-Nd isotopic results: Isotopic data for previously analyzed minerals from a LBS (U-type) gabbronorite [22] define a precise mineral isochron age of 2701 $\pm$ 8 Ma and an initial Nd isotopic composition of ε_{Nd} = -2.8 (MSWD = 0.04). Previous wholerock Nd isotopic data [22] for U-type cumulates (only one sample was from A-type, MBS anorthosite) suggested Nd isotopic homogeneity of the intrusion. However, Nd isotopic data for wholerocks of this study lie distinctly off of the mineral isochron along a trajectory of increasing ε_{Nd} and increasing (Nd/Sm)n. If the Nd isotopic systematics of these rocks have not been disturbed following crystallization at 2700 Ma, these new data preclude formation of the complex from one isotopically homogeneous magma. If, however, the samples are grouped according to magmatic affinities (*i.e.* cumulates which crystallized from U-type magmas and those which crystallized from A-type magmas), U-type cumulates have initial ε_{Nd} = -1.8 to -2.2 and A-type cumulates have initial ε_{Nd} = -1.5 to +0.5 (Fig. 1). The first significant change in ε_{Nd} occurs over a 4 ft interval at the base of TAZ I, from ε_{Nd} = -1.9 in norites of the footwall ore zone to ε_{Nd} = -0.3 in anorthosites of the main ore zone. AFC calculations suggest that deviation of ε_{Nd} from +2 (similar to mantle-derived rocks of the Superior Province) to -2 could only be accounted for by assimilation of > 45 % by weight of a material similar to footwall hornfels (21 ppm Nd, ε_{Nd} = -5.7), assuming the uncontaminated magma had 8 ppm Nd. If the primary Stillwater U-type magma was ultramafic (~4 ppm Nd) or was derived from more enriched subcontinental mantle (ε_{Nd} = 0), only 25% contamination is required. However, the Nd isotopic homogeneity observed in U-type cumulates of the UMS and LBS and the presence of a compositionally diverse suite of Late Archean rocks in the Beartooth Mountains all with ε_{Nd} ~ -2 [23] dictates that contamination could not have occurred *in situ*. The ε_{Nd} and REE variations observed in this study are consistent with either significant heterogeneity in the Archean subcontinental mantle and/or with crustal contamination of the U-type magma. Although contamination is quite successful in explaining the Nd isotopic data, the extreme light-REE enrichment of Stillwater parental magmas (including footwall sills) may require additional source enrichment [6,15].

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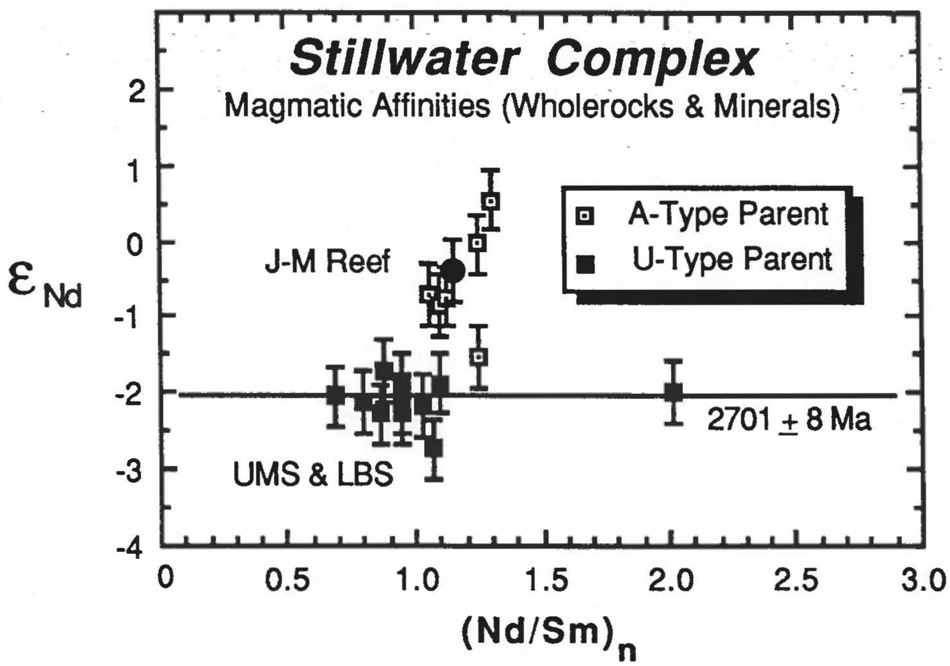

Figure 1. Initial Nd isotopic composition (ε_{Nd} at 2700 Ma) plotted vs. chondrite-normalized Nd/Sm for wholerocks and minerals from the Stillwater Complex. Samples have been subdivided on the basis of magmatic affinities (U-type cumulates and A-type cumulates). UMS = Ultramafic series samples, LBS = Lower Banded series samples. The J-M Reef (A-type parent) is highlighted as a filled circle. Mineral isochron [22] is shown for reference.

THE DIAMOND-KOMATIITE PARADOX: HOT MANTLE-THICK LITHOSPHERE.

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In a lithosphere with homogeneous thermal properties, the thickness of this lithosphere is inversely proportional to heat flow, and thus high Archean heat flow may be expected to indicate thin lithosphere. A model has been developed of a heterogeneous thermal lithosphere with localized regions of thick lithosphere in equilibrium with relatively high mantle temperatures. In this model, geotherms similar to modern "shield" geotherms, which pass through the diamond P-T stability field, can be produced in the regions of thick lithosphere, with high asthenosphere temperatures compatible with komatiite eruption temperatures.

Heat flow in the modern earth is very variable, ranging from near zero over subducting slabs to several thousands of mW m^{-2} in areas of young volcanism. Much of this variability is associated with the advection of heat by tectonic and magmatic processes, but heat flow is also significantly variable in stable continental regions, ranging from 25-30 mW m^{-2} to in excess of 100 mW m^{-2} (variations outside this range are generally due to shallow advection of heat by groundwater). This variability in stable regions is due primarily to heterogeneity in upper crustal radiogenic heat generation, and heat flow from the lower crust (reduced heat flow) appears to be relatively uniform at about 27 $\pm$ 4 mW m^{-2} *(1)*. Heat flow data indicate that there is no "shield" geotherm, but a family of geotherms which diverge in the upper crust, due to variations in upper crustal heat generation, then run sub-parallel through the lower crust and mantle lithosphere until they converge on an asthenosphere adiabat *(1,2)*. Apart from the result that heat flow from the lower crust and mantle lithosphere is about 27 mW m^{-2}, there is little constraint on the shape of the geotherm in the lower lithosphere beneath stable areas. Seismic low velocity zones and electrical conductivity anomalies, which can be used to infer depths to certain isotherms, are typically poorly developed, or absent beneath stable regions. Data which indicate a thick lithosphere (or "tectosphere") beneath stable regions *(3,4)* can only be reconciled with heat flow data if significant lower crustal and upper mantle heat generation is assumed *(1)*. In this contribution, the possible role of upper mantle heat production is explored, with the goal of investigating the possible role of mantle heat production in stabilizing thick continental lithosphere relative to changing asthenosphere temperatures.

It is reasoned that if there is little of no heat transfer from the asthenosphere to a particular piece of lithosphere, i.e., the lithospheric conductive geotherm is asymptotic to the asthenospheric convective geotherm, then that piece of lithosphere should be stable relative to thermal perturbations in the underlying asthenosphere. Three tests of this hypothesis are proposed: 1) Can such a geotherm be created? 2) Are the parameters required to create this geotherm reasonable? and 3) Does this geotherm stabilize the lower lithosphere against convection?

A very simple thermal model of the mantle lithosphere is assumed in the absence of any reliable information concerning variations in mantle thermal parameters. It is assumed that a heat flux q flows through the Moho, which is at temperature T_m. The Moho is arbitrarily designated as zero depth, $l = 0$. At the base of the lithosphere, depth $l = L_a$, the lithosphere geotherm is constrained by the asthenosphere temperature, $T = T_a$. Mantle heat production, A, and thermal conductivity, K, are assumed constant. Lateral variations are assumed to be small relative to the lithosphere thickness, and the model uses solutions to the 1-D heat conduction equation for the mantle lithosphere geotherm.

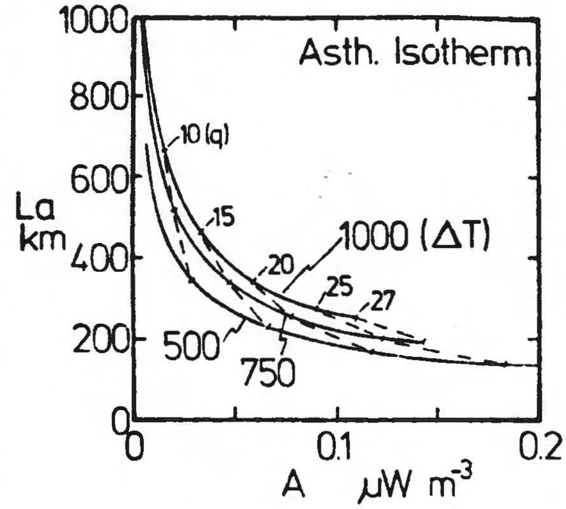
Two extreme models of asthenospheric thermal conditions have been tested. In the first, the asthenosphere is assumed to be isothermal, which gives the following lower boundary conditions to the model: i) Temperature at base = T_a = constant; and ii) Gradient at base of lithosphere = 0. These conditions have been solved for the thickness and heat production in the lithosphere with the following results:

$$L_a = q/K \qquad\qquad A = q^2/[2K(T_m - T_a)].$$

The second model assumes an asthenosphere with a linear geotherm (adiabat approximation), which gives the following lower boundary conditions to the model: i) Temperature at base = $T_x + gL_a$, where T_a is the adiabat temperature at the Moho, and g is the adiabatic gradient; and ii) gradient at base of lithosphere = g. These conditions have been similarly solved, yielding:

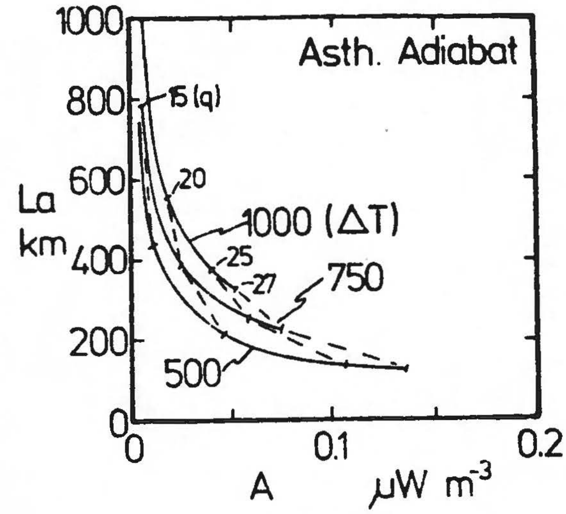
$$L_a = [2K(T_x - T_m)/A]^{0.5} \qquad A = (q^2/K - 2qg + Kg^2)/[2(T_x - T_m)].$$

Both models yield suitable geotherms with reasonable choices of parameters, as shown in Figures 1-3,



Family of curves of L_a vs. A for isothermal asthenosphere and different values of the temperature drop across the mantle lithosphere (ΔT), with corresponding values of q indicated.

Figure 1: Isothermal Asthenosphere L_a vs. A.



Family curves for "adiabatic" asthenosphere with different temperature differences between the adiabat and geotherm at the Moho ($\Delta T = T_x - T_m$), and different values of q indicated.

Figure 2: Adiabatic asthenosphere, L_a vs. A.

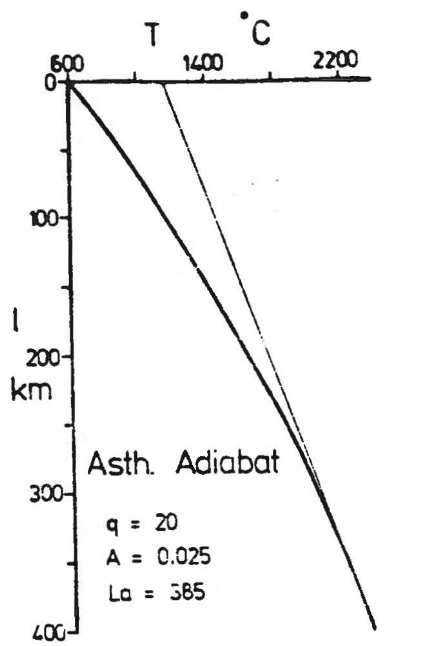
and thus the first two tests of the hypothesis are positive.

The stability of thermally thickened lithosphere as described above has been qualitatively investigated using the results of published numerical experiments on the onset of convective instability in the earth's mantle by Houseman and McKenzie *(9)*. This study investigates small-scale convection in the Rayleigh-Taylor instability at the base of the lithosphere. The lithosphere is assumed to have a stable mechanical upper boundary layer, and a lower, potentially unstable lower thermal boundary layer overlying mantle in which temperatures are controlled by convection in a material of temperature-dependent viscosity. The important model parameters in the model for the present discussion are the thicknesses of the upper thermal boundary layer and the underlying convecting layer in the system. The thickness of the thermal boundary layer is the parameter which may be expected to increase with the introduction of heat production into the mantle lithosphere.

Houseman and McKenzie use a critical cooling time to describe the time for a cooling thermal boundary layer to become unstable. This critical cooling time increases as the ratio of the thickness of the thermal boundary layer to the total layer thickness decreases. Thus, at least qualitatively, a lithosphere thickened by mantle heat production, should be more stable than a thinner lithosphere under similar conditions for small-scale convection.

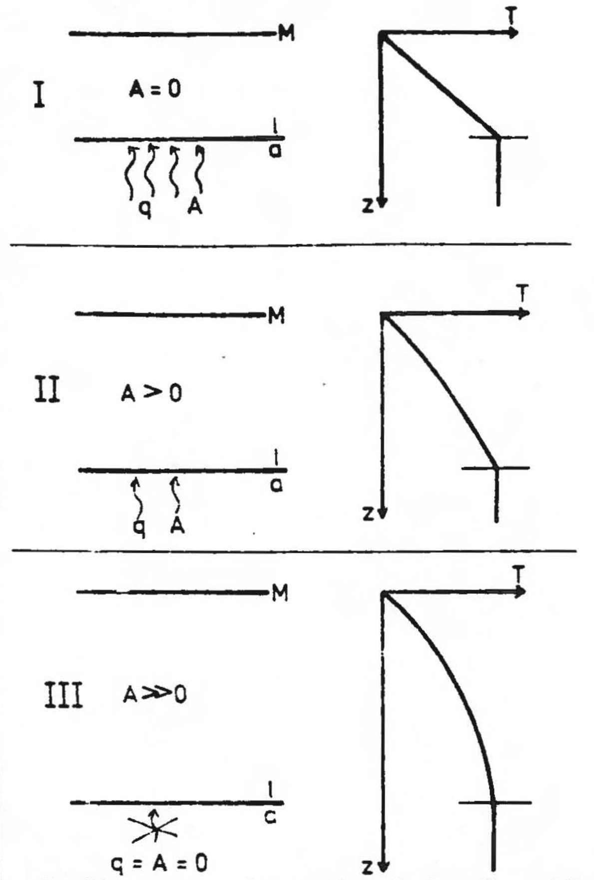
The results of this crude study indicate that very small concentrations of radiogenic heat production can significantly alter the geotherm in the mantle lithosphere and thicken the thermal lithosphere. The trade-offs between heat production A and lithospheric thickness L_a shown in Figures 1 and 2 suggest that the conditions for stabilization of the lower lithosphere with respect to the underlying asthenosphere are relatively insensitive to the temperature drop across the lithosphere, and that geotherms can be generated giving thick lithosphere for significantly high mantle temperatures, as may be expected from a more dynamic Archean thermal regime as indicated by komatiites. Higher global heat loss from the Archean earth than from the modern earth, as predicted by secular cooling of the earth, would be lost by an average thinner lithosphere, greater hot spot heat loss, greater oceanic lithosphere heat loss, or some combination of these mechanisms. However, the higher global heat loss does not preclude local areas of thick lithosphere, perhaps stabilized by the mechanism described above.

Figure 4 illustrates possible mechanisms by which the "stable" thermal lithosphere may be generated. Part I illustrates an upper mantle geotherm representative of mantle lithosphere with no heat production. Heat



Geotherm asymptotic to extreme conditions for adiabatic asthenosphere (Basalt Dry Solidus, T = *1050 + 3l* °C). A 385 km thick lithosphere is predicted for a Moho heat flow of 20 mW m^{-2} and mantle heat production of 0.025 $\mu W\ m^{-3}$. A constant thermal conductivity of 3.5 W $m^{-1}\ K^{-1}$ was assumed for this model.

Figure 3: Example of geotherm asymptotic to linear adiabat.



Possible sequence of generation of thermally stabilized lithosphere. I Mantle lithosphere with no internal heat generation, but high basal heat flux and metasomatism including the introduction of heat generation. II As mantle lithosphere heat generation increases, basal heat flux and metasomatism decrease. III Final "stable" stage with minimum basal heat flux and metasomatism. Stage III is produced from stage II lateral compression and/or continued basal metasomatism.

Figure 4: Model for generation of thermally stable lithosphere.

flow across the Moho in this model would be completely derived from heat flow into the base of the lithosphere from the convecting asthenosphere. Intermittent metasomatism associated with this basal heat flux would be capable of transferring the incompatible heat production elements (U, Th, K) into the lithosphere, resulting in a mantle lithosphere which receives part of its heat from below, and part of its heat from internal heat generation, as shown in part II. At this stage, the mantle lithosphere has increased in thickness, and its basal heat flux, and presumably any associated metasomatism, have been reduced to a fraction of the Moho heat flow. This process could conceivably continue with an ever decreasing basal heat flux and rate of metasomatism until the "stable" lithosphere is created, as shown in part III. Alternatively, and perhaps more likely, tectonic lateral compression of the lithosphere shown in part II could result in the necessary increase in mantle heat production to produce the "stable" condition shown in part III. Too much compression would result in a lithosphere with an "excess" heat generation, which would be thermally thinned, removing heat generation from its base, until it became in equilibrium with its underlying asthenosphere. The "stable" lithosphere may not be stable with time if the cooling rate of the asthenosphere does not exactly match radiogenic decay in the lithosphere. However, heat production in the lithosphere may be "topped-up" by basal metasomatism if the lithosphere cools faster than the asthenosphere resulting in an increase in basal heat flux into the lithosphere.

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Models for the Thermal Evolution of the Earth

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The most general form of the thermal evolution of the Earth problem consists of solving a globally averaged energy equation of the form

$$\frac{d}{dt}\int_v \rho\, c_p\, T\, dv = \int_v H\, dv - \int_s F\, ds$$

where ρ is density, c_p is the specific heat, T is temperature, H is the rate of volumetric heating (dominantly radiogenic) , and F is the surface heat flux. When this equation is applied to the present day the flux F is known and the rate of volumetric heating H can be derived from estimates of the bulk composition of the Earth as a whole. The result is that the global flux exceeds the rate of radiogenic heating by about a factor of two, thus there must be a secular cooling (dT/dt) contribution of order 50-100°C per billion years. This rate of cooling suggests that the mantle temperature in the Archean was several 100°C hotter than that of today, a result in accord with the view that the high magnesian komatiites of the Archean required a significantly hotter mantle source than the present mantle.

In order to use the equation given above to model thermal evolution, one must be able to specify a relation between the surface flux and the mean interior temperature of the planet, and also specify a bulk composition from which the rate of heating is determined. A parameterization for F(T) can be obtained from laboratory or numerical convection experiments once one decides what is the general style of the convective flow. If one wants to address the thermal regime of Archean continental areas I would argue that one must consider at least two distinct convective styles. On the one hand one should allow for a style of convection that could be called "oceanic" in which the lithosphere is an active part of the flow as in the spreading and subduction of present day oceanic plates. The other style of convection might be called "continental" where the lithosphere acts as a conductive lid over the actively convecting interior. In effect one is constructing a regionalized thermal evolution model that can take account of the difference in the style of heat loss of oceanic areas compared to continents. Given that the present day Earth is quite clearly regionalized in terms of its thermal regimes, a model hoping to describe the past must at the very least include a similar regionalization.

The regionalized thermal evolution model has been used to try to understand the implications of the widely held view that the thermal gradients of Archean continental areas were not much different from those of todays continental areas. Another way of posing the problem is to ask what are the implications of the discovery of diamonds of Archean age for the thickness and evolution of the continental lithosphere. It has been suggested that local Archean continental areas could be protected from high thermal gradients by a very efficient style of heat loss in other areas, including greater heat loss from a more active "oceanic" convective regime. The regionalized thermal evolution models can be used to show that this type of "protection" does not occur, indeed the real question is not what is going on elsewhere but how does the continental lithosphere respond to the hotter interior temperature of the Archean mantle.

If the thickness of the continental lithosphere is assumed to extend to a fixed rheologically determined cut-off temperature (as seems reasonable for the oceanic lithosphere), then its response to a increase in internal temperature is to thin and develop a proportionally steeper geothermal gradient. An increase in interior temperature of order 200°C, as seems likely for the Archean, will result in a lithospheric thickness of the order of 10 km and a geothermal gradient about ten times the present one. To the extent that this is not acceptable in terms of the various arguments that Archean thermal gradients were similar to those of today, another mechanism, much less sensitive to temperature, for controlling the thickness of the lithosphere must be invoked. One way out of this dilemma is to consider the possibility of a chemically distinct continental lithosphere that would owe its thickness to composition instead of temperature. Jordan has for some time argued for such a chemical lithosphere on the basis of seismic velocities, but it is arrived at here through thermal structure and thermal evolution arguments.

I now hold the view that those parts of the Archean continental lithosphere that have survived to this day must be in their mantle portions chemically distinct from the rest of the upper mantle, including the mantle part of the oceanic lithosphere. Only chemically distinct lithosphere can have survived the effects the hotter interior temperature of the Archean. As the interior temperature of the planet cooled there must have come a time when a rheological continental lithosphere could be stable for a long period of time. Thereafter continental areas with "normal" mantle parts would become preserved as well and one would expect to see a record of greatly enhanced continental stabilization. The data on continental mantle separation ages are still very sparse, but to the extent that they exist, they are suggestive of a major stabilization of continental mass during the early proterozoic. This might represent the transition from a time when only very special chemically distinct lithosphere could survive to the more modern situation when a normal geothermal gradient is a sufficient attribute for survival.

THE ECLOGITE COMPONENT OF THE SUBCONTINENTAL LITHOSPHERE: OBSERVATIONS BEARING ON ITS ORIGIN AND ABUNDANCE; Daniel J. Schulze, Department of Geological Sciences, Queen's University, Kingston, Ontario, Canada K7L 3N6

It is generally agreed that the Earth's upper mantle is dominantly garnet peridotite, with a subordinate amount of eclogite, the origin of which remains controversial. The traditional view, that eclogite represents basaltic magma crystallized at high pressure (e.g., 1, 2) has been challenged by workers proposing that mantle eclogites formed by subduction of ocean floor basalts and gabbros (e.g., 3-6). Accessory and trace constituents of mantle eclogites, such as diamond, graphite, kyanite, corundum, amphibole, coesite, and sanidine, can be used to help constrain the equilibration conditions of these rocks, as well as processes that led to their formation.

The first occurrence of coesite in an eclogite xenolith was documented by Smyth and Hatton (7) in a sanidine-bearing grospydite (kyanite eclogite with >50% grossular in garnet) from the Roberts Victor kimberlite in South Africa. Although numerous other sanidine-bearing eclogites have been described (e.g., 5, 7, 8), examples of coesite, or its pseudomorphs, have remained uncommon (10, 11) until recently (12).

Eclogites containing fresh coesite, or pseudomorphs of quartz or quartz + talc after coesite, have now been found to be relatively common, occurring at the Roberts Victor, Lace, Blaauwbosch, and Jagersfontein kimberlites in South Africa and at the Zagadochnaya pipe in Siberia. At Roberts Victor, Lace, and Blaauwbosch, coesite eclogites occur throughout much of the compositional range established for each suite and, as a group, coesite (and sanidine) eclogites span most of the known compositional range of mantle eclogites.

Although fractional crystallization of basalt, a process purported to account for the compositional range of mantle eclogites (e.g., 1, 2, 13) might be expected to result in a residual liquid enriched in silica and potassium, such a process would not account for the wide compositional range of coesite and sanidine eclogites. Furthermore, basaltic magmas are not expected to form at pressures greater than approximately 30 kb (14, 15), the conditions under which most mantle eclogites are thought to have formed. Green and Ringwood (16, 17) showed, however, that prograde metamorphism of MORB during subduction would yield an eclogite containing both coesite and sanidine, and sea floor alteration of oceanic basic rocks might be expected to further expand the range of compositions that would contain coesite and sanidine following subduction of such rocks. The compositional range of coesite and sanidine eclogites is considered to be strong evidence against an origin of such rocks through *in situ* fractional crystallization of basaltic magmas in the upper mantle, but is consistent with an origin for some mantle eclogites through subduction and prograde metamorphism of ocean floor basalts.

Most kimberlite xenolith suites are dominated by garnet peridotites, a fact that has led, in part, to the conclusion that the upper mantle is mostly peridotite. In some xenolith suites, however, such as Roberts Victor, Bobbejaan, Lace, Blaauwbosch, Orapa, and Zagadochnaya, eclogite is much more abundant than peridotite. Such data have been used to support models in which it is proposed that eclogite plays an important petrologic and geodynamic role in the upper mantle (e.g., 6, 18).

Garnets from heavy mineral concentrates from three kimberlites with eclogite-dominated xenolith suites (Roberts Victor, Bobbejaan, Zagadochnaya) have been analyzed. In contrast to their xenoliths suites, each of the concentrates contains a significant proportion of peridotite-derived garnets. Garnets from the Roberts Victor concentrate are 40% peridotitic, those from Zagadochnaya 59% peridotitic, and those from Bobbejaan 82% peridotitic. Correction for the average modal abundance of garnet in eclogites and peridotites (approximately 50% and 6%, respectively) results in estimation that the Roberts Victor concentrate represents a mantle that was 85% by volume garnet peridotite, the Zagadochnaya concentrate represents a mantle that was 92% peridotite and the Bobbejaan data represent 97% peridotite.

The Zagadochnaya kimberlite is severely and deeply weathered, with all olivine serpentinized (Sobolev, 1977), which is probably the reason that garnet peridotites do not exist there as intact xenoliths. A similar situation exists at the Orapa kimberlite, where olivine is completely serpentinized, eclogites are abundant and peridotite xenoliths have not been recovered, although peridotitic garnets are common in concentrate (Shee, 1978).

Such an explanation does not account for the Roberts Victor and Bobbejaan data, however, as fresh olivine, and some intact garnet peridotites, occur at both pipes. It is suggested that prior to xenolith incorporation in these, and other micaceous kimberlites (e.g., Lace, Blaauwbosch), orthopyroxene in the garnet peridotite wall rock reacted with the K-rich magma, forming secondary phlogopite. The presence of this phlogopite rendered the peridotite structurally weak, relative to the orthopyroxene-free eclogites, allowing the eclogites to survive the processes of xenolith incorporation, kimberlite ascent and emplacement, while the garnet peridotites disaggregated, leaving only xenocrysts as evidence of their prior existence. It is concluded that the eclogite-rich xenolith suites in micaceous kimberlites are not representative of the upper mantle sampled by the kimberlites and, therefore, that eclogite is even less abundant in the upper mantle than previously estimated.

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THE Pb AND Nd ISOTOPIC EVOLUTION OF THE ARCHEAN MANTLE; S.B. Shirey and R.W. Carlson, Department of Terrestrial Magnetism, Carnegie Institution of Washington, 5241 Broad Branch Road N.W., Washington DC 20015.

The geochemical evolution of the mantle in early Earth history must be inferred from the bulk chemistry of the Earth [1] and the few samples of Archean mafic-ultramafic volcanic rock [2] and juvenile granitoids that survive in the cratons. The oceanic crust created from 4.55 to 3.8 Ga, however, may have played a significant role in Archean mantle chemistry. Creation and destruction of oceanic lithosphere was the dominant Archean heat loss mechanism, similar to present plate tectonics [3] and it would have produced large volumes of lithophile element enriched crust that would have been recycled into the mantle [4]. The processes that affect the chemical composition of the present oceanic mantle serve as a model for this long destroyed Archean component. The present mantle, as sampled by basalts erupted on ocean islands and at ocean ridges is chemically heterogeneous on a variety of scales (e.g. [5]) which has been suggested to reflect the presence of recycled oceanic lithosphere [6,7] recycled continental crust [8] or lithospheric mantle [9,10] and recycled pelagic sediment [11]. Similar recycling could have occurred via the pre-Archean oceanic crust and could have been one factor in the depletion and heterogeneity apparent in the Pb and Nd isotope data for the mantle that melted to produce the Archean cratons.

Nearly all Archean mantle-derived volcanic rocks and many granitoids have positive ϵ_{Nd} indicating that non-chondritic, light REE depleted mantle has dominated the upper mantle source of crust throughout the Archean [12-15]. A striking feature of the Archean data set is the near constant ϵ_{Nd} of +2 to +4 through the period from 3.8 Ga to 2.7 Ga (Fig. 1). If the moon was formed by a giant impact [16], then a major early terrestrial fractionation could have taken place within the molten silicate mantle. The observed Nd isotopic composition of the Archean mantle is the opposite expected for the long-term light REE enrichment that would have occurred from a molten mantle by removal of magnesium silicate perovskite or majorite at lower mantle pressures [17]. Either the Earth never melted to the depths of majorite or perovskite stability or convection in the molten Earth did not allow significant perovskite separation. The second major fractionation from the mantle involved removal of pre-3.8 Ga crust. Mass-balance models assuming continental crustal removal from the upper mantle was the only cause for its depletion require full recycling of continental crust with ϵ_{Nd} of −5 to −7 by 4.0 Ga [18]. The Hf and Nd isotope data base for the cratons is inconsistent with wholesale continental crust removal because some remnant of early crust would be expected to be preserved. One possibility to cause the positive ϵ_{Nd} characterizing the Archean mantle is the removal by subduction of a basaltic crust at some time before 4.0 Ga [19–20]. Reassimilation of this basaltic component, occurring only partially in the early Archean, would have limited the maximum extent of differentiation of the depleted mantle especially if the mantle had reached a steady-state between rates of extraction of new oceanic crust and assimilation of old subducted crust [21]. The noticeable increase in ϵ_{Nd} values of the depleted mantle in the Proterozoic may have been due to the Archean period of continental crust removal.

The Pb isotope systematics (two-stage) of Archean rocks, independent of the data base from conformable galenas (e.g. [22,23]), show little in the way of regular, time-dependent change in initial Pb isotopic compositions of the Archean mantle from 3.8 to 2.7 Ga but maximum variability in Pb isotopic composition of the Archean mantle exists by 2.7 Ga. For mantle-derived rocks or juvenile crust initial $^{238}U/^{204}Pb$ (μ_1) ranges from 7.7 to 8.7 and initial $^{232}Th/^{238}U$ (κ_1) ranges from 3.5 to 5.2 (Figs. 2,3). The average values for the Archean are surprisingly close to time-averaged μ_1 of 8.3 [5] and κ_1 of 4.2 for the oceanic mantle reservoir today [24]. Pb evolution models that attempt to match average crustal [22] or mantle [25,26] reservoirs to a single stage of Pb growth do a poor job of matching the U/Pb systematics of Archean rocks,falling ~0.5 μ low for all terrains except the Superior Province and the recycled rocks of the North Atlantic Craton. Th/Pb systematics are somewhat better matched by these single stage models , but the scatter due to crustal fractionation of Th from U is large.

Mantle derived and crustal rocks from individual Archean cratons have distinct differences in their initial Pb isotopic compositions [27,28,29]. Crustal rocks encompassing komatiites through granitoids from the Superior Province show evidence for a significantly lower μ_1 compared to rocks from other cratons (Wyoming Craton $\mu_1 = 8.3$; Baltic, Pilbara, Yilgarn Craton's $\mu_1 = 8.0-8.2$). When Nd and Pb isotope data are considered together, ϵ_{Nd} does not always show a simple negative correlation with μ_1. For example, slight but systematic differences between the eastern and western Superior Province suggest regional differences existed between portions of the Superior Province mantle. A negative relationship between ϵ_{Nd} and μ_1 compared to depleted mantle is present, however, for rocks of the Wyoming, Slave and Yilgarn cratons. This and their association with earlier Archean crust make it impossible to rule out crustal assimilation as a important process. It is important to entertain another alternative, that the increasing variability in initial isotopic composition reflects the increasing heterogeneity in the sub-cratonic lithospheric mantle. This could have been caused by the injection of large ion lithophile enriched fluids from the asthenosphere or by the incorporation of slightly older crustal components recycled by subduction.

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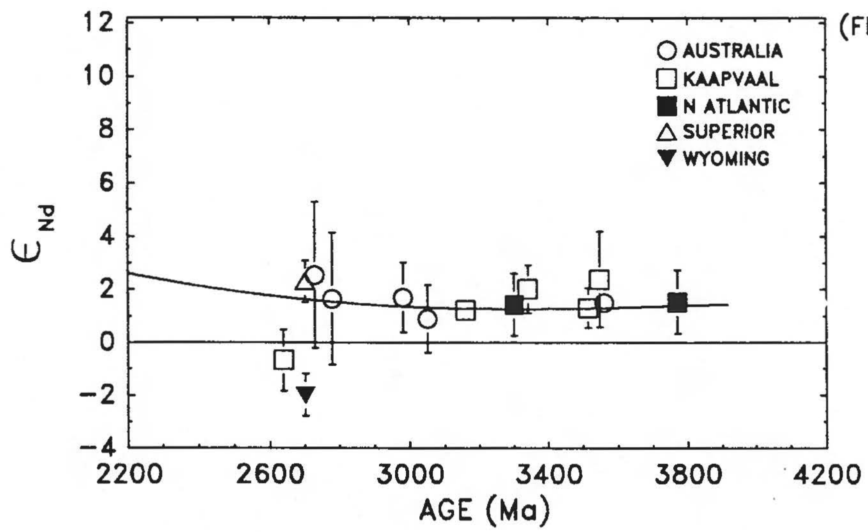
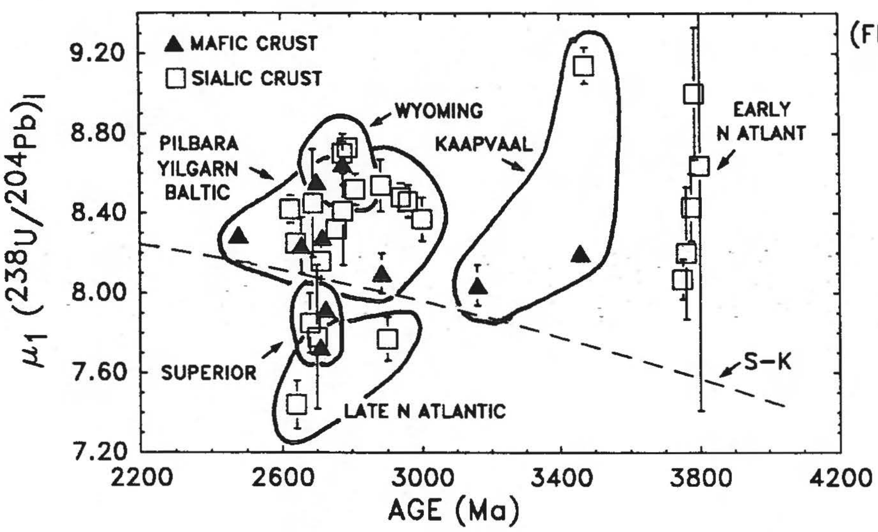
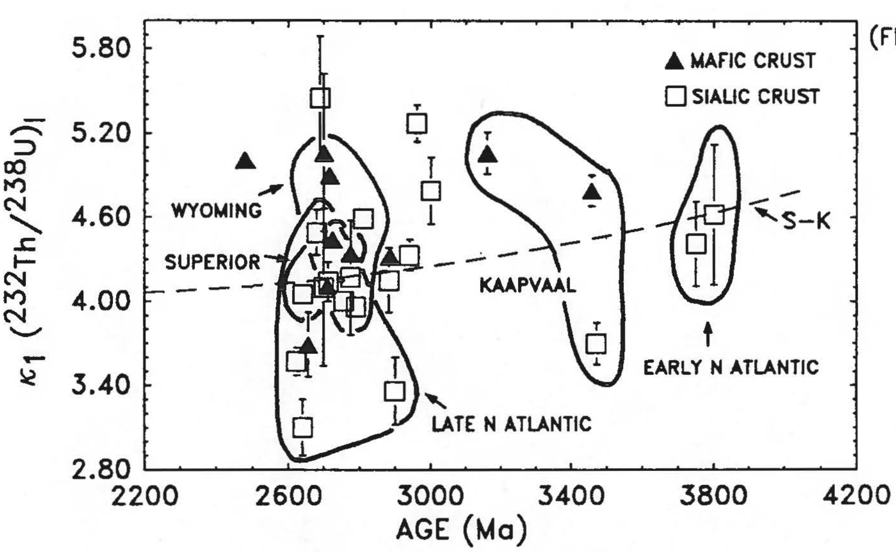
FIGURES: Initial Pb and Nd isotopic data versus age for Archean terranes taken from the literature. Fig. 1 shows the average ϵ_{Nd} and the range for terranes within specific cratons. Fig. 2 shows the initial $^{238}U/^{204}Pb$ (μ_1) calculated from Pb-Pb isochrons using a two-stage model. An average crustal growth curve [22] is shown for comparison. Fig. 3 shows the initial $^{232}Th/^{238}U$ (κ_1) calculated from Pb-Pb data arrays and the initial isotopic composition from the two-stage isochrons used in Fig. 2.



(FIG. 1)



(FIG. 2)



(FIG. 3)

MANTLE HETEROGENEITY AS EVIDENCED BY ARCHEAN MAFIC AND ULTRAMAFIC VOLCANIC ROCKS FROM THE CENTRAL LARAMIE RANGE, WYOMING

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Recent isotope studies of Archean terranes (Mueller & Wooden, 1988a, 1988b; Shirey & Carlson, 1988) suggest that heterogeneity of the Archean mantle may be related to recycling or assimilation of early Archean crust or by injection of enriched melts into the lithospheric mantle. Mafic and ultramafic volcanic rocks of tholeiitic and komatiitic affinities, which occur in the central Laramie Range of southeastern Wyoming, may provide further evidence for mantle heterogeneity of the types noted above.

These mafic and ultramafic rocks occur within a sequence of supracrustal rocks known as the Elmer's Rock Greenstone Belt (ERGB) located at the southern edge of the Archean Wyoming Province, and were first identified as a komatiitic sequence by Graff and others (1982). This small (15 sq km) fragment of a greenstone belt is enclosed by 2.5-2.8 Ga granitic gneiss. The mafic and ultramafic rocks from the northwestern portion of the ERGB were chosen for a detailed study (Smaglik, 1987, 1988) and represent a volcanic succession of tholeiites, komatiites and komatiitic basalts interbedded with intrusive(?) gabbro, garnetiferous amphibolite and several types of metasedimentary rocks such as metagreywacke, metagreywacke conglomerate with granitic clasts and marble. Pillow lavas are preserved in the tholeiitic layers but the primary minerals and textures of all the rocks within the belt have been destroyed by subsequent amphibolite grade metamorphism and deformation.

Major and trace element data for the mafic and ultramafic rocks and garnet amphibolite within this area are listed in the table below.

Ranges of Values for ERGB rocks

Component		Tholeiites	Komatiites	Gabbros	Gt-amph
SiO2	%	50 - 53	46 - 53	49 - 52	59
TiO2		.5 - 2	.18 - 1.8	.5 - .8	1.5
FeO*		9 - 13	8 - 15	8 - 11	17
MgO		6 - 11	14 - 31	7 - 12	1.4
CaO		10 - 12	3 - 12	10 - 13	5.5
Al2O3		12 - 16	4 - 11	12 - 17	10
Mg#		.49-.64	.68-.89	.66-.68	.15
Cr	ppm	35 - 175	850 - 5000	150 - 750	0
Zr		25 - 100	8 - 180	30 - 50	260
Y		9 - 150	2 - 25	9 - 15	70
Nb		0 - 5	0 - 31	0 - 2	13
V		250 - 370	100 - 360	140 - 230	95
$(Ce/Yb)_N$		1.0 - 1.8	5.8 - 14.7	1.0 - 1.3	1.0

With the exception of the garnet-amphibolite and a Mg-rich basalt, the major and trace element compositions of the tholeiites are close to those of other Archean tholeiites. The REE systematics of these rocks indicate derivation by partial melting of a garnet bearing source (Fig. 1a). The composition of the Mg-rich basalt lies between that of the komatiitic and tholeiitic rocks in both major and trace elements (Fig. 1a). The garnet-amphibolite is different than the other rock types in both major and trace element composition (Fig. 1b). The REE patterns for the gabbros are shown in Fig. 1c.

Unlike most Archean komatiities, the ultramafic rocks of this suite are enriched in Ti, Zr and Nb as well as the LREE (Ce_N = 3.5 to 101) Some of these high-Mg rocks have REE patterns suggestive of cumulates, probably from the komatiite magma (Fig. 1d). The other high-Mg rocks which were analyzed for REE have very unusual fractionated patterns compared to most Archean komatiites. These rocks were probably derived from partial melting of a garnet-bearing source.

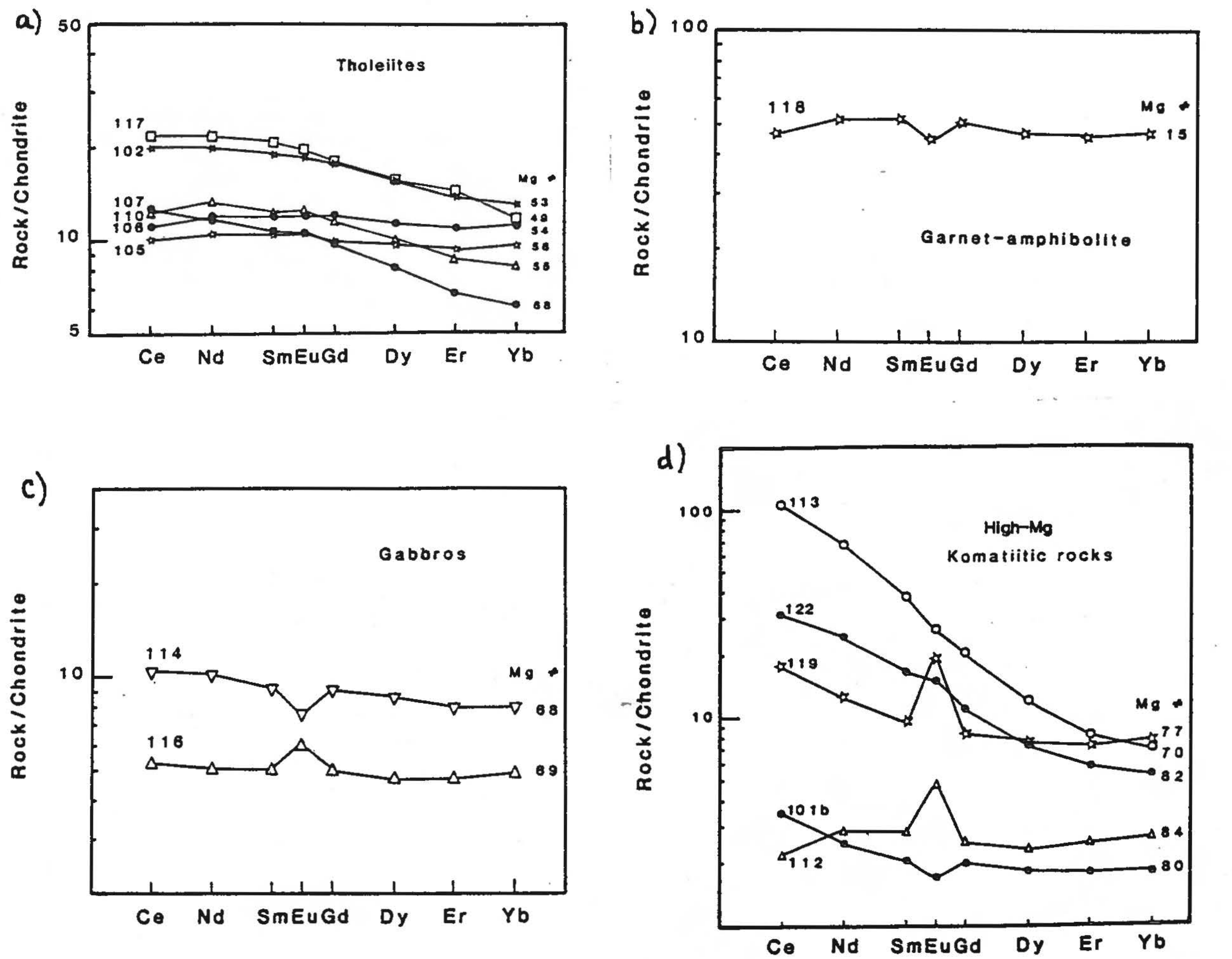

Figure 1.

The unusual trace element characteristics and decoupling from the major element compositions of these ultramafic rocks can be explained by 1) melting of a previously metasomatized portion of the mantle, 2) mixing of the magma with an IE-enriched fluid or 3) contamination by crustal material duriing ascent.

The differences between the tholeiitic and komatiitic rocks indicate that they were probably derived from sources which had distinctly different histories. There is evidence for magma mixing between these two end members, resulting in a magnesian basalt that is LREE enriched($(Ce/Yb)_N = 2.0$). A self-consistent model for this suite suggests that the tholeiitic rocks were formed by partial melting of a diapir derived from a chondritic source which selectively separated garnet. Some of the komatiitic rocks are cumulates of an ultramafic melt. Others were derived by partial melting of an enriched source along with early separation of garnet, followed by fractional crystallization of the resulting melt.

These magmas were probably derived from diapirs of a compositionally heterogeneous mantle in a tectonic setting that allowed mixing or contamination of magmas, such as the Archean equivalent of the subduction of an oceanic spreading center near a convergent continental margin. Radiogenic isotope analyses of the ERGB rocks may be able to differentiate the source of IE-enrichment in the ultramafic rocks and help to explain the nature of the mantle heterogeneity in the southern part of the Archean Wyoming Province.

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Re-Os ISOTOPIC CONSTRAINTS ON THE CHEMICAL EVOLUTION OF THE ARCHEAN MANTLE; R. J. Walker, S. B. Shirey and R. W. Carlson (CIW-DTM, Washington, D.C. 20015), J. W. Morgan (U.S. Geological Survey, Reston, VA 22092).

Because of the unique geochemical characteristics of Re and Os (siderophile and chalcophile) compared with the lithophile elements that comprise the other long-lived radiogenic isotope systems, the ^{187}Re-^{187}Os system potentially can provide previously unobtainable chronologic and chemical information regarding the evolution of the Archean mantle. Three major applications will be reviewed: 1) Re-Os fractionation during core formation and the possible importance of accretion following core formation to the interpretation of terrestrial Re-Os isotopic systematics, 2) dating mantle-derived Archean rocks and noble metal ores, and 3) examination of peridotites from depleted lithospheric mantle and implications for Archean crustal extraction.

Recently, the Re-Os isotopic systematics of eight carbonaceous chondrites have been examined [1]. ^{187}Re/^{186}Os and ^{187}Os/^{186}Os range from 2.4 to 3.7 and from 1.0 to 1.12, respectively, with average ^{187}Re/^{186}Os = 3.3 and present day ^{187}Os/^{186}Os = 1.06 (= 0.80 at 4.55 Ga). Abundances of Re and Os in the upper mantle as determined by analysis of peridotite xenoliths are approximately 0.2 ppb and 3 ppb, respectively [2–4]. These abundances indicate a similar Re/Os to that in carbonaceous chondrites, although concentrations are lower in the mantle by a factor of 300 relative to chondrites. The mantle's lower Re and Os abundances presumably resulted from the incorporation of most of the Earth's siderophiles into the core during its formation. Os isotopic data from osmiridiums, komatiites, mantle peridotite xenoliths, oceanic peridotites and basalts [5–11], confirm that the Re-Os system in the upper mantle has evolved in a manner grossly similar to its evolution in chondritic meteorites but with some significant differences.

The retention of near chondritic Re/Os in the mantle following the Earth's core formation is difficult to explain. It seems unlikely that the partitioning behavior of Re and Os between the silicate Earth and the metallic material that formed the core would be identical. Alternate explanations include the possibility that certain phases that contain high Re and Os abundances and chondritic Re/Os (sulfides ?) were retained in the mantle during core formation and "buffer" the abundances at their present level [12]. Another explanation is that most of the Re and Os contained within the mantle was added by the accretion of extraterrestrial material onto the Earth following core formation [13]. A definitive resolution of this puzzle could provide new insights into the processes of core formation and the rates of both the accretion that followed core formation and the subsequent homogenization of the silicate Earth. However, much additional information regarding the Os isotope evolution of the mantle through time, the sites for Re and Os in the mantle, and silicate-metal and silicate-sulfide partitioning characteristics for Re and Os must be obtained.

Two Re-Os isotopic studies of Archean komatiites of the Superior Province [7,9] have yielded isochrons that give 2.7 Ga crystallization ages, similar to ages determined using other techniques. These results indicate that the system might be useful for dating Archean mafic and ultramafic rocks that in general have proven difficult to date using other isotopic techniques. The Re/Os ratios in many basalts are so high that it may be possible to precisely date single samples of basalt in a manner analogous to U-Pb dating of zircons, yet closed system behavior remains to be demonstrated especially for basaltic and komatiitic rocks at amphibolite grade metamorphism. Significant mobility of Re and Os has been shown for the same crustal settings where Au is mobile [14] and the similarity of Re and Os to other noble metals (e.g. Pt) suggest the system will be useful for studying the genesis of noble metal ore deposits (e. g. [15]).

Deviations from "chondritic" Re-Os evolution in portions of the mantle are now documented [11,16]. During mantle melting, Re is an incompatible element and Os is compatible. Thus, melting events that produce crust from the mantle lead to major depletions of Re relative to Os in the resulting mantle residue. Concentrations of Re averaging approximately 1 ppb in many basaltic rocks indicate that even low extents of partial melting of a mantle source should leave little Re in the residue, hence, the Os isotopic composition of residues are frozen in time unless subsequent addition of Re occurs. This Re depletion process provides a new way to examine the chronology of Archean craton development and corresponding effects on the subcontinental lithosphere. We have observed as much as a 14% depletion in ^{187}Os relative to what would be expected for chondritic mantle evolution in certain garnet peridotite xenoliths from the Kaapvaal craton of southern Africa. The depletions are noted primarily in xenoliths from which a basaltic or komatiitic component has been removed. The intersection of the Re-Os growth trajectory of a depleted xenolith with a chondritic growth trajectory provides chronologic information regarding the depletion event, and by inference craton formation. The results from Kaapvaal xenoliths indicate melt extractions a minimum of 2.8 Ga ago, but these depletion events could correspond with the formation of the Kaapvaal Craton. Perhaps even more importantly, these results corroborate the presence of a stable lithospheric "keel" to the craton, which has remained isolated from chemical exchange with the sub-lithospheric mantle [17, 18].

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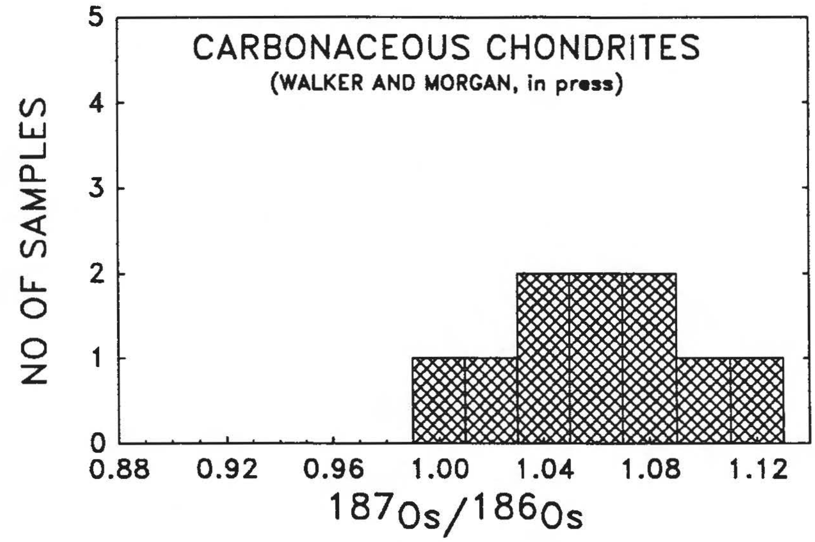
FIGURES: Os isotopic compositions in carbonaceous chondrites, oceanic basalts, oceanic peridotites and garnet peridotites from the Kaapvaal Craton, Southern Africa. Present-day measured compositions are given for the chondrites and basalts. With the exception of the samples from the Premier kimberlite, the garnet peridotites are corrected for the 80 Ma age of host kimberlite eruption. The Premier samples were erupted at 1100 Ma and are corrected for this age.


CARBONACEOUS CHONDRITES
(WALKER AND MORGAN, in press)
NO OF SAMPLES
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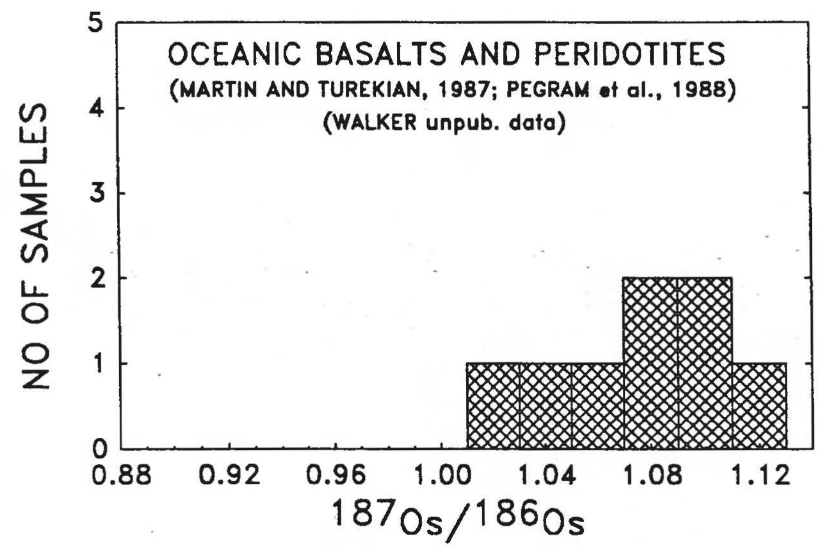
187Os/186Os


OCEANIC BASALTS AND PERIDOTITES
(MARTIN AND TUREKIAN, 1987; PEGRAM et al., 1988)
(WALKER unpub. data)
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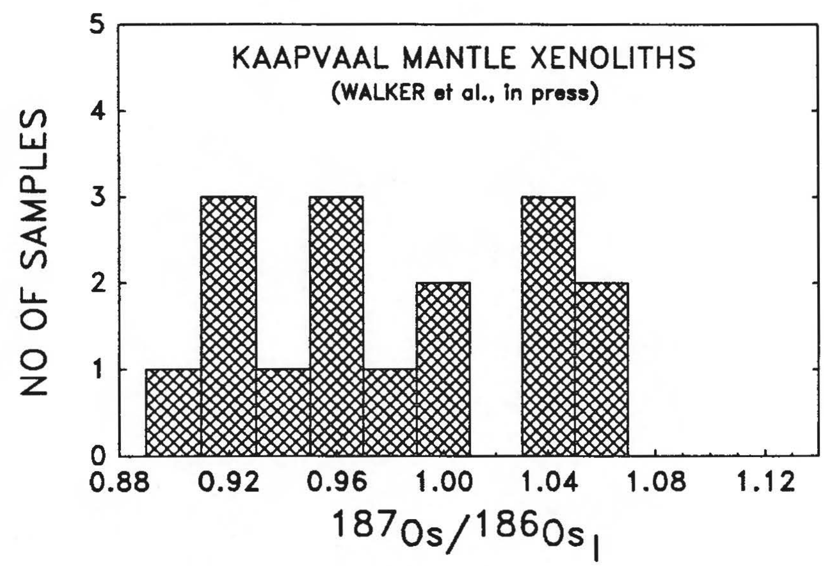
KAAPVAAL MANTLE XENOLITHS
(WALKER et al., in press)
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