WORKSHOP ON
THE ARCHEAN MANTLE

NASW-4066
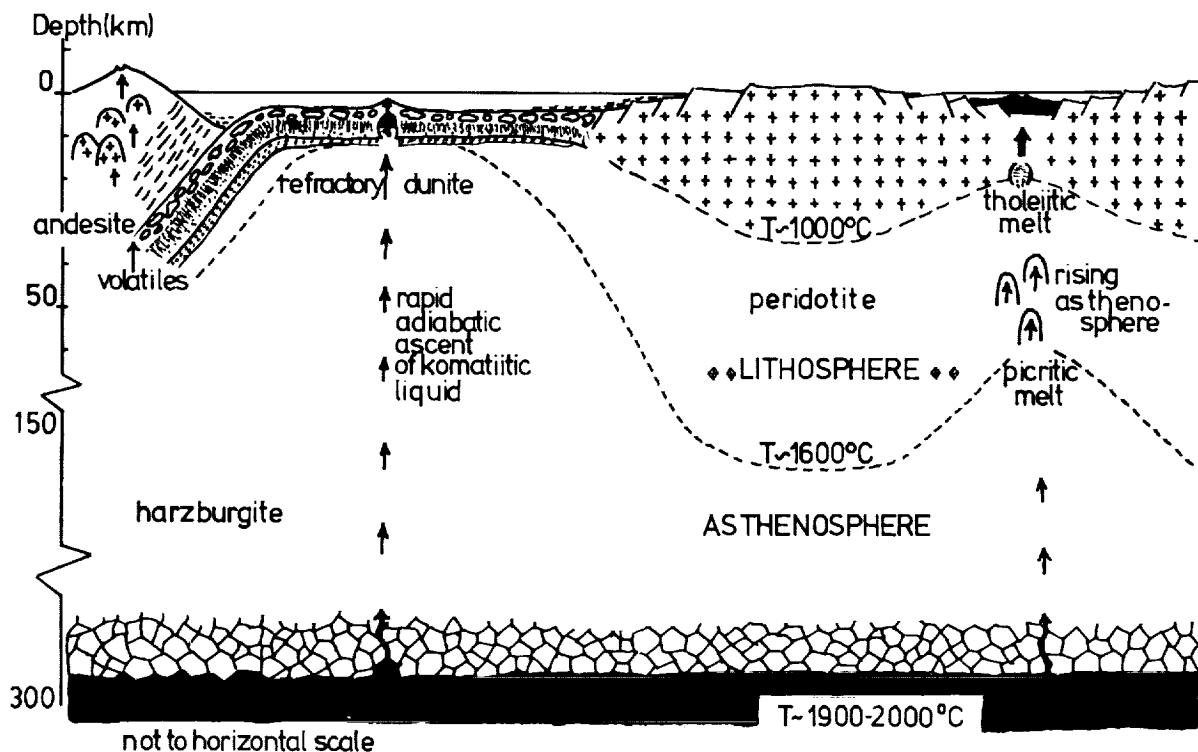
Depth(km)

andesite — volatiles — refractory dunite — ↑rapid adiabatic ascent ↑of komatiitic liquid — harzburgite — peridotite — LITHOSPHERE — ASTHENOSPHERE — T~1000°C — T~1600°C — tholeiitic melt — rising asthenosphere — picritic melt — T~1900-2000°C

not to horizontal scale

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WORKSHOP ON
THE ARCHEAN MANTLE

Edited by

L. D. Ashwal

Organizing Committee

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Cover: Cartoon, modified slightly from E. Nisbet (The Young Earth, 1987, Unwin Hyman, Inc., Winchester, Massachusetts), showing a schematic model of the Archean uppermost mantle and crust. In this model deeply hydrated oceanic crust is komatiitic and thicker than today, possibly by as much as 25 km. In the hotter Archean system, forces driving and resisting plate motion may all have been much smaller than today. Subduction zones would have operated in a hotter environment: The main higher level product would have been tonalitic. Any addition of volatiles to the system would have added more melt, not wetter melt. Continents were probably comparable in thickness to modern continental crust or thicker—the depth of the oceans is also, by implication, comparable to or greater than today's. In tensional regimes, such as in back-arc settings, continents would have rifted apart with initial eruption of komatiitic liquid, followed by mafic liquid after the establishment of high-level fractionation chambers. In places, older lithosphere was up to 150 km (or more) thick beneath continents, and contained diamonds. Uppermost mantle is harzburgite to dunite, with buoyant dunite floating over a komatiitic magma ocean located at depths below 250 km. Note that vertical scale is simply imagination and horizontal scale does not exist at all in this cartoon.

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Introduction

The rationale for a Workshop on the Archean Mantle as part of the Early Crustal Genesis Program comes from the seemingly obvious conclusion that planetary mantles are the ultimate sources of planetary crusts. Consideration of the entire lithosphere system is appropriate, therefore, in broad-scale studies of how crust forms and evolves. Direct determination of mantle properties is possible only for Earth in the present or recent past through studies of xenoliths and xenocrysts carried to the surface by kimberlites, lamproites, and alkali basalts, or through studies of exposures of upper mantle made possible by the vagaries of tectonics. Indirect means are necessary to determine the nature of Earth's ancient mantle and those of other planets. Characterization of Earth's Archean mantle, for example, is possible by petrologic, geochemical, and isotopic study of ancient mantle-derived melts such as komatiite or basalt. Inferences can also be made from theoretical studies of thermal, chemical, and tectonic evolution of the early Earth. With these prospects in mind, the Workshop on the Archean Mantle was organized with the objectives of considering and discussing evidence for the nature of Earth's Archean mantle, including its composition, age and structure, influence on the origin and evolution of Earth's crust, and relationship to mantle and crustal evolution of the other terrestrial planets. The workshop was convened at the LPI on January 11–13, 1989, and was attended by 41 participants from 5 countries. This volume contains extended abstracts of papers presented at the technical sessions, and extensive summaries of these sessions prepared by a few courageous "volunteers."

Lewis D. Ashwal
Houston, Texas
May, 1989

Program

Evidence for Subduction and Spreading in the Archean Rock Record: Implications for Archean Tectonic Style and the Evolution of the Sub-Continental Lithosphere
  H. H. Helmstaedt and D. J. Schulze

Discussion

SESSION IV: CONSTRAINTS ON MANTLE EVOLUTION FROM XENOLITHS
Chairman: A. J. Naldrett
Summarizer: A. J. Irving

Precambrian Mantle Beneath Montana and British Columbia: Geochemical Evidence from Eocene Volcanics and Their Xenoliths
  A. J. Irving, H. E. O'Brien, and I. S. McCallum

The Archean Mantle Lithosphere Beneath the Wyoming Province
  D. H. Eggler

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Thursday Afternoon, January 12, 1989

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The Constitution of the "Real" Upper Mantle as Seen from Xenoliths
  D. Schulze

Evidence for a Differentiated Mantle and Plate Tectonics During the Late Archean Deduced from Eclogite Xenoliths in the Bellsbank Kimberlite
  C. R. Neal, L. A. Taylor, A. N. Halliday, P. Holden, and J. P. Davidson

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SESSION V: CONSTRAINTS ON MANTLE EVOLUTION FROM MANTLE DERIVED MELTS
Chairman: S. B. Shirey
Summarizer: D. Elthon

Kolar Amphibolites-Archean Analogues of Modern Basaltic Volcanism?
  S. Balakrishnan, G. N. Hanson, and V. Rajamani

The Kolar Schist Belt, South India: Implications to the Nature of the Late Archean Mantle
  V. Rajamani, S. Balakrishnan, E. J. Krogstad, and G. N. Hanson

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Mendon Formation Komatiites: Extreme Al_2O_3/TiO_2 Variation in the Uppermost Onverwacht Group of the Barberton Greenstone Belt
  G. R. Byerly

Archean Flood Basalts from South Africa: Implications for Local Heterogeneity in the Archaean Mantle
  N. W. Rogers and J. S. Marsh

Geochemistry and Geochronology of Late Archean Mafic-Ultramafic Supracrustal Amphibolites from the Northeastern Sino-Korean Craton, China
  W. G. Ernst and B.-M. Jahn

Discussion

Friday Morning, January 13, 1989

SESSION VI: CONSTRAINTS ON MANTLE EVOLUTION FROM MANTLE DERIVED MELTS
(Continued)
Chairman: L. D. Ashwal
Summarizer: C. T. Barrie

Petrogenesis of High Mg#, LILE-enriched Archean Monzodiorites and Trachyandesites (Sanukitoids) and Granodioritic Derivatives in Southwest Superior Province
  R. A. Stern, G. N. Hanson, and S. B. Shirey

Summary of Technical Sessions

These summaries of presentations and discussions are based on recordings made during the workshop and on notes taken by those participants who kindly agreed to serve as summarizers. Discussion summaries are printed in italics. In most cases those participants who asked questions or offered comments are identified, but this was not always possible. We apologize to those we may have misquoted, misidentified, misinterpreted, or ignored.

SESSION I:
ISOTOPIC AND CHEMICAL ASPECTS OF
MANTLE EVOLUTION
L. D. Ashwal

After a brief introduction by L. Ashwal, the workshop opened with a talk by J. Jones on constraints that might be placed on the Earth's mantle at the beginning of the Archean. Formation of the Earth's core depleted the mantle in siderophile elements, as shown by the lower concentrations of Ir, Au, Re, Os, etc., in mantle xenoliths compared to chondritic meteorites (factor of $1-10^{-3}$). The constant Co/Mg of basaltic melts since the Archean shows that core formation was complete before 3.0–3.5 Ga. Although the earliest mantle was likely to have been in equilibrium with Fe-Ni metal (at or below the IW buffer), its oxidation state was increased to QFM or thereabouts by 3.0–3.5 Ga. The relatively constant Ni, Co, and Ir concentrations of mantle xenoliths suggest that a large-scale homogenization event took place at least as early as 3.0–3.5 Ga (from diamond inclusion ages), and possibly much earlier. Positive ϵ_{Nd} values of Archean mantle-derived magmas indicate that a large-scale (but incompletely understood) depletion event took place in the upper mantle between 4.4 and 3.9 Ga. Jones believes, however, that some portions of the mantle may have escaped this differentiation, retaining, for example, undepleted heavy REE abundances as seen in some mantle xenoliths.

In discussion, H. Newsom asked Jones to elaborate on the existence of undifferentiated mantle. Jones stated that this would be precluded by the "giant impact" theory whereby the Moon formed by collision of a Mars-sized body with the earliest Earth, but that this theory is by no means proven. Other models could allow the preservation of "pristine" mantle. L. Ashwal asked Jones to clarify whether this pristine mantle represented material undepleted in core-forming or crust-forming components, or both. Jones replied that he was referring to mantle undepleted in crust-forming components; refractory lithophile elements such as heavy REE are present in almost

"undisturbed" abundances. He pointed out that this could also be accounted for, although with difficulty, by complex recycling of crust and mantle. Jones reiterated his view that the giant impact mechanism should result in a much more differentiated mantle, and "pristine" characteristics would not likely be preserved. T. Irving pointed out that garnet lherzolite xenoliths do not show the undepleted heavy REE patterns. Jones stated to the concurrence of several participants that sheared garnet lherzolites did show flat-heavy REE. He also stated that differentiated mantle materials are to be expected, but that it would be extremely important if undifferentiated materials could be identified. B. Leeman asked how any ultramafic rock unaffected by differentiation or accumulation effects could be uniquely identified, considering that many xenoliths are probably crystal cumulates, and others are affected by interaction with fluids or melts. He further stated that it was amazing to see such homogeneity in siderophile abundances considering these effects. One possible explanation could be a buffering effect related to the high partition coefficients of siderophiles in phases like olivine and orthopyroxene. Jones agreed that the siderophiles, in addition to the heavy REE behaved compatibly in this case but argued that their abundances represent primordial values. S. Shirey asked if the core could have buffered the composition of the mantle over the course of geologic time considering the work of Jeanloz and coworkers indicating that the core-mantle boundary is extremely reactive. Shirey stated that if this is the case and there is no apparent signature of buffering effects, then this might support models involving a stratified mantle. Jones replied that this depends entirely on how much O is in the core. An additional basis behind the idea of a highly reactive core-mantle boundary relates to experiments showing that at high temperatures U oxide dissolves in metal, implying that lithophile cations following O can voraciously enter metallic melts. Whether O is significantly abundant in the core, however, is uncertain. B. Kaula pointed out that if the core were so voracious, this would produce a chemically differentiated layer at the bottom of the mantle. Whether or not this is the case is a subject of much current debate. Jones replied that this depends on whether the core is saturated in mantle components. Newsom stated to the agreement of Jones that if the apparent homogeneity of the mantle in siderophiles over time is due to buffering by the core, then this would imply the unlikely conclusion that the entire mantle interacted with an O-rich core very early in Earth history. G. Ryder asked Jones about what was required to oxidize the mantle to QFM conditions. Jones replied that it would take a fair amount of material to change 8 wt.% FeO to 90% FeO × 10% Fe_2O_3. This is not a problem in models involving accretion and later homogenization of a late-stage

carbonaceous chondritic veneer, which would contain about 20% H_2O. Leeman pointed out that H_2O acting as a mantle oxidizing agent might have been more readily supplied by subduction of oceanic crust and sediments. Jones wondered where the original H_2O in the crust came from. T. Naldrett mentioned that recent work on deep-sea glasses indicates that the mantle may be much less oxidized than QFM, perhaps QFM-2. This is consistent with evidence from magmatic sulfide deposits, which crystallize pyrrhotite, not magnetite, indicating lower f_{O_2} than QFM. D. Eggler pointed out that the mantle is probably not as reduced as IW (as indicated by intrinsic f_{O_2} measurements), nor as oxidized as QFM, and therefore much less early oxidation would be required. Jones expressed his view that some change in the redox state of the mantle must have taken place even if it is currently as reduced as IW. Newsom asked about the timing of this oxidation event. Jones stated that it must have taken place very early, because the oldest samples measured have similar siderophile/lithophile element ratios as modern materials, although once core formation stopped, the mantle redox state could continue to change by other processes. P. Morgan expressed the possibility that the Earth may still have been subjected to significant impacts after collision with a Mars-sized object. He also pointed out that we must consider the energetics of the core-forming process—the Earth might be substantially different, for example, if core formation continued to relatively late in Earth history. Jones replied that in terms of energetics most everything was tied up in the Mars-sized object. Regarding core-forming energetics, this appears to be model-dependent. Whereas a totally molten Earth might be expected from rapid, early core formation, models such as that of D. Stevenson, in which core formation is delayed until the Earth is about Mars-sized could result in largely subsolidus heating. Jones clarified his position that the amount of post-Archean core formation is trivial. G. Ryder pointed out that he understood Wetherill's model to show that the Mars-sized body probably would have been the among the last objects to hit the Earth. Jones stated this was model-dependent, but Kaula disagreed, stating that there is a consensus among dynamicists that the main phase of Earth's accretion involved impacts by large bodies (regardless of how the Moon formed), and there would be a "tail-off" of smaller impacts lasting about 100 Ma. He pointed out that the giant impact hypothesis succeeds where others fail in accounting for the Moon's depletion in Fe. Jones agreed that although the bulk Moon is depleted in Fe, the silicate portion of the Moon is enriched in FeO compared to the Earth (unless D. Anderson is correct that Earth's lower mantle is twice as Fe-rich as the upper mantle). Newsom stated that better evidence for the giant impact theory is the 23.5° tilt of the Earth's spin axis, but Kaula pointed out that this was used by Safronov to argue against giant impact models. Leeman asked how lunar siderophile abundances compared to those of chondrites and Earth's mantle. Jones replied that lunar

siderophiles were also depleted compared to chondrites, with the most highly siderophile elements showing the highest depletions (factor of 10^{-5}–10^{-6} for Ir, Re, and Os). Lunar materials, therefore, behave as though they were in equilibrium with metal. Leeman argued that since lunar samples are older than any Earth materials, the differentiation event involving siderophile depletion must have taken place very early. Jones pointed out that one fly-in-the-ointment is the commonly held belief that the Moon has a very small core. Ryder offered another: The Moon contains a substantial fraction of materials from the Mars-sized impactor. Jones again said that this was model-dependent. If, for example, the impactor had its own core, then most of that material would wind up in the Earth. Kaula agreed and reminded the participants that any accretionary model must account for the equivalence of lunar and terrestrial oxygen isotope ratios. Jones added that if Ringwood is correct that the Moon is composed of <20% of impactor-type material, then the FeO content of the impactor can be calculated (assuming 8 wt.% FeO in Earth's upper mantle and 12 wt.% FeO in the Moon). The result is about 28 wt.% FeO, implying a carbonaceous chondrite impactor! Chairman G. Hanson ended the discussion at this point.

The next presentation was given by Shirey, on the Pb and Nd isotopic evolution of the Archean mantle. The dominance of *depleted* upper mantle throughout the Archean is demonstrated by the positive ϵ_{Nd} values of most Archean rocks. This depletion cannot have been produced by fractionation during the global molten stage implied by the giant impact theory because removal of Mg silicate perovskite or majorite should cause light REE *enrichment* of the upper mantle, not depletion, given the partition coefficients of Kato and Ringwood. Extraction of Pre-Archean continental crust is also an unlikely explanation because mass-balance models require it to be totally recycled back into the mantle by 4.0 Ga. Instead, removal of early basaltic crust may account for the observed depletions, and recycling by subduction may account for the apparently constant ϵ_{Nd}, μ_1, and κ_1 values of mantle-derived rocks throughout the Archean. The heterogeneity and provinciality of latest Archean and Proterozoic Pb isotopic compositions are similar to those of present oceanic mantle and may be similarly attributable to recycling of basaltic crust. The increase in ϵ_{Nd} values of mantle-derived materials at about 1.8 Ga may have been caused by extraction of late Archean continental crust.

In discussion, P. Mueller asked about the fate of altered Archean basaltic crust. Shirey replied that presumably it was subducted, but it must have been isolated from upper mantle from which crust is withdrawn long enough to produce the observed depletion effects. Both the size of Archean mantle

reservoirs and the type of convection operative (e.g., whole-mantle or layered) then are unknown. Ashwal asked if Shirey's model would allow any early Archean continental crust. Shirey replied that this was difficult to determine, but any continental material created very early must have been recycled back into the mantle wholesale. Models attempting to account for modern Pb isotope distributions involve creation of "mature" continents, and if similar processes operated during early Earth history, such continents should have been preserved. Newsom then asked about later recycling of continental crust and the amount of crust present at the end of the Archean, referring to recent work by S. Jacobsen. Shirey finds it difficult to evaluate this model (which involves complete recycling of continental crust with ϵ_{Nd} of -10 by 3.8 Ga) because of its assumptions regarding interactions between discrete crust and mantle reservoirs. He expressed regret that Jacobsen was unable to attend the workshop. R. Stern asked if the light REE-enriched basaltic crust required by Shirey's model was reasonable. Shirey responded that it was, considering that most of the extraction would be governed by pyroxene-type distribution coefficients, resulting in slightly light REE-enriched basaltic melts. The amount of enrichment depends, of course, on the degree of melting. Stern then asked about the consequences of largely komatiitic rather than basaltic magmatism. Shirey replied that in this case extraction must take place at sufficient depths so that garnet played a significant role in controlling light REE distributions. Considering that komatiitic magmatism requires high degrees of partial melting, with residual garnet unlikely, this type of crust would probably be unsuitable for Shirey's model. C. Chauvel asked about the thickness of basaltic crust required by Shirey's model. Shirey replied that a 10-20% basaltic fraction of upper mantle was required to produce the depletion, and 20-25% of this must be recycled to account for the relative constancy of isotopic ratios during the Archean. Chauvel expressed skepticism about the constancy of Archean isotopic data, suggesting, for example, that some of the samples in Shirey's compilation may have been affected by crustal contamination. Chauvel is convinced that there is, in fact, evidence for progressive depletion of the Archean mantle, expressed as an increase in ϵ_{Nd} in progressively younger rocks. Chauvel argued that the ϵ_{Nd} values of some of the late Archean rocks shown in Shirey's compilation were lowered by crustal contamination, and that if these data points were removed, a progressive increase of ϵ_{Nd} with time would be evident, although with considerable scatter reflecting mantle heterogeneity. Chauvel believes that at 2.7 Ga, ϵ_{Nd} values vary between +2 and +8, the latter values being from the Yilgarn block of Australia (e.g., Kambalda). Shirey asked Chauvel if this would imply a single-stage extraction event, and Chauvel replied that this was possible. Shirey then asked about the Kambalda samples, which show relatively uniform Pb isotopic signatures but variable ϵ_{Nd}. Chauvel replied that the Pb isotopic signature of these rocks is swamped by crustal Pb even for the most depleted samples. Hanson commented

that the environment of greenstone belt formation is not sufficiently understood. We do not know, for example, whether the melts observed were derived from subcontinental lithosphere or oceanic mantle, and it may be erroneous, therefore, to construct mantle evolution models. Leeman concurred and stated further that μ and κ calculations are also model-dependent; single-stage μ values may not be appropriate if lithospheric models are more complex. Shirey agreed, but added that it is useful to compare the Archean data set to that for modern rocks to see, for example, if the same level of heterogeneity exists. Leeman stated that for many isotopic databases, there is inadequate characterization of trace elements and that until such work is carried out many questions will remain unanswered. R. Lambert pointed out that two-stage, Pb isotopic evolution models might be too simplistic. A third stage of short duration involving pronounced fractionation of U/Pb would cause "complete chaos" on Pb isotope evolution diagrams. Lambert cited evidence for this from the Pilbara block of Australia where galenas and other sulfides associated with felsic rocks have higher μ values compared to Pb associated with basic rocks. A third stage of 10-20 Ma duration, therefore, can cause significant shift of apparent μ_1 values. He also stated that he published μ_1 values of about 7.5 for Amitsoq gneiss (3.8 Ga), whereas Shirey uses values of about 8.5 for early Archean rocks, suggesting a potential calculation problem. The lower values would plot on the Stacey-Kramers evolution curve. Shirey stated that the Amitsoq gneiss is unique in being from the only early Archean terrane that behaves coherently in terms of Pb; this is evidently not the case for other early Archean terranes. With regard to Lambert's first point, Shirey stated that there may be a problem in assuming that Pb isotopic compositions of galenas represent those of the mantle. Shirey argued that galenas and other sulfides represent a separate upper crustal reservoir with elevated μ values. J. Wooden commented that this was clearly recognized as a crustal reservoir by Stacey and Kramers when they published their evolution model. Shirey agreed, stating that he used this only as a reference to show that according to his calculations, the Archean data did not show the early low-μ stage. This prompted spirited discussion of Pb isotopic systematics among several participants.

B. Jahn then returned the discussion to the Nd isotopic signature of the Archean mantle, stating that in considering possible causes for the depleted signature of the Archean mantle, extraction of basaltic vs. continental-type crust are not mutually exclusive processes. Models of granitoid formation involve derivation from a basaltic precursor; and therefore we should think of both types of crust-formation as part of the same process. Shirey asked Jahn what mechanism he favored for destruction of continental rocks. Jahn replied that mass transfer of continental material back into the mantle took place by physical and chemical erosion and by subduction of the resulting sedimentary materials. Jahn stated that the

ϵ_{Nd} signature of Archean mantle-derived rocks includes a significant recycled component, and a unique solution to unravel this effect does not yet exist. Shirey commented that it is interesting that continental extraction does not seem to affect the Pb isotopic signature considering the Pb, U, and Th concentrations in upper vs. lower continental crust and the expectation that ancient continents weather from the top down. The Pb isotopic signatures should be expected to be more sensitive to these effects than Nd. Wooden commented that maybe we do see the signature of a recycled component in Pb isotopic compositions, citing his work with Mueller as a possible example. He stated further that it would not be necessary to recycle much continental material to account for the Pb isotopic signature, but this was dependent upon the nature of crust involved. Shirey agreed that this seems to work well in explaining the data from the Wyoming Province, but he expressed concern about the effects upon the Pb isotope systematics of an early proto-crust. Jones asked if it were possible that U and Pb are so incompatible compared to the REE that their signature in basaltic rocks represents largely recycled components. Shirey agreed that this was possible, referring to work by Galer and colleagues that suggests that the Pb concentration in the upper mantle is dominated by contributions from other reservoirs such as the lower mantle or continental crust.

Morgan commented that arguments against recyling of continental crust due to its inability to be subducted may be misleading. It is thickness, not composition that is the important factor: Thin continental crust is just as subductible as oceanic crust. Shirey agreed but added that in many places continental crust does not subduct because it is underlain by relatively buoyant, depleted mantle lithosphere. Morgan reiterated that crustal thickness is the controlling factor in subductibility. Leeman pointed out that most workers consider suduction of sediments rather than wholesale blocks of continental crust, and there is abundant evidence for this process. Shirey agreed but stated that in the early Earth, some mechanism must be called upon to destroy all of the extant continental crust, not just some fraction of it. G. Ernst commented that the 4.1–4.2 Ga zircons from Western Australia imply the existence of at least some continental crust, which must have been subducted or otherwise removed. Shirey replied that all that remains of continental material from the first 600 Ma of Earth history are about 100 zircons and perhaps one rock from the Slave Province. Nearly all continental material, if it ever existed, must somehow have been destroyed. Leeman stated that Shirey's model relates to the unresolved issue of whether the crust formed continuously or episodically. Shirey replied that it was surprising that no signature of early continental extraction was present in Pb isotopic systematics. Hanson terminated the discussion at this point and adjourned the workshop for a coffee break.

The next talk was given by A. Smith, who discussed the evolution of Archean-depleted mantle considering data from the Nd and Hf isotopic systems. His approach is to try to overcome potential problems with isochrons representing mixing lines or reset ages by recalculating Nd initial ratios using ages obtained from Pb-Pb or U-Pb systems. This results in a large variation in initial Nd ratios and conflicts with models favoring smooth evolution of ϵ_{Nd} with time. Instead, Smith and colleagues favor a two-stage model of mantle depletion since 4.55 Ga. The first stage established mantle heterogeneities, resulting either from shallow magma ocean fractionation or early basalt extraction. These are represented by Al-depleted komatiites (ADK) and ancient eclogite xenoliths (both showing the highest ϵ_{Nd} values) as well as Al-undepleted komatiites (AUK) and tholeiites (both showing lower ϵ_{Nd} values). The second stage, from the early Proterozoic to the present, shows relatively uniform increase in ϵ_{Nd} of the upper mantle at a rate of about 2.2 ϵ units per Ga. Smith suggested that the early Archean mantle was compositionally (and isotopically) stratified, but these heterogeneities were reduced at about the end of the Archean, perhaps by the gradual inception of convection.

In discussion, Jahn suggested that the difference between the ADK and tholeiite sources may have been produced by garnet fractionation, and Hf isotopes might better distinguish the trends. Smith replied that there are Hf isotopic data available for Pilbara and Abitibi rocks, although not for the same samples run for Nd isotopes. The results show ϵ_{Hf} values up to +8 for 3.5 Ga Pilbara samples. Jahn commented that these data were not reliable because of difficulties with analytical procedures and the presence of included zircons even within komatiites. Jahn stated that he might present more reliable Hf isotopic data from Onverwacht (South Africa) samples in the afternoon session. Smith added that ϵ_{Hf} values of up to +12 for Abitibi (Superior Province, Canada) samples were reported by J. Patchett in 1981. Jahn wondered if Patchett would still consider these data reliable. Smith stated that the Al-depleted komatiites showing the highest ϵ_{Nd} values have not been anaylzed for Hf or Pb isotopes. Jahn questioned whether the ADK and AUK source trends shown by Smith could be distinguished unambiguously. Smith replied that if all data are compiled, the ADK suite have consistently higher ϵ_{Nd} values, which he illustrated with a table. Jahn pointed out that changes in Sm/Nd ratios in these samples, for example by alteration, could cause dramatic effects in calculated ϵ_{Nd} values. Smith replied that this was not compatible with the apparently consistent relationship between composition (ADK vs. AUK) and ϵ_{Nd} value. Chauvel asked Smith to explain how ADK and AUK were distinguished. Smith replied that this was done on the basis of Al/Ti ratios and the amount of heavy REE depletion. Jones wondered if AUK could possibly

represent ADK affected by crustal contamination effects. Smith replied there were petrological arguments against this. Jones did not seem convinced. N. Rogers then suggested that detailed studies of immobile trace elements were needed to evaluate whether crustal contamination effects are important. Jahn commented that the Ta concentration of Onverwacht (South Africa) komatiites shows a distinct crustal signature, interpretable either as contamination or source enrichment with crustal components. He added that many (but perhaps not all) komatiites show some contamination effects. Smith agreed but emphasized that crustal contamination cannot account for the very high ϵ_{Nd} values of ADK, unless their source had even higher ϵ values. D. Elthon asked about the possibility that some komatiites may have had their Sm/Nd ratios changed by interaction with pyroxene-rich cumulate materials during magmatic scouring and corrosion during emplacement. Smith said that this is possible, but that ϵ_{Nd} values would be reduced by only about 2 ϵ units if the effects of such a processes were taken into account. Leeman raised the general question of the extent to which the Sm/Nd ratios of these rocks were changed by secondary processes such as metamorphism, etc., and the effects this would have on calculated ϵ_{Nd} values. Smith replied that the rocks were at greenschist grade and that REE mobilization was a possibility, but this process would have had to affect ADK and AUK selectively. An unidentified questioner wondered if this was geologically reasonable, i.e., whether they are found together in the same greenstone belt. Smith noted that most ADK are found mostly in early Archean greenstone belts, but in the Norseman-Wiluna belt (Yilgarn Block, Western Australia) ADK and AUK are found together. Leeman asked if the two types were ever found interlayered with one another, and G. Byerly said this was the case in the Barberton greenstone belt (South Africa). Smith added that except for Norseman-Wiluna samples, isotopic analyses of ADK and AUK from the same greenstone belt were not available. Leeman commented that this would represent a good research project.

The final talk in the morning session was given by R. Walker, who summarized the geochemical and isotope systematics of the Re-Os system and discussed potential uses it may have for constraining early Earth processes and events. The near equivalence in $^{187}Re/^{186}Os$ between chondrites (3.2) and Earth's mantle (3.3) is difficult to explain. Possibilities include: similar Re and Os partitioning between core and mantle, retention of Re- and Os-rich phases with chondritic Re/Os such as sulfides in the upper mantle during core formation, or post-core-formation accretion of the upper mantle. The Re-Os isotopic system may also be used for geochronology, particularly for mafic-ultramafic rocks, as shown by data for Archean komatiites from the Superior Province of Ontario. The decoupled behavior of Re (highly incompatible) and Os (highly compatible) suggests that this system can be used as a tracer

of crust-mantle evolution. Peridotite xenoliths from South African kimberlites show marked depletions in ^{187}Os with Re-Os model ages of about 2.8 Ga, possibly indicating removal of basaltic or komatiitic melts at or before this time. With the exception of these rocks, the few samples analyzed to date for Re-Os isotopes plot at or near the chondritic evolution line and do not show the long-term isotopic depletion that is well established in other isotopic systems such as Sm-Nd.

In discussion, Naldrett commented that the geochemistry of Re partitioning may depend on the amount of sulfide that remains in the residual mantle source. Rhenium, for example, may be left behind in residual sulfides during basalt genesis. Walker replied that this is not supported by data for basalts that indicate Re concentrations as high as 1-2 ppb. Naldrett then suggested that the amount of sulfide left behind during magma genesis may have changed with time. Walker replied that more data would be needed to evaluate this. He also mentioned the possibility that extraction of continental materials, which can be expected to contain less Re than basalts, may tend to cause lesser Re depletions in the mantle. Jones asked if it was possible that the depletion event that affected the Sm-Nd system may have predated the addition of Re-Os to the mantle. Walker replied that this was possible, but that it is highly speculative at this point. Newsom commented that variability in incompatibility is documented in other geochemical systems and that this would likely be discussed in the afternoon session. Shirey asked if Re-Os might behave like the U-Pb system during basaltic recycling. Perhaps some Re could be added to the upper mantle in this way, and if so, it might be fruitful to look for correlations between Pb and Os isotopic compositions. Walker said that this was possible but that most of the material would have to be mixed back in because the Re-Os system will be very sensitive to changes in the Re/Os of the upper mantle. Schulze asked if the grouping of Os isotopic compositions among peridotite xenoliths correlates with high-temperature vs. low temperature xenolith types. Walker replied that there was no good correlation between Os isotopic composition and high vs. low temperature types, but there is some correlation with mg*. He reiterated that the best correlation seems to be with the amount of basalt depletion in the xenoliths. Schulze pointed out that basalt-depleted xenoliths tend to be low-temperature types and asked if it were possible to judge whether those xenoliths with higher Os isotopic compositions may have had components added to them recently, for example, by metasomatic effects. Walker was not sure. D. Eggler wondered if one of the data points with low Os isotopic composition might be from sample "1611." Shirey replied that they did not analyze that sample. An offer was made to provide it, and Walker cautioned the generous participant that they would need a rather large quantity of sample. Elthon asked if there was any indication as to which mineral phases contained the

Os. Walker said that this was a problem. Even if good mineral separate data were obtained, the possibility could not be eliminated that the Os was contained in trace phases such as osmiridium. He added that it is important to carry out petrographic work on those samples selected for isotopic analysis. Elthon asked if there was any evidence for mobilization of Re or Os, such as differences in isotopic compositions between metasomatized vs. nonmetasomatized xenoliths. Walker replied that there was no evidence in the isotopic compositions for such effects. In terms of concentrations, however, one sample of highly sheared spinel lherzolite from Lashaine in Tanzania (reported in the Basaltic Volcanism volume) has extremely low concentrations of Re and Os, but Walker asked if anyone knew whether this is a metasomatized sample. We were told that this unusual sample shows trace element enrichment but major element depletion. Walker added that this sample has a very low Os isotopic composition but doubted if this could be assumed representative of metasomatized mantle. Walker stated his expectation that metasomatism should not affect Os because of its immobility. At this point Chairman Hanson adjourned the workshop for lunch.

SESSION I:
ISOTOPIC AND CHEMICAL ASPECTS OF MANTLE EVOLUTION (CONTINUED)
S. M. McLennan

After lunch the session continued with B. Leeman acting as chairman. The first paper was given by P. Mueller, who evaluated the Pb isotopic evidence for crustal recycling and mantle heterogeneity during the Archean. Three types of Archean cratons were distinguished on the basis of Pb isotopic ratios and included: (1) those falling on the mantle growth curve (Type I; new crust without components of older recycled crust, e.g., Superior Province); (2) those falling below the mantle growth curve (Type II; crust undergoing high grade metamorphism early in its history, e.g., Labrador and Southwest Greenland); and (3) those falling above the growth curve (Type III; crust that is differentiated early in its history, e.g., Wyoming Province). Recycling into the mantle of these different crustal types may impart considerable isotopic heterogeneity on the mantle, although recognition of the type of craton that may be involved often is not straightforward; crust-mantle interaction associated with development of Type III cratons is most likely to produce recognizable enrichments. It is also a difficult matter to estimate the timing of the introduction of heterogeneities. Mueller suggested that young volcanic rocks found in the northwestern U.S.A. (e.g., Snake River Plateau) may have been derived in part from mantle that was enriched through interaction with Type III cratonic material during the Archean.

The discussion began with a question from S. Shirey who wanted to know about the Pb and Nd isotope mass balance for recycling of 3.3 Ga crust into the mantle, given the available constraints for the isotopic composition of the recycled crustal component and the depleted mantle. Mueller responded that the generally accepted values for "depleted mantle" were derived, to a large extent, from the southern Superior Province and it was not at all clear if such values were appropriate for the Beartooth region. He pointed out that similar 3.2 Ga rocks from west of the Beartooth gave higher ϵ_{Nd} values (-1). In addition, Mueller noted that all rocks from the Beartooth region have essentially the same Nd-isotopic signature, with no apparent evidence for subcratonic mantle depletion, over the period 3.2–2.7 Ga and that very efficient mixing must have been taking place to produce the limited range in isotopic composition during the late Archean.

G. Hanson continued the questioning and asked what age was produced by the regression of initial Pb isotopic ratios. Mueller responded that the data were highly scattered but that for the rocks that were considered to be the oldest in the region, Nd model ages, Pb-Pb whole rock scatterchrons, and Rb-Sr scatterchrons all produced ages of about 3.4 Ga. He also noted that a couple of Nd-model ages and some Hf ages on zircons, published by J. Patchett, gave ages of about 3.6 Ga.

While some minor technical difficulties with an overhead projector were sorted out, a final questioner noted that an arc analogue was being proposed and questioned whether the isotopic homogenization that was observed was consistent with isotopic systematics seen in present arcs. J. Wooden (coauthor of the paper) responded that the variations were comparable to modern arcs, except those that display extreme radiogenic signatures. Leeman noted that even in young arcs displaying highly radiogenic isotopic signatures, such as the Lesser Antilles, the highly radiogenic component may be added at high levels (i.e., contamination) and that the material going down the subduction zone may be relatively homogeneous. Mueller pointed out that once the Primitive Mantle separates into different reservoirs, all interaction between reservoirs can be seen as contamination. He noted that, in general, a narrow range in isotopic composition suggested deep efficient mixing, whereas a wide range suggested shallow, less efficient mixing.

The second paper of the afternoon was presented by C. Chauvel. She first reviewed the Nd isotopic evidence relating to the Archean mantle from noncontaminated volcanic rocks and banded iron formations. She concluded that the Archean mantle, from 3.8 Ga, was generally depleted in nature but displayed considerable isotopic heterogeneity. This presented a dilemma because enriched continental components appear to be minor. A model was presented to explain these and other features of the Archean record. Prior to about 3.8 Ga, the model calls

for a thick (<40 km), slightly enriched basaltic crust that was readily recycled into the mantle, resulting in an isotopic record that essentially followed that of the contemporaneous mantle. Melting at the base of the crust resulted in granitic magmas that made up to about 20% of the overall crust. An important aspect of the model is that this granitic component was well mixed with basalt into a regolith by intense meteorite bombardment. This resulted in the observed mantle depletion and a crust with significant enrichments, on average, but no record of a separate, highly enriched continental crust.

Shirey opened the questioning by asking about the timescales for survival of LREE-enriched basaltic crust at the surface of the Earth before the formation of the granitic magmas. He noted that a long-term survival would allow for the production of granitic magmas with significant ϵ_{Nd} values. Chauvel responded that any negative ϵ_{Nd} values that were produced in granitic magmas would be essentially lost during the mixing with the basaltic crust. Shirey asked for clarification of whether the granitic rocks were derived from the enriched basalts or the mantle, and Chauvel responded that the enriched basalts were the source but that mixing of basalt and granite effectively removed the separate, highly enriched reservoir. She agreed that the basalt would have to be rapidly recycled into the mantle. Another participant asked what mechanism was responsible for recycling the basalt back into the mantle. Chauvel responded that delamination was one possibility.

The final paper of the session was presented by Jahn, who first reviewed the geochemistry and isotopic characteristics of Archean basalts and komatiites. On the basis of major element, REE, and Nd isotopic evidence, he concluded that garnet fractionation processes played a role in the origin of Archean komatiitic rocks. He also noted that, with the exception of peridotitic komatiites, Archean mafic to ultramafic volcanic rocks are less depleted in LREE than midocean ridge basalt (MORB) and are in some cases LREE-enriched. This was interpreted as suggesting (1) that less continental crust was present, (2) that continental crust was recycled back into the mantle, or (3) that mantle-derived mafic-ultramafic volcanics were contaminated by older continental crust. He further suggested that the geochemical and Nd-isotopic evidence tended to favor alternative (2) or (3). The generally depleted initial ϵ_{Nd} values found in Archean mantle-derived rocks was ascribed to likely being the result of continental crust formation, and it was also noted that slightly LREE-enriched basaltic rocks may have been the precursor to continental crust.

At this stage, a general discussion of the previous three papers ensued. H. Newsom returned to the model presented by Chauvel and suggested that between 4.2 and 3.8 Ga large impacts would have been less severe than in the earliest part of Earth history; they would only have had the effect of breaking up the crust and another mechanism, perhaps subduction, would be required for recycling into the mantle. Kaula responded that in large impacts, such as the lunar Imbrium basin, very efficient mixing takes place vertically over tens of kilometers but with very little horizontal movement. Leeman then asked about the expected maximum depth of excavation for the larger impacts. Both Kaula and J. Head responded and agreed that the exact depths are not precisely known and most evidence is indirect. Kaula suggested that depths may reach into the upper mantle. Head noted that mantle material is rare in the ejecta and that depths probably did not greatly exceed about 60 km. Discussion ensued among Chauvel, Shirey, and others regarding the rate of impacts between 4.5 and 3.8 Ga. It was generally agreed that the overall rate declined rapidly over this time, but it was considered less clear how this decline would affect the efficiency of mixing called for in the model proposed by Chauvel.

Leeman then turned to the question of recycling into the mantle and asked Chauvel how deep the recycling may take place and whether it would affect the source regions of the basaltic rocks. Chauvel responded that the granitic rocks would tend to concentrate on the surface and that crustal recycling into the mantle may result from delamination at the base of the crust. Leeman then pointed out that sediment subduction, if it were to take place, would be an efficient method for returning average (mixed) crust to mantle. In reply, Chauvel noted that if the granitic component of the crust were recycled efficiently back into the mantle, the mantle would not be expected to display the high ϵ_{Nd} values.

Kaula then turned to the thermal regime of the Archean Earth and noted that current thermal models of present-day subduction processes did not appear to favor subduction during the Archean when thermal gradients are thought to have been much higher. G. Ernst suggested that mantle circulation, required to produce the large amounts of basaltic crust during the Archean, demanded that some sort of subduction process was in operation. An exchange among Kaula, Ernst, Jones, and others then ensued over the questions of whether geothermal gradients were in fact high or low and the need for return viscous flow to the mantle, with no apparent consensus. R. Lambert addressed the question of the thick basaltic crust called for in the Chauvel and Arndt model. He pointed out that because heat production would have been three times the present value during the Archean, a basaltic crust would have melted. He suggested that a thick and stable Archean crust would therefore require komatiitic compositions.

A final point raised by Leeman was that the vertical and horizontal scale over which sampling (and accordingly, heterogeneities) takes place is not always clear in Archean studies. Chauvel and Jahn then described the scale of sampling in their studies and pointed out that samples were taken over fairly restricted, and well documented, scales. Lambert pointed

out that detailed physical geology of various greenstone belts also differed considerably and that this should be taken into consideration when making comparisons.

SESSION II:
CONSTRAINTS ON MANTLE EVOLUTION FROM SEDIMENTARY MATERIALS
S. M. McLennan

The first paper of this brief session was presented by S. McLennan, who suggested that the scarcity of negative Eu-anomalies in greenstone belt turbidites suggested that intracrustal fractionation processes, in the crustal precursors, were limited. Trace element and Nd-Sr isotope chemistry of modern continental margin turbidites indicate that such sediments commonly had a significant young mantle-derived component. Comparisons were made between Archean and Recent turbidites to see if there were differences that could have implications for mantle compositions. Archean turbidites tended to have higher Eu/Eu*, suggesting that they had been less affected by intracrustal processes. Archean turbidites commonly had high Gd/Yb ratios indicating a significant HREE-depleted component; such a component is absent from Recent turbidites. He suggested that a HREE-depleted mantle-derived component would indicate P-T conditions of crust generation and/or mantle compositions may have differed. It was also noted that Recent active margin turbidites commonly have low Th/U ratios (1.0–3.0), probably reflecting a depleted mantle source. Such low ratios are seen to be absent from Archean turbidites, perhaps indicating that Archean mantle sources of the crust were less depleted then at present.

The first questioner asked whether simple in situ decay could explain the high Th/U ratios for the Archean samples. McLennan responded that he did not think that decay could cause such large changes in the ratio (up to a factor of 3) but that in any case all of the mantle sources would equally suffer from in situ decay; therefore, the differences between Archean and Recent Th/U ratios could not be explained in such a way. S. Shirey then asked how many cratons were represented with Th/U data. McLennan responded that the Pilbara, Yilgarn, Kaapvaal were represented with a few samples from the Superior Province. He further noted that much of the available data was by instrumental neutron activation analysis and that the quality of the Th/U data was often difficult to judge by this technique and therefore not included. C. Chauvel then asked if there was a distinction between Early and Late Archean samples in terms of Th/U ratio. McLennan could not recall specifically whether such differences existed, but he had examined sedimentary trace element data

for secular variations and probably would have noted a difference in Th/U ratios.

Another participant asked how a turbidite was best sampled. McLennan suggested that a lower coarse-grained and upper fine-grained sample should be taken but that any pelagic component preserved in the E-unit should be avoided. In response to a query about whether significant differences existed between coarse and fine fractions, McLennan noted that in some cases, but not all, a separation of provenance components may take place, resulting in significantly different Nd-isotopic compositions. The next question centered on the role of accessory minerals in explaining differences in REE, Th/U, and other trace element abundances. McLennan replied that there is no special enrichment in heavy minerals that could explain such differences; for example, Zr abundances were generally low at <200 ppm. Jahn then asked whether the HREE-depleted signature in Archean turbidites was best explained by a TTG (tonalite-trondhjemite-granodiorite) component. McLennan agreed and noted that the sediments would provide a larger-scale average and indicated that this HREE-depletion was a fundamental characteristic of Archean crust, but not of young crust, and that this had implications for the processes of crust formation and/or mantle composition through time.

The final paper of the session was presented by K. Sims. Forming ratios with elements of similar geochemical behavior, he noted that Archean and Phanerozoic mantle-derived and continental rocks had similar Mo/Ce ratios. This suggested that the primitive mantle had a similar Mo/Ce ratio and was also considered to be inconsistent with continual core formation. In contrast, W/Ba ratios of crustal rocks are somewhat higher than mantle-derived oceanic rocks suggesting the primitive mantle W/Ba ratio is higher than oceanic volcanics. Sb/Ce and As/Nd appear to be considerably higher in continental crustal rocks relative to mantle-derived oceanic rocks. Thus W, Sb, and As are enriched in comparison to other elements with similar levels of incompatibility. The enrichments were compared to the Pb/Ce data of A. Hofmann and the recycling model of Hofmann and steady-state model of Galer and O'Nions were assessed. The data under discussion did not provide constraints that could distinguish the models. Hydrothermal alteration and/or inorganic complexing were suggested as possible mechanisms for the enrichment. Hydrothermal processes may be more important in the generation of continental crust than generally recognized.

Lambert noted that rocks today have about twice as much Pb in them now as they did in the Archean and that this would have to be considered. He further noted that if Ba was seen to behave in a similar manner as Pb, then hydrothermal controls were less likely and a relatively simple

mechanism may be in operation. Sims responded that the Pb/Ce data were from Hofmann's studies and that he suggested Pb and Ba behaved similarly in early crustal formation but with later fractionation Pb and Ce behaved similarly.

H. Newsom then asked for comments on Hofmann's model, which calls for early crust formation (with enriched Pb relative to Ce) and a subsequent mantle homogenization event resulting in constant Pb/Ce ratios for ocean island basalt (OIB) and MORB reservoirs. He also noted that the model required little crustal formation or recycling after this time. A vigorous and wide-ranging discussion ensued. G. Hanson noted, and B. Leeman agreed, that the K_d's in melts are very low and, in order to fractionate the highly incompatible elements, very low degrees of partial melting would be required. He went on to say that he agreed that movement of fluids, which likely constitutes a small proportion of the system, may be a mechanism that would allow fractionation of these elements. Shirey pointed out that the average age of the MORB and OIB reservoirs is about 1.6-1.8 Ga and perhaps is dominated by Proterozoic and Phanerozoic history with the information of Archean heterogeneity being lost by subsequent mixing. Hanson noted that calculations by F. Richter indicated that heterogeneities were very rapidly lost in the mantle with 3-4 cycles of convection, each on the order of 200 Ma.

The discussion then turned to the question of crustal growth rates. It was noted that certain ratios among highly incompatible elements, such as Pb/Ce, were constant for OIB and MORB reservoirs, and this would not allow for significant crustal growth since the Archean. This was apparently inconsistent with models calling for <50% of the crust by 2.7 Ga or with models calling for significant recycling of crustal material back into the MORB or OIB reservoirs. Hanson suggested that one possible explanation is that the highly incompatible element under discussion may be transported back into the crust by fluids during subduction. Leeman then asked if the partitioning values between fluid and melt were known for these highly incompatible elements, and Newsom responded that, although it is likely they are enriched in the fluid, the necessary experiments have not yet been done. J. Jones asked if these elements were enriched in metasomatized mantle xenoliths, but this was not known.

Leeman then asked if Mo, W, As, and Sb data were available for modern island arc rocks, and Sims responded that they were not, but that he did intend to collect such data. Leeman suggested this could be very important; his work showed that boron partitioned strongly into water-rich melts and that the mantle wedge and crust were essentially transparent to movement of B, and also Be, during the subduction process. These elements are not recycled into the mantle but "stream through" the mantle wedge and lower crust, into the overlying crust. He further noted that differential fractionations are observed for B and Be in some back arc regions and that in a melt all these elements might be expected to behave incompatibly, but if a fluid was involved, differential fractionation may take place. D. Eggler pointed out that the nature of the fluid would strongly control the ability to transport such elements; chloride complexes would form in chlorine-bearing hydrothermal fluids, whereas hydrous mantle fluids would behave more like melts.

Jones then returned to the presentation of McLennan and asked how much Archean material was incorporated into the modern turbidites that he had studied. McLennan responded that it was quite variable but difficult to calculate precisely from Nd-isotopic data because both old and young crustal components had rather variable isotopic composition. In passive margin settings, the amount of Archean material incorporated could be large but in most active margin settings it was unlikely if such material played an important role. Another questioner asked if the trace element ratios had been plotted against Nd-model age. McLennan responded that he did not think this would be a useful approach, because many of his samples had model ages less than 1.0 Ga and he felt there was difficulty in interpreting the geological age significance of Nd-model ages less than about 500 Ma.

T. Naldrett returned to the papers of Jones (morning session) and Sims et al. and pointed out that Mo and Pb are only moderately chalcophile, whereas the platinum group elements (PGE) are highly chalcophile and thus should be stripped even more efficiently from the mantle during any sulphide segregation in core formation. Jones pointed out that the partition coefficient for Mo between metallic liquid and Fe-metal is about 1.0 and about 2.5 in favor of metal over sulphide. Accordingly, the fractionation of Mo between silicate and sulphide would be of the same order as between metal and silicate. Naldrett observed that Mo is not generally concentrated in magmatic sulphide ores and that the fractionation of Mo would therefore be much less than PGEs during sulphide segregation during core formation and that PGEs would be a more sensitive way to look at the problem. Newsom pointed out that the appropriate PGE analyses have not been carried out to characterize the various mantle reservoirs but that there were many lines of evidence (e.g., Mo data, Re-Os) that allowed the sulphide segregation model to be ruled out.

At this stage, the discussion returned to the problem of fractionating the highly incompatible elements because of their very low distribution coefficients and the possible role of fluids. Several points that were made earlier were restated and the chairman brought the session to a close.

SESSION III:
PHYSICAL ASPECTS OF MANTLE EVOLUTION
P. Morgan

The four papers presented in this session covered a variety of physical models and data that relate to Archean mantle evolution. The session was opened by F. Richter, who

presented his latest models for thermal evolution of the mantle. His calculations, constrained by the deductions that continental geotherms have not changed significantly but that the Archean global heat loss was greater than at present, indicate that the mantle has been cooling at a rate of 50–100°C/Ga, and the Archean mantle was about 300°C hotter than the modern mantle. He suggested that the only lithosphere preserved in the Archean was a distinct temperature-insensitive, chemically layered lithosphere. The Archean-Proterozoic boundary was interpreted to mark the time at which mantle temperatures dropped to a level where all continental lithosphere was preserved.

K. Burke opened the questions for Richter's paper by asking if there are any chemical data to support the very refractory lithosphere required in Richter's models (and previously published tectosphere models of T. Jordan). Richter replied that xenolith data indicate refractory mantle to depths of 150 km, but the interpretations of deeper sheared xenolith data are uncertain. Shirey remarked upon the variability in thickness of lithospheric roots beneath shields, to which Richter replied that seismic data used to develop these models average lithospheric properties over large areas. G. Hanson asked for an interpretation of the upper-mantle seismic V_s data in terms of mineralogy and chemistry. Richter responded by referring to publications of Jordan on the tectosphere, and summarized by saying that the mantle lithosphere was highly depleted. Leeman asked why the 400-km-thick tectosphere of Jordan bothered Richter, to which Richter replied that his models only required a 200-km-thick lithosphere and any greater thickness was superfluous. Kaula questioned Richter about mechanisms to achieve the lateral upper-mantle heterogeneity required by the models. Richter replied that his models did not yet address this problem, although it was a worthy topic for future studies, and computational resources are just becoming available that might make the problem tractable in two dimensions. R. Lambert commented that there is some critical level to which the Earth must cool before a lithosphere can form, "something to do with the rheology." D. Schulze commented that sheared mantle xenoliths do not constrain lithosphere thickness because of their possible association with the asthenosphere and may not be a good sample of old mantle material. N. Rogers remarked that some xenoliths indicate extraction of a komatiitic component, and this extraction may be significant in development of the lithosphere, to which Richter replied that in his models only the property that the material is relatively undeformable at high temperatures is important. J. Jones requested information about the distribution of heat production in the models, to which Richter responded that some heat production was concentrated in the uppermost layer (crust) but that the main part of the mantle was assumed to be adiabatic and well stirred, and thus relatively homogeneous.

In the next talk P. Morgan discussed his investigations of the possibility that shield mantle may be stabilized thermally to produce the lithosphere boundary layer. In order to explain a thick Archean continental lithosphere (as suggested by Archean-age diamonds) with high mantle temperatures (as suggested by Archean komatiites), he proposed a thermal model of the lithosphere in which a small concentration of heat-producing radioisotopes in the lithospheric mantle cause the lowermost lithospheric geotherm to be asymptotic to the asthenosphere adiabat. He demonstrated that such conditions were not theoretically unreasonable and may be a consequence of metasomatism and tectonics associated with stabilization events in the continental lithosphere.

D. Eggler opened the discussion with a remark concerning the problems in determining mantle heat generation because of metasomatism of the samples. Morgan agreed with the restrictions caused by this problem but concluded that his models are consistent with reasonable interpretations of available data, even accounting for metasomatism. F. Richter suggested that Morgan should test the temporal stability of his thermal lithosphere models, to which Morgan responded that this would be a good next step in the study. The discussion of this paper continued with a request by K. Burke for clarification of the mechanism proposed by Morgan for increase in mantle lithosphere heat generation by collisional mechanisms, which Morgan explained in terms of pure lateral strain in the lithosphere. R. Lambert made the final remark of the discussion by noting that the Atlantic cut through portions of shield lithosphere.

An extraterrestrial analog for Earth's Archean heat loss and tectonics was suggested in an enveloping review of Venus geology and tectonics by J. Head. He examined Venus in terms of possible zones of convergence and divergence, intraplate volcanism and tectonics, global patterns of tectonics, the forces driving tectonics, and the link between tectonics and mantle convection. Similarities and differences between Venus and Earth suggest that Venus may be used as a viable laboratory to study terrestrial processes under different conditions to modern Earth. Venus has a very high present surface temperature (560°C), possibly resulting in a hot, thin lithosphere as may have existed on Earth in the Archean. Head concluded that the equatorial highlands of Venus may represent fundamental aspects of deeper convection in the venusian interior, perhaps a model for terrestrial mantle convection.

B. Kaula opened the short discussion of this paper with a comment that Head had shown that there may be an Atlantic-type (slow) spreading ridge on Venus, but there was no Pacific-type (fast) spreading ridge, unless it was in the

20% of the planet not mapped by the Pioneer Venus altimeter. In this respect, Venus may be the normal planet and Earth may be abnormal. The dominant heat loss mechanism from Venus does not appear to be sea-floor spreading, and although mantle convection must exist to explain the high plateaus on Venus, the important question is whether it is impinging on a lithosphere or a crust. This discussion was cut short by the chairman because of lack of time. S. Shirey asked if there were any geochemical data for Ishtar Terra, the continent-like area in the northern hemisphere of Venus. Head replied that the only geochemical data available for Venus was from Soviet landers in Beta Regio in the equatorial regions of the planet. The data indicate high MgO, but additional data that may be able to detect the effects of recycling are not yet available. Further questions were postponed to the general discussion.

The final paper of the session, presented by D. Schulze (for H. Helmstaedt), was a discussion of the role of subduction in the evolution of Archean subcontinental lithosphere. Lithologic, isotopic, mineralogic, and xenolith data were presented to argue that ophiolites are preserved in Archean and Proterozoic greenstone belts, which are tangible evidence for early sea-floor spreading and subduction. By linking higher Archean heat loss with higher rates of spreading, they assumed that Archean subduction zones were characterized by high convergence rates and low-angle subduction. They suggested that entire cratons must have been underplated by oceanic lithosphere, resulting in complex imbrication of the Archean subcontinental upper mantle, probably somewhat homogenized during high-grade metamorphism, partial melting, and later intrusions.

A. Smith opened the discussion with a question about what would happen to some of the ages given in the paper if the primordial ϵ_{Nd} value were not zero but positive. Schulze responded that these data were not his own, but that they were not central to his arguments. T. Irving asked if Schulze had any new data concerning carbon isotopes in diamonds. Schulze responded that these isotopes were different from normal mantle isotopic ratios, and probably indicated a recycling origin for the carbon in diamonds. G. Ernst asked if the diamonds were associated with eclogites, to which Schulze replied that younger diamonds were associated with eclogites, the Archean diamonds were associated with peridotites. S. Shirey asked how it was possible to distinguish eclogite xenoliths from subduction zones from those of lower crust. Schulze explained that they could be distinguished on the basis of mineralogical equilibration temperatures and their very different thermal histories. L. Ashwal asked if the grospydites in the rocks discussed by Schulze may not originate from Ca-rich anorthosites, although they would still have a subduction event in their histories. Schulze replied that he could not be

certain of their protoliths. Jahn asked if there was a way to be certain that the eclogites were of Archean age, to which Schulze replied that he could not be certain; they were model ages that he presented, and they were not his data. R. Stern concluded the discussion of this paper by asking what lay beneath the base of the ophiolites. Schulze referred the question to his absent coauthor, but the audience offered the suggestion that the ophiolites were underlain by granites.

SESSION IV:
CONSTRAINTS ON MANTLE EVOLUTION FROM XENOLITHS
A. J. Irving

Two presentations by T. Irving and D. Eggler dealt with the petrogenesis of Cretaceous-Tertiary potassic igneous rocks in Montana, Wyoming, and Colorado and the geochemical and xenolithic evidence for the existence of ancient (probably Archean) subcontinental mantle lithosphere beneath these regions. Irving presented geochemical data for Eocene minettes and related rocks from the Highwood Mountains and made comparisons with data for other potassic rocks from the Wyoming province. He argued for the existence of three distinct source components. The large negative ϵ_{Nd} values and 1.87–2.1 Ga Pb-Pb ages found for the Highwood and Smoky Butte volcanics appear to be readily explained by interaction of asthenospheric melts with Precambrian mantle lithosphere related to the Wyoming craton. Irving also proposed a third component related to Eocene subduction processes in order to explain the Rb-Sr isotopic systematics.

In discussion, Eggler questioned such a direct link between active subduction and the potassic volcanism, preferring instead a back arc, postsubduction model. The existence of metasomatized ancient mantle lithosphere beneath central Montana was supported by Irving's descriptions of mica-bearing ultramafic xenoliths containing veins of glimmerite. He suggested that the veins could be dated isotopically and may turn out to be Precambrian metasomes, possibly related to ancient subduction events. S. Shirey recommended that the samples definitely would be amenable to Rb-Sr dating techniques.

Eggler summarized his extensive work on alkalic volcanics from the Crazy Mountains and Absaroka Mountains in Montana and on peridotite and eclogite xenoliths from Colorado-Wyoming kimberlites. He further developed the idea of a thick mantle lithospheric keel composed of metasomatized, previously depleted perioditite beneath the Wyoming province. In an intriguing comparison of present-day geophysically determined geotherms and fossil geotherms deduced from thermobarometry calculations on

xenoliths, he concluded that much of the pre-Cretaceous lithospheric keel has been advectively thinned. As a result the only remaining thick portions are in central Montana and southeastern Wyoming.

Discussion followed. J. Wooden made a plea for caution in interpreting Pb-Pb whole rock ages. R. Lambert pointed out the evidence for extension of the mantle keel to the north beneath the Crows Nest volcanics.

Eclogite xenoliths found within kimberlite pipes were the focus of two presentations by D. Schulze and C. Neal. The Sr and Nd isotopic studies of inclusions within diamonds have indicated that some of these eclogites are Proterozoic to Archean in age. There is no question that these rocks are a component of the Precambrian mantle, representing possibly frozen basaltic liquids, cumulates, or subducted and metasomatized basaltic rocks, but there is much uncertainty as to their abundance relative to peridotite. Schultze described many examples of coesite and sanidine-bearing eclogites from South African and Siberian kimberlites and concluded that they most likely represent subducted ancient ocean floor basalts rather than fractionated basaltic liquids. He contended further that there is a sampling bias in xenolith suites from kimberlites because of the greater cohesiveness of eclogite relative to garnet peridotite, and this appears to be borne out by his analysis of mineral concentrates from the pipes. Thus eclogite might constitute only 3–15% of the Precambrian mantle. Schultze made the suggestion that garnet peridotite xenoliths might be more readily disaggregated because of reaction between their orthopyroxene and the kimberlite magma; however, Neal questioned the viability of such a mechanism.

Neal presented some exciting elemental and isotopic data for a suite of eclogite xenoliths from a South African kimberlite. The study is important because it is one of the first to obtain coordinated Sr-Nd-O isotopic data on ultrapure mineral separates from these rocks. Three types of eclogite were recognized and interpreted as mantle cumulates, subducted oceanic basalts, and subducted gabbros (preserving positive Eu anomalies in both garnet and clinopyroxene). The most startling result is the extremely high ϵ_{Nd} and 2.3–2.5 Ga model ages for eclogites of the second group, which Neal explained by proposing a late Archean, light REE-depleted MORB progenitor.

Much discussion followed, particularly by C. Chauvel, P. Morgan, and G. LaBerge. F. Richter expounded on the semantic point that the mounting evidence for a subducted ancient MORB origin for many eclogites did not necessarily argue categorically for Archean plate tectonics. Further commentary on this ensued, with the general consensus that some form

of plate motion was the most reasonable mechanism for recycling crustal material into the Archean mantle.

SESSION V:
CONSTRAINTS ON MANTLE EVOLUTION FROM MANTLE-DERIVED MELTS
D. Elthon

G. Hanson opened this session with a discussion of the P-T conditions of origin of komatiites and tholeiitic basalts and then turned to a discussion of the geochemical results on the Kolar Schist Belt in southern India. He distinguished four different terranes in the region: (1) a belt of felsic gneisses in the west, (2) a western belt of amphibolites that have LREE depletions, (3) an eastern belt of amphibolites that are LREE enriched, and (4) a belt of felsic gneisses in the east. The protoliths for the amphibolites are considered to be mostly tholeiitic/komatiitic basalts, with a few komatiites. The eastern and western belts differ in their Nd and Pb isotopes. It was suggested that these different terranes were derived from different source regions and were assembled into their present configuration at 2500 Ma ago.

In discussion, K. Burke asked Hanson about the conditions of melting and what differences there were from melting in the present-day mantle. Hanson suggested that the komatiites were produced during the initial phase of melting at high pressures (50 kbar?), but the basalts were produced by melting at a later stage in the ascent of the mantle at lower pressures (20–25 kbars). T. Naldrett made a general comment that komatiites can assimilate a substantial amount of material during ascent because of their high temperatures and suggested that these effects should not be neglected. H. Newsom asked Hanson about the percentages of melting involved in the production of magmas in the Kolar Schist Belt. Hanson replied that he, unlike others, did not advocate high extents of partial melting but preferred a model involving a small percentage of melt production at high pressures. J. Jones noted that at very high pressures, where the liquidus and solidus of peridotite converge, relatively small temperature changes can produce substantial changes in the extent of melting.

The next presentation was by V. Rajamani in which he pursued the question of the relationship between the tholeiitic and komatiitic rocks from the Kolar Schist Belt. He proposed that komatiites were produced by melting at >100 km depth, but that the tholeiitic basalts were produced by melting of a modified mantle at <40 km. This modified mantle was proposed to be produced by the addition of a komatiitic melt to the mantle, which increases the mantle Fe/Mg. Liquid line of descent calculations

indicate that the tholeiites are not derived from either the komatiites or from a common parental liquid, at least by any relatively simple model. He concluded that the tholeiites were derived from a variety of Fe-rich mantle compositions and that the tholeiites were not related to each other by crystal fractionation processes.

In discussion, Elthon noted that modern basalts, like these samples, typically have Fe/Mg too high to be in equilibrium with the mantle and that most interpretations suggest that this is an effect of crystal fractionation, not melting of an Fe-rich mantle. Rajamani and Hanson collectively noted that the compositions of these basalts do not lie along any common liquid line of descent as would be expected if crystallization dominated. They also noted that the geochemical data (e.g., Ni vs. Mg) often clustered in a quite small region of a plot and that there were no associated cumulates found in the region. Burke, however, questioned whether cumulates might have been originally present but are no longer found in the region due to tectonic processes. P. Smith asked how close the samples studied here were collected from areas of gold mineralization and noted that LREE enrichment is found in Abitibi samples associated with gold mineralization. Rajamani responded that these were collected 500-600 m from gold mineralization areas and did not feel that LREE enrichment associated with gold mineralization had influenced his samples. S. Shirey noted the HREE fractionation seen in the Kolar samples was similar to that described for numerous Archean samples the previous day by Jahn. Jahn agreed and noted that Fe-rich basalts such as those described here are quite common among Archean samples. He also noted that they are often associated with banded iron formations.

The session continued with G. Byerly's discussion of the geochemical relations within komatiites from the Mendon formation of the Barberton Greenstone Belt. He noted that there have been several distinctive episodes of volcanism, but low angle faults and folds complicate the stratigraphy of the volcanic rocks. With the use of three distinctive marker beds, however, a volcanic stratigraphy of the region has been developed in which six distinctive flows have been identified. Komatiites from the Mendon formation are characterized by a high Al_2O_3/TiO_2 of 30 to 100, whereas most other komatiites from Barberton have a ratio of ~10. The Al and Ti abundances are well correlated, particularly in the relatively fresh samples, suggesting that these elements are relatively immobile. Alteration is extensive in many of the samples, however, and it appears that many of the highly altered samples lie along quartz-sericite mixing lines. Chromium spinels are found in many samples and appear to reflect magmatic rather than metamorphic conditions; most spinels have $Cr/(Cr+Al)$ of 0.55 to 0.90. The ratios of several incompatible elements are quite variable, particularly in

the Mendon formation. For the freshest rocks, the abundances of Hf, Th, and Ta suggest that these samples were part of a magmatic arc terrane.

In discussion, Jones inquired about the conditions under which strong silica enrichment occurs. Byerly responded that these effects were probably related to hydrothermal convection cells, possibly one in which periodic evaporation produced concentrated brines. He suggested that the environment of formation may have been in a back arc plateau with high heat flow. Shirey asked if he had looked at the silica-rich zones to determine their chemical relationships. Byerly responded that these zones are mixtures of silica, sericite, and carbonate material. C. Chauvel asked whether these samples were the same as those that Wasserburg's group had studied. Byerly responded that they were from the same region but were not the same samples.

N. Rogers briefly reviewed the types of petrological data that are relevant to discussions of the composition of the Archean mantle in the context of evaluating the geochemical variations in Archean Dominion Group basalts from South Africa. In particular he noted that South African garnet peridotites have lower FeO^* than spinel peridotites and that the spinel lherzolites have a slightly (~1%) higher density as a consequence. He suggested that parental MORBs have approximately the same FeO^* as spinel peridotites, but that komatiites have higher FeO^* and would be more suitably linked with the garnet peridotites. The Dominion Group basalts have low TiO_2 (often <0.75%) and moderate SiO_2 (51–56%), suggesting a calc-alkaline trend. Most of the elemental variations within these samples are explicable in terms of low-pressure crystallization. Assimilation of crustal rocks by komatiite to produce the Dominion Group basalts will work for most elements, but not for Sc and V. It is proposed that these samples were formed in a fore-arc extensional basin.

In discussion, D. Schulz noted that probably the most relevant comparison for examining density and compositional differences between garnet peridotites and spinel peridotites would be to compare them using only spinel lherzolites from kimberlites rather than spinel lherzolites from world-wide collections. Rogers agreed but noted that he had not looked at data spinel lherzolites from kimberlites as thoroughly.

In the final presentation in this session, G. Ernst described geochemical and geochronological work on rocks from northeastern China. He noted that these samples have been extensively metamorphosed and recrystallized, but their protoliths seem to have been tholeiitic basaltic komatiites. Most of the samples were LREE enriched although some were LREE depleted. The samples have ages of 2.66 Ga, which is substantially younger than they

anticipated based on previous reports of Early Archean dates. The basaltic rocks were derived from depleted mantle that had been depleted over approximately 1 Ga.

In discussion, Rajamani asked what the rocks were like petrographically at present. Ernst replied that they had been strongly recrystallized with no pillowed or spinifex textures remaining. The dominant minerals are hornblende, intermediate plagioclase, and clinozoisite. Jahn noted that it is possible that the oldest samples in the area may not have been sampled in this study. He indicated that rocks of 2.99 Ga ages have been reported from this general region. Burke and R. Lambert noted that the geology of the region is very complex, with 2400 Ma and 1800 Ma metamorphic events, and numerous intrusions and faults that cross-cut the region. These subsequent events complicate and obscure the Archean geology.

SESSION VI:
CONSTRAINTS ON MANTLE EVOLUTION FROM MANTLE-DERIVED MELTS (CONTINUED)
C. T. Barrie

The last session of the workshop opened with a talk by R. Stern on an unusual suite of mildly alkaline, predominantly intrusive rocks found in the southwestern Superior Province. The suite has chemical characteristics similar to LIL-and LREE-enriched, high-Mg andesites known as sanukites in the Setouchi volcanic belt of Japan. Accordingly, this suite has been termed a "sanukitoid" suite, along with spatially and chemically related monzodiorites and granodiorites. Using FeO or Ni vs. MgO plots and REE ratio diagrams, it is apparent that the more primitive rocks of the sanukitoid suite cannot be derived from typical lamprophyric or tholeiitic compositions through any combination of fractional crystallization, partial melting of any single mantle source, or contamination by reasonable crustal compositions. Stern suggested that the primitive sanukitoids were derived from a hydrous, LREE- and LIL-enriched mantle source by partial melting. This would explain the rather constant Ce/Nd ratios over a wide range of Ce concentrations, which cannot be accounted for by variable degrees of partial melting with a garnet-bearing residuum. The more evolved granodiorites can be modeled as fractionation products from sanukitoid parental magmas.

This talk was greeted with a very strong interest from the audience. T. Naldrett requested clarification on the relationship between the hydrous mantle source environment for the sanukitoids and the trace-element enrichment process. Stern stated that the timing of the enrichment process must have been nearly synchronous with sanukitoid emplacement, as localized andesitic melts in the mantle would certainly rise shortly after formation by virtue of their lower density and viscosity with respect to surrounding mantle material. B. Leeman questioned whether the isotopic composition of the rocks could constrain the timing of mantle extraction. Stern referred to recent work by Shirey and Carlson that found that the sanukitoid suite has ϵ_{Nd} values of +1 to +2.5, suggesting that the source had a long-term history of LREE depletion. However, the suite's LREE-enriched chemical signature would imply that the enrichment event occurred shortly before emplacement. H. Newsom wondered about the physical characteristics of the suite and implications for the size and geometry of the mantle sources. Stern said that based on his studies of the Roaring River Complex, sanukitoid magmas probably fractionated en route to supracrustal levels, accounting for the associated, relatively voluminous granodiorites. Few lavas have been found that may be included within the suite. L. Ashwal mentioned that tholeiites in the region have similar ϵ_{Nd} values and queried whether they could be derived from the same source that had not been subjected to local contamination immediately prior to partial melting and extraction. Stern replied that this was possible in a general sense if you could account for variable MgO and FeO in the source; one possibility to produce this variability would be to call on earlier extraction events.

At this time a forest of hands rose in the audience. D. Schulze asked for clarification on the depth of partial melting. The response was that it is constrained to 10–15 kbars by experimental work on hydrous peridotite melts. T. Irving wondered about the high sodium content. Stern replied that the suite does have unusually high sodium contents, perhaps attributable to melting of plagioclase or jadeitic pyroxene, or to sodium behaving as an incompatible element in an enriched fluid phase. B. Jahn asked about the high silica content of mantle-derived melts and alluded to the possibility of silica being part of the fluid phase added to the mantle. Stern made the analogy with boninites, which are commonly believed to be mantle-derived and are silica rich, and agreed that high silica contents could be attributed to a supercritical fluid melt. R. Lambert requested a petrological description for these rocks, considering the possibility of mixed magma sources, and wondered where the LREEs reside. The mineralogy is variable but generally typical of diorites, with the bulk of the trace elements tied up in sphene and apatite. Jahn made an analogy between the sanukitoid suite and syenodiorite suites in China and France and wondered if alkali basalts could serve as parental magma. Stern said that there are no known alkali basalts in the region, but lamprophyres have been considered as possible parent magmas and they are easily dismissed considering their relatively high Mg numbers. In the Setouchi region of Japan, alkali basalts are found near the type localities but are apparently unrelated and have isotopically distinct signatures.

The session continued with a structural, geochemical, and isotopic study of the Kamiskotia area in the westernmost Abitibi Subprovince by T. Barrie. Supported by high precision U-Pb geochronology, the lithologies were divided into older siliceous and tholeiitic rocks, the Kamiskotia gabbro-volcanic suite that apparently formed in a back arc-like extensional regime (2707–2705 Ma), a series of granitoids formed in a predominantly compressional regime (2695–2694 Ma), and young alkalic dikes, several of which postdate late transpressive deformation in the region (2687 Ma). The Nd and Sr isotopic data support the derivation of the Kamiskotia suite from a depleted mantle reservoir with no evidence for interaction with an enriched crustal component.

A compilation of southern Superior Province ϵ_{Nd} values and U-Pb ages for mantle-derived magmas, including five suites from the Kamiskotia area, revealed that: (1) tholeiites and komatiites occurred from 2740–2698 Ma, whereas most alkaline rocks were emplaced from 2700–2670 Ma; (2) tholeiites and komatiites of the southern Abitibi are consistently isotopically depleted, with ϵ_{Nd} from +2 to +3, whereas those from the western subprovinces are more variable from +1 to +3; and (3) alkaline rocks have ϵ_{Nd} predominantly from +1 to +2, slightly enriched with respect to the southern Abitibi-depleted mantle. Trace element signatures for southern Abitibi alkalic rocks are similar to alkalic suites found in Cenozoic destructive plate margin settings and are consistent with a derivation from a hydrous mantle influenced by a subducted sedimentary component. As the alkalic rocks are relatively isotopically enriched, an older sedimentary component may have been involved in their genesis.

K. Burke opened the discussion by noting his approval for field-based structural studies that provide a tectonic framework for follow-up geochemical and isotopic work. J. Wooden asked if it were possible to distinguish between slightly different sources and contamination to produce the difference. Barrie responded by agreeing that it is difficult to distinguish between these possibilities for the mantle-derived magmas. However, the coincidence of a transpressive tectonic regime and spatially associated late alkalic magmatism observed across 1200 km of the southern Superior Province would imply that some uniform process affected the late Kenoran mantle underlying the entire region. A subducted sedimentary component associated with a subducted oceanic slab would be consistent with this. Newsom asked if the Destor Porcupine Fault Zone represented a sedimentary lithologic break and whether gold mineralization is found along any preferred strata. Barrie said that there is some evidence that the major fault zones in the southern Abitibi were originally listric normal faults formed in an extensional tectonic regime, such as associated fault scarp(?) breccias and turbidites. It would appear that these faults were reactivated during subsequent compression and

transpression and served as mantle-tapping conduits for late alkaline magmatism and as conduits for gold-bearing fluids from unknown sources.

N. Rogers mentioned that the alkaline rocks of the central Italian province were highly potassic and was curious about the meaning and derivation of the more sodic rocks found in the southern Abitibi. Leeman also requested a characterization of the alkaline rocks. The alkaline rocks discussed range from lamproite dikes to the basanites and trachytes of the Timiskaming Group. Generally, the lamproite dikes have 50% SiO_2 Mg# = 65–80, Na_2O from 1% to 5%, K_2O from 0.5% to 2%, relatively high LIL, LREE, and transition elements, and relatively low HFS traces. Timiskaming volcanics have similar characteristics but as a suite are more siliceous (48–61% SiO_2), more sodic (3.5–6.5% Na_2O), more potassic (1–7% K_2O), and less magnesian (45–60 Mg#).

At this time discussion returned to sanukitology. Leeman noted the chemical similarities between the Archean sanukitoid suite and the Eocene shoshonitic Challis volcanic rocks in the western United States. He cautioned that close comparisons with boninites have strong tectonic implications that may not be appropriate for Archean rocks of the western Superior Province. G. Hanson commented that considering chemistry, except for the silica content, the suite is similar to alkali basalts. If partial melting of an alkali basalt source occurs at shallower depths under hydrous conditions, one would expect the melt to be on a peritectic between olivine and silica, producing a higher silica content. Many people commented on the relatively common occurrence of alkaline rocks with similar chemistry but with different names, such as latites found in Idaho and Montana and syenodiorites found in China. Jones requested that we find a type locality with a shorter name. Hanson responded by saying that he and S. Shirey chose the name for the Archean suite after a literature search to find a name with no connotations.

After a coffee break, R. Lambert filled in a vacant time slot with a short talk on the thermal history of the mantle. First, he reviewed geotherm models for the modern mantle developed over the last 20 years, highlighting the differences between subcontinental heat flux, which requires an attached lithospheric keel, and suboceanic mantle, where convection efficiently dissipates excess heat. Recent seismic tomography has indicated a probable thermal discontinuity at approximately 700 km depth, with possible gradients of 15°/km over about 20-km intervals. These data are commonly interpreted to represent the thermal boundary layer between separate convection regimes in the upper and lower mantle. D. Anderson would suggest that only a solid mantle is present below 700 km and that there is very little chemical communication across the 700-km boundary. Considering the higher radiogenic heat production at 2600 Ma, it would appear that the gradient would be more like 25°/km across a 700-km thermal

discontinuity, and this would intersect most estimates for the mantle solidus resulting in extensive partial melting. Given these conditions this would imply that either a magma ocean existed in the Archean, or that an Archean thermal boundary layer did not exist. An alternative promoted by Anderson is that radiogenic heat-producing elements were not present in the Archean mantle and that a stratified mantle could have existed in Archean times.

Discussion was opened by Jones, who pointed out that those who believe in the origin of the Moon by fission from the Earth due to a giant impact promote an entirely molten Earth and the extraction of radiogenic elements from the lower mantle would result as a consequence, consistent with Anderson's views. Lambert retorted that this would also result in the formation of cumulates from a magma ocean, resulting in highly variable ϵ_{Nd} *values, which is not observed. Schulze reviewed the scant evidence for Archean diamonds and thermal gradients derived from mineral pair geothermometers in diamond-bearing eclogites and sheared lherzolites, emphasizing that the constructed Archean deep lithospheric and asthenospheric thermal gradients are tenuous at present.*

The session continued with Lambert's talk on trace element and radiogenic isotope constraints on the evolution of the Stillwater Complex. Previous workers have postulated that two parental magmas (U-type: ultramafic and A-type: anorthositic) underwent complex magma chamber processes to account for Stillwater's petrology, chemistry, and mineralization. Using REE isotope dilution for mineral separates and Sr-Nd-Os isotope systematics on whole rocks, both U-type and A-type magmas were characterized in detail. The U-type magmas show LREE and I_{Nd} enrichment in comparison to the A-type magmas, which are more closely associated with the J-M reef. The Sm-Nd system was closed and behaved coherently, whereas the Rb-Sr system was at least partly reset at 1390 Ma. New Re-Os data presented shows that this system has remained relatively closed, producing a reasonable isochron that agrees with the Sm-Nd isochron for U-type derivatives, with a consistent ^{187}Os enrichment at +23.5 gamma Os units (percent with respect to chondritic Os) for six of seven samples. The trace element and radiogenic data are consistent with either crustal contamination or a heterogeneous mantle source region beneath the Wyoming craton for Stillwater parental magmas in the late Archean.

The first audible comment in discussion was by Jones, who wondered why the Re/Os ratios were so incredibly low in the analyzed rocks, particularly in the chromitite samples. Lambert replied that little is known in detail, but both are concentrated in trace phases and are found in relative abundance in the chromitites. Osmium is known to partition into chromite or

at least into trace phases associated with chromite. Naldrett elaborated on our knowledge of the partitioning of PGE in these rocks. It is well known that magmatic sulfides have high $K_{D}s$ *for all of the PGE in this environment. Most of the chromite seams, like the J-M reef, contain all of the PGEs but are relatively enriched in Pt and Pd, possibly reflecting a greater abundance of Pt and Pd in the host magma. However, the G chromitite is not enriched in Pt and Pd in comparison to the other chromitites. This may signify that the magma chamber was undersaturated with respect to sulfur at the time of G formation. If this was true, then the abundances of Os, Ir, and Ru in the G chromitite may reflect the scavenging of these elements by chromite during crystallization under sulfur undersaturated conditions. Lambert commented that N. Page has noted sulfide pods below the G chromitite locally. Naldrett believed them to represent pegmatitic pods of sulfide-rich material probably more closely related to upwardly migrating interstitial liquids that reached sulfur saturation in contact with the chromitites. Lambert noted that this would not explain the different Os isotopic signatures found in the G seam. Naldrett replied that it is possible that mixing with A-type magma may have been responsible for G seam formation. Leeman then sought a description of the configuration of coeval, isotopically distinct magma chambers in the lower crust or mantle that fed the Stillwater magma chamber. This is a very good question, and it remained unanswered when the chairman terminated the discussion to move on to the next talk.*

P. Smith provided a poster of Hf and Pb isotope systematics of the Wawa Subprovince, Superior Province, for discussion during the reception on the second day of the workshop. One relatively young basalt (2.70 Ga) has a μ_1 value essentially equal to Abitibi komatiites and basalts, whereas older basalts and rhyolites (2.76 Ga) have relatively enriched μ_1 values, consistent with undepleted or crustally contaminated sources. Rhyolites are consistently enriched relative to coeval and spatially associated basalts. This relationship is similar to volcanic suites found in intercontinental rift areas such as the Yellowstone bimodal volcanic field, where this relationship is attributed to the influence of an enriched lower crustal component on the rhyolites. From these and other data, there appears to be a general trend toward lower μ values over from 2.89 Ga to 2.7 Ga, indicating an increasing influence of depleted mantle sources through this period. Smith also presented Pb isotope models for HCl and HNO_3 leaching experiments, using several basalts and sulfide separates that have ages constrained by U-Pb geochronology. These experiments were performed in order to explain the scatter of whole rock data on Pb isochron plots, a common feature of many studies of Archean mantle-derived rocks. The results indicated that the perturbations were caused by the presence of Pb-rich sulfides that had undergone resetting

of their isotopic systems during events long after basalt extrusion. However, the alignment of the data for acid-leached residues to isochrons giving ages in agreement with the U-Pb ages suggests that the effects of the reset sulfides can be removed to yield primary μ_1 values.

The final talk of the workshop was by S. Smaglik on trace element evidence for mantle heterogeneity in amphibolite grade metavolcanic rocks from the Laramie Range in Wyoming. The study area is enclosed by granitic gneiss and outcrop photographs demonstrate that it is moderately to highly tectonized. Ultramafic rocks exhibit a wide range of trace element chemistry, with high Ce_N/Yb_N values between 5.8 and 14.7, and Zr up to 180 ppm. Tholeiitic rocks have relatively flat REE patterns with no Eu anomalies. These data were interpreted to represent separation of partial melts from a mantle diapir, with mantle enrichment, crustal contamination, and/or residual garnet in the source region accounting for the unusual characteristics of the ultramafic rocks.

In discussion, Burke queried about early and late mafic and ultramafic dike emplacement through both the granitoid rocks and the greenstone rocks. Naldrett cautioned about the usage of the term komatiite for the ultramafic rocks and wondered if basalts adjacent to the ultramafics could be differentiates for the ultramafic rocks that have cumulate characteristics, which would provide supporting evidence for a truly komatiitic origin. Smaglik did not have the data to address this question. The chairman then closed the discussion period.

Ashwal briefly thanked the speakers and participants of the workshop and then adjourned the meeting at 11:30 a.m.

ABSTRACTS

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 ± 136 Ma with $epsilon_{Nd}$ of +5±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±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±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.

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Balakrishnan, S. et al.
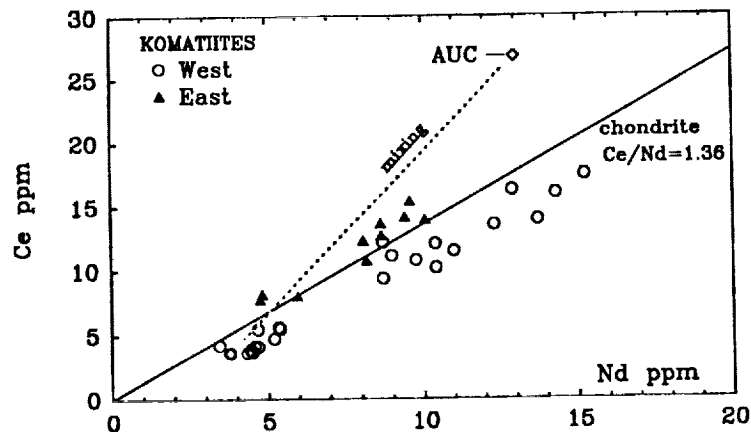
Fig. 1. Ce versus Nd concentrations of the western and eastern komatiitic amphibolites compared to a line with chondritic Ce/Nd ratio and to a mixing line between light REE depleted komatiite and Archean upper crust (AUC) after Taylor and McLennen (2). The granitoids in the Kolar area plot on the extension 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.
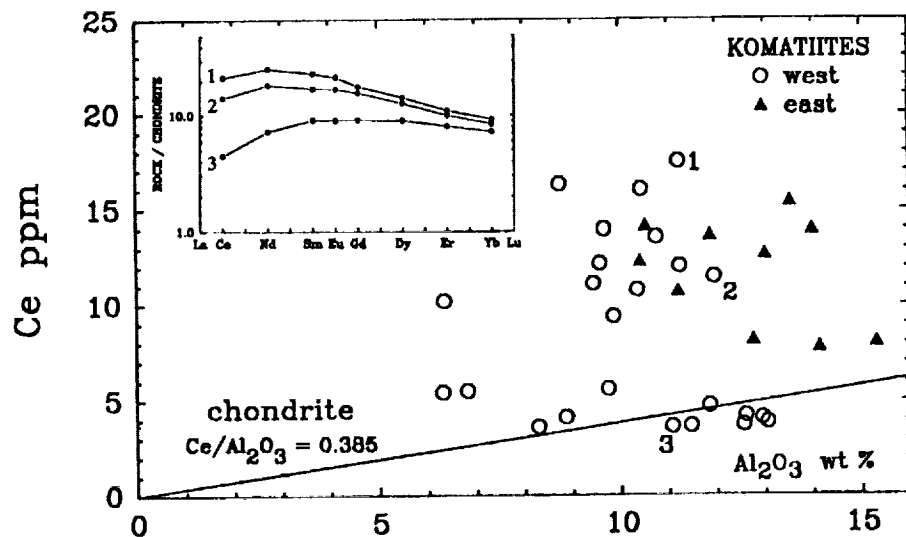
Fig 2. Ce versus Al_2O_3 concentrations of western and eastern komatiitic amphibolites compared to a line with chondritic Ce/Al_2O_3 ratio. Ce and Al are essentially incompatible in olivine and pyroxenes, whereas Al is an essential structural constituent of garnet. The melts leaving garnet in the residue 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.
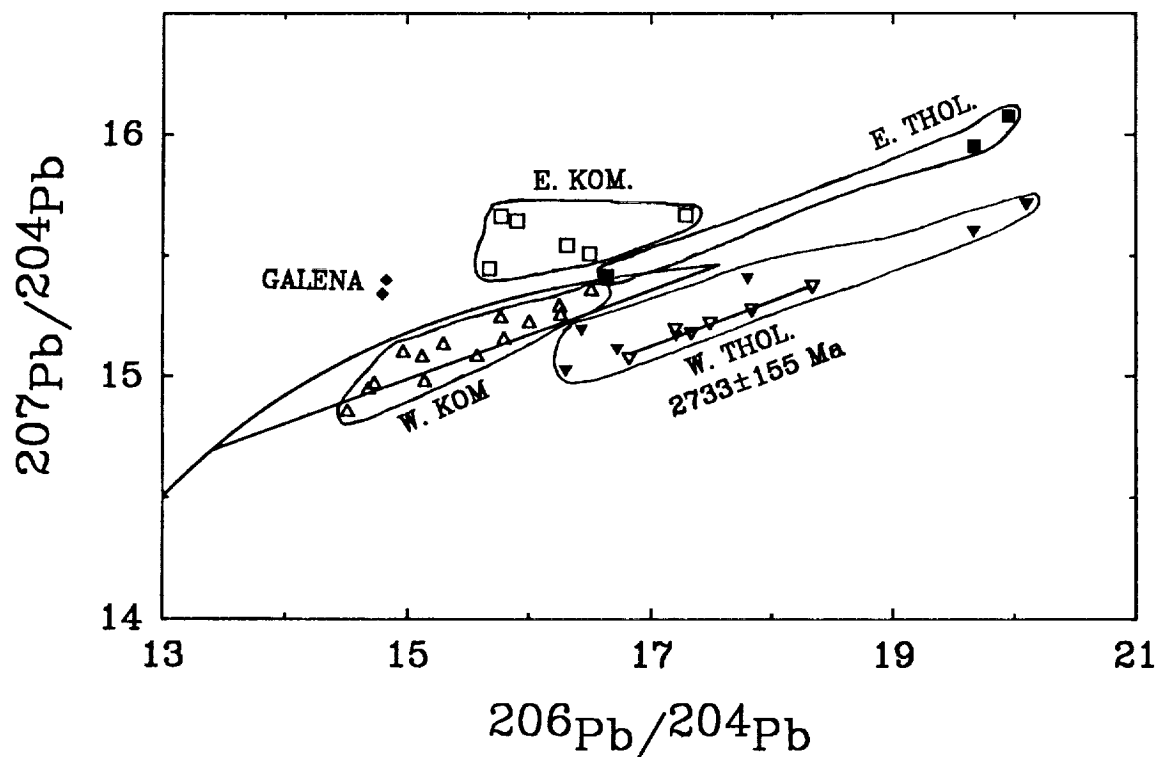
Fig. 3. Pb isotope data on eastern and western komatiitic and tholeiitic amphibolites compared to the Pb isotope data for galena from within the belt (3). Whereas the Pb data for the western tholeiites from a number of outcrops show a scatter, the data for samples from one outcrop lie closely about a line and give an age of 2733±155 Ma.

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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 2687 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 >1200 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.

Geochemistry and Nd-Sr Isotope Systematics

Barrie C. T. and Shirey S. B.

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FIGURE 1.

SYMBOLS REPRESENT AVERAGE OF 1 TO 15 ANALYSES.
OPEN SYMBOLS: THIS STUDY
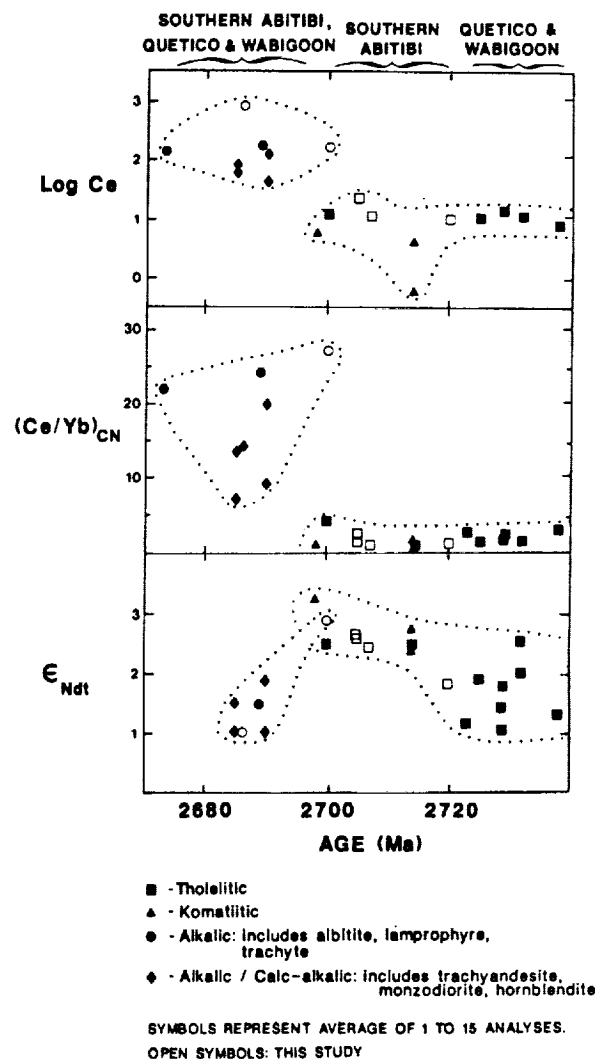
MENDON FORMATION KOMATIITES: EXTREME AL2O3/TIO2 VARIATION IN THE UPPERMOST ONVERVACHT GROUP OF THE BARBERTON GREENSTONE BELT, Gary R. Byerly, Department of Geology and Geophysics, Louisiana State University, Baton Rouge, LA 70803

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.
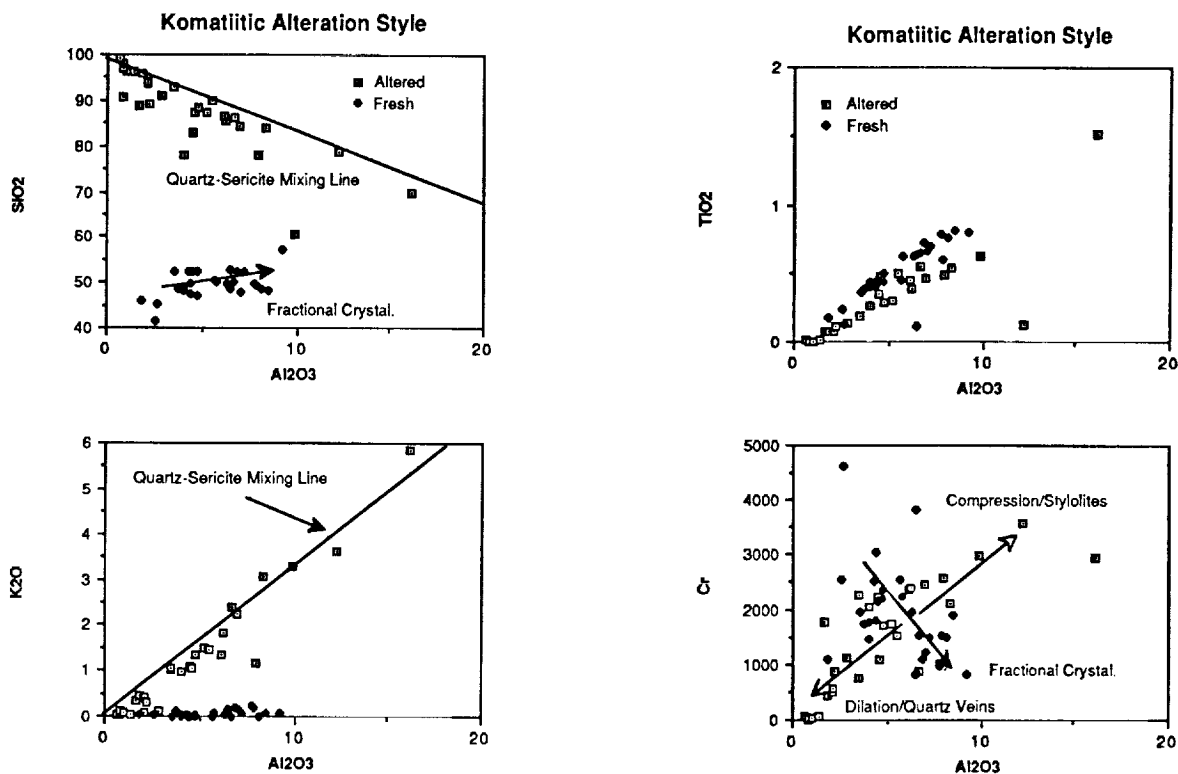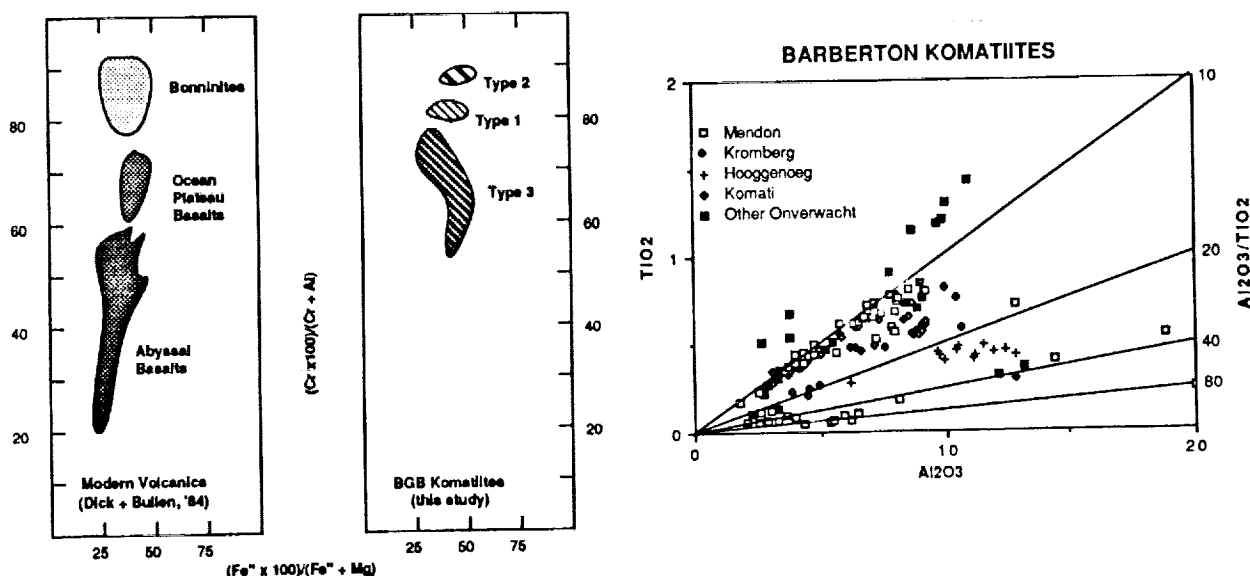
Mendon Formation Komatiites: Al2O3/TiO2 Variation
Gary R. Byerly

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) Fractional depletion or enrichment of garnet in an initially chondritic mantle source. This could have taken place early in Earth history but should have resulted in a radiogenic isotopic signature apparently not found in Archean komatiites, thus garnet redistribution immediately prior to, or during, partial melting is necessary (8). B) Assimilation of crustal rocks with very high A/T. 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) Mantle metasomatism of a depleted mantle source. 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
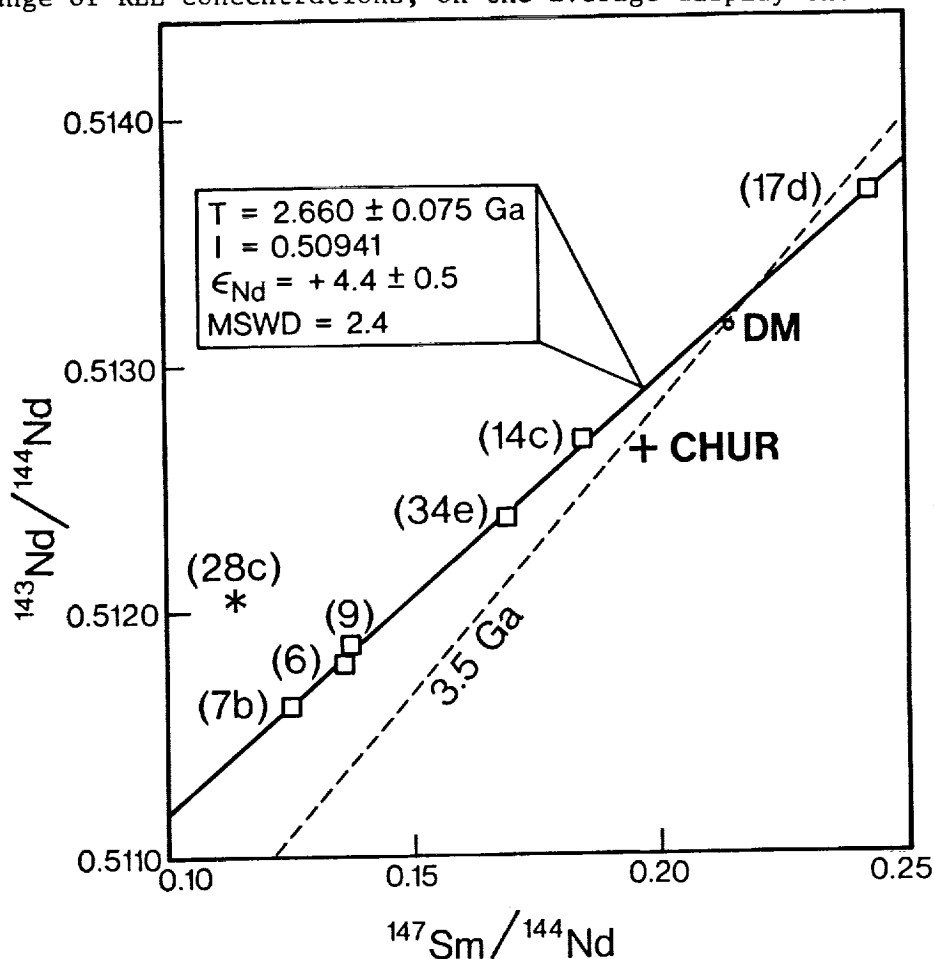
Fig. 1. Nd-Sm bulk-rock isochron diagram for seven analyzed mafic-ultramafic metamorphic rocks from the southern Jilin/eastern Liaoning basement series. The six supracrustal amphibolites of komatiitic chemical affinities define an isochron of Late Archean age. The mafic xenolith in tonalitic gneiss (no. 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.

2.66 GA METAKOMATIITES, NE P.R.C.

Ernst W.G. and Jahn B-M

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 $+4.4\pm0.5$ 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).

2.66 GA METAKOMATIITES, NE P.R.C.

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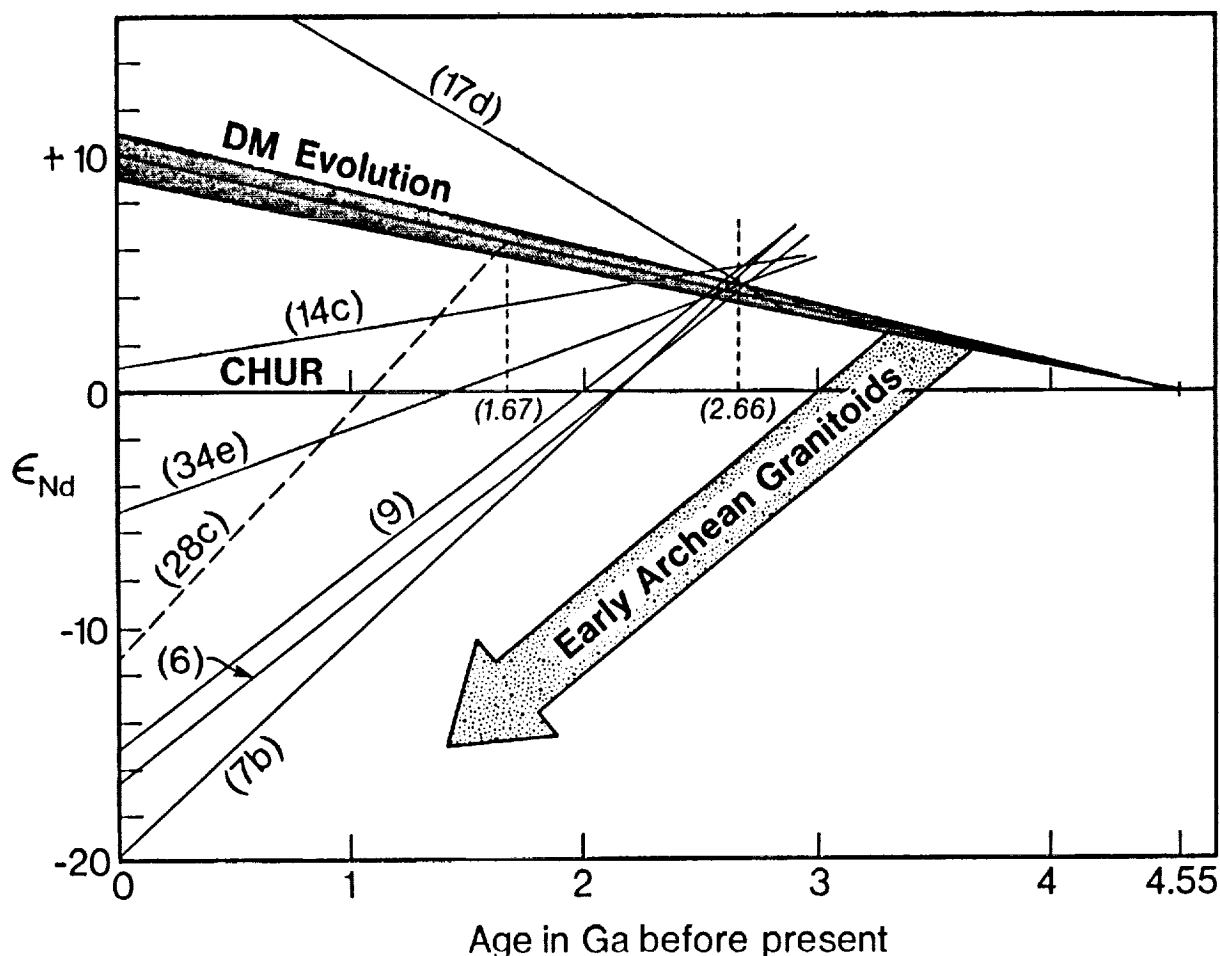
Fig. 2. ε_{Nd} evolution diagram for the analyzed mafic-ultramafic metamorphic rocks from southern Jilin/eastern Liaoning Provinces. The six supracrustal metakomatiitic amphibolites possess Nd isotopic curves which intersect the depleted mantle ε_{Nd} line in the vicinity of 4.4±0.5 in Late Archean time. 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;

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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°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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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
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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

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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;

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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 mixed source melting model (Figure 4).

Rocks from the Highwood and Bearpaw Mountains have elevated $^{87}Sr/^{86}Sr$ compared with the other alkalic subprovinces (Figure 1), which may in part be explained by a range in Sr isotopic composition within the ancient subcontinental lithosphere. However, 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 Rb/Sr variation is a young feature and therefore not related to the ancient lithospheric component. We believe by analogy with Recent potassic volcanics from Italy, Sunda-Banda and western Mexico that a third Rb-enriched component may have been added to the asthenopheric wedge during the well-documented regional Eocene-Oligocene subduction event. Similarly we ascribe the relative depletions in HFS elements shown by most of the Montana alkalic rocks (Figure 3) largely to young subduction processes, although we cannot rule out a contribution from ancient lithosphere. The Nb-Ta enrichment shown by the Haystack Butte monticellite peridotite may result from perovskite accumulation. 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.

PRECAMBRIAN MANTLE BENEATH MONTANA
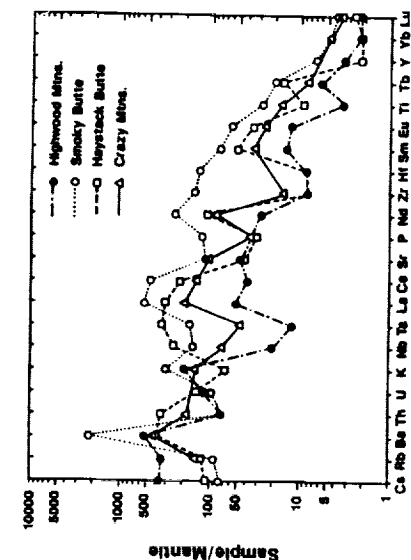A. J. Irving et al.

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).
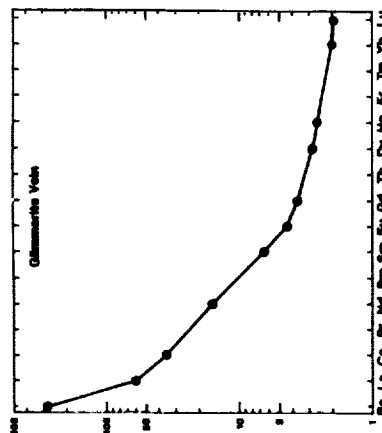
Figure 6. Chondrite-normalized rare earth element abundances and primitive mantle-normalized Ba abundance for a phlogopite glimmerite vein within a harzburgite xenolith from a primitive minette from the Highwood Mountains.
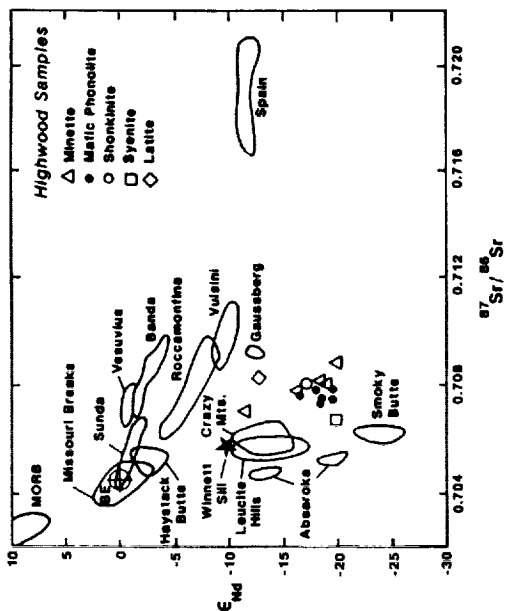
Figure 2. Plot of Nd and Sr isotopic compositions for potassic volcanics from Montana-Wyoming and elsewhere (data from Hawkesworth and Vollmer, 1979; Vollmer et al., 1984; Fraser et al., 1985; Nelson et al., 1986; Dudas et al., 1987; Menn and Eggler, 1987; O'Brien et al., 1988; Stolz et al., 1988; Scambos and Farmer, 1988).
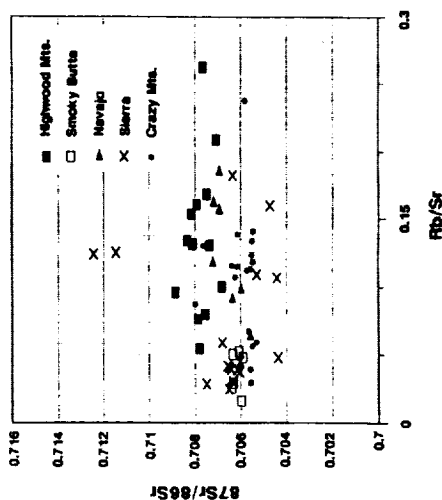
Figure 5. Variation of $^{87}Sr/^{86}Sr$ with Rb/Sr for potassic mafic rocks from the Highwood Mountains and elsewhere (data from O'Brien, 1988; Fraser et al., 1985; Alibert et al., 1986; Dudas et al., 1987).
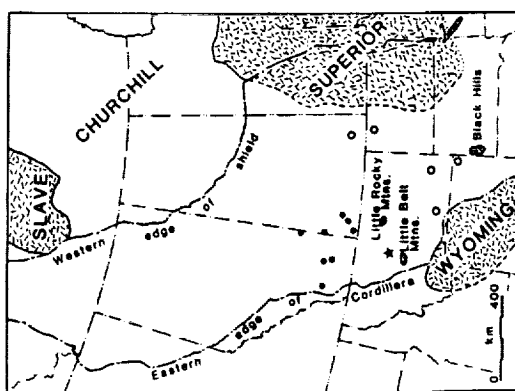
Figure 1. Map showing outcrop of Archean rocks in the interior Platform and adjacent Canadian Shield (pattern), and locations of basement cores yielding Precambrian dates. Open circles indicate Archean cores and dots indicate cores giving 1.8 Ga K-Ar ages but 2.8 Ga Nd model ages (from Frost and Burwash, 1986). Asterisk = Highwood Mountains.
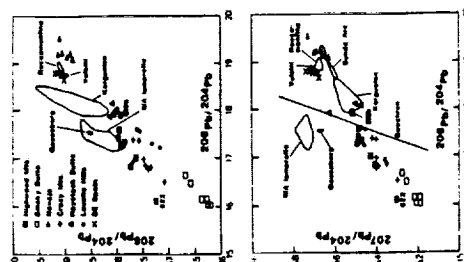
Figure 4. Pb isotopic compositions for potassic mafic rocks from Montana-Wyoming (data from O'Brien et al., 1988; O'Brien, 1988; Vollmer et al., 1984; Fraser et al., 1985; Dudas et al., 1987), Navajo province (Alibert et al., 1986) and elsewhere (after Nelson et al., 1986).

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, of stored basaltic magma, 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 (Fig. 1). 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. A few reliable Hf isotopic data for various REE typological groups are indistinguishable, hence rendering the hypothesis of long-lived stratified mantle (and magma ocean) untenable. (b) Light REE distributions in basalts and komatiites are highly variable (Fig. 2). 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 and by implication, of its immediate protolith - basaltic crust. 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 (Fig. 3). It first implies that the upper mantle has been significantly depleted, likely by removal of continental material and its basaltic protolith, 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 Nd value rapidly, up to +10 by 2.5 Ga. The lack of very high Nd 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

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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, unreasonably massive quantity of plagioclase (20 to 30% of mantle source region in some cases) would be required to separate to form anorthositic crust (Fig. 4). 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 unlike dry lunar magmas, terrestrial magmas are probably more hydrous and are not dense enough to float plagioclase. If garnet precipitation is to be 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.
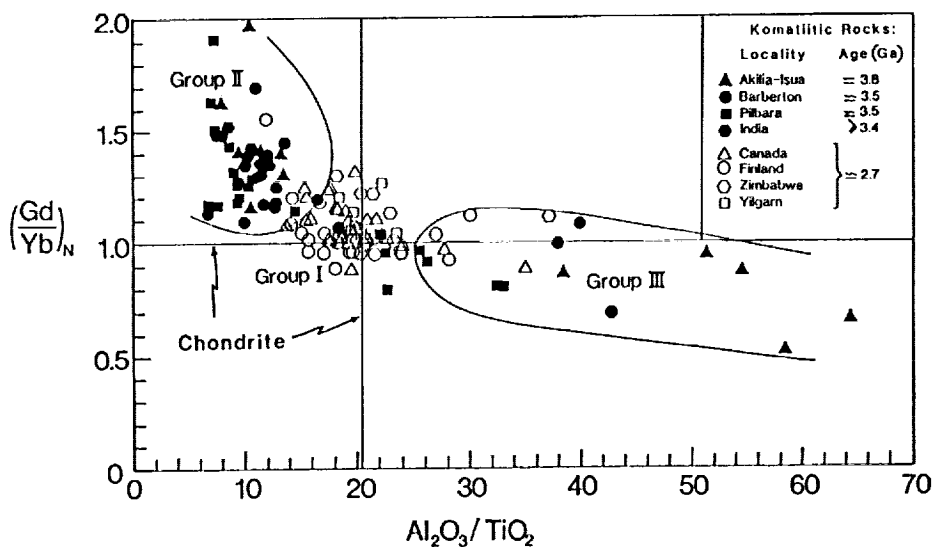
Fig.1. HREE typological classification of komatiites. Note that Groups II and III rocks occur mainly in the early Archaean.
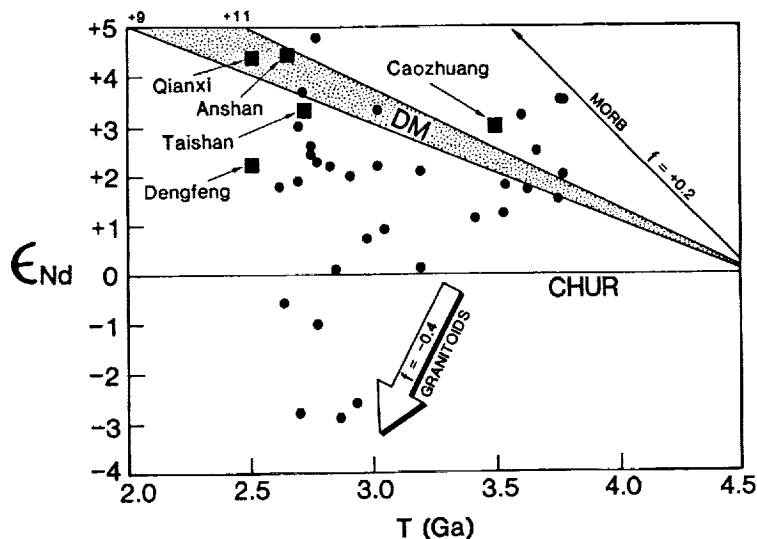
Fig. 3. ε_{Nd} vs T diagram for Archean rocks. For data compilation, see Jahn et al. (1987), Precam Res 34:311-346. For chinese data (solid squares), see also:Jahn et al.(1988) Precam Res 38:381-403; Ernst and Jahn (1989), this volume.

Fig. 2. Plot of $(La/Sm)_N$ vs Sm_N for early and late Archean rocks. $(La/Sm)_N$ represents degree of LREE fractionation and Sm_N indicates the general level of REE abundances. The very low $(La/Sm)_N$ ratios of many PK, BK and metabasaltic suites clearly indicate the largely depleted nature of Archean (particularly, late Archean) mantle.
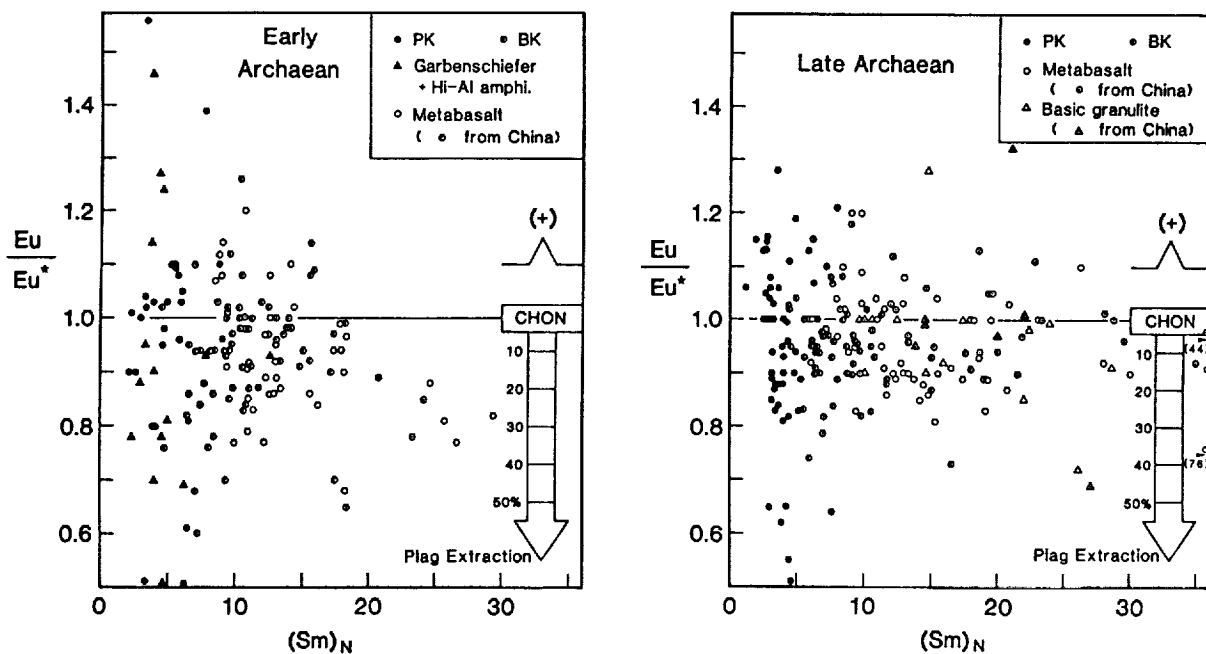
Fig. 4. Eu anomalies in Archean rocks. Both positive and negative Eu anomalies are observed and the range of such anomalies is generally greater for rocks of lower REE concentrations (or Sm_N).

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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

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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 or 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

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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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MAGMA EVOLUTION IN THE STILLWATER COMPLEX, MONTANA: REE, Sr, Nd, AND Os ISOTOPIC EVIDENCE FOR ARCHEAN LITHOSPHERIC INTERACTION;

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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 [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 subcontinental mantle* may have been a source for some of the parental 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 with ages of 3200 Ma to 2750 Ma [10]. The age of the Stillwater Complex is well constrained at 2701 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 by [13]) or troctolite-anorthosite zones (TAZ's by [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 that may have had ultramafic or boninitic major element affinities (U-type magma [5]). We have documented the nature, source, and mixing characteristics of these magmas at the Stillwater Complex by utilizing isotope dilution REE data for cumulus orthopyroxenes from the BS, UMS, and LBS to predict magma REE patterns. These trace element data have been coupled with wholerock Sr, Nd, and Os isotopic data for sulfide-bearing cumulates and samples of fine-grained sills and dikes.

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). These values are 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]. Calculated REE abundances in

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magmas parental to the 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 followed by 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 followed by plagioclase), such as leuconorite dikes of the Nain Complex [19] and modern high-Al tholeiites. 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.

Sm-Nd isotopic results: Isotopic data for previously analyzed minerals from a LBS (U-type) gabbronorite [22] defined a precise mineral isochron age of 2701 $\pm$ 8 Ma and an initial Nd isotopic composition (ε_{Nd}) of -2.0 (MSWD = 0.04). Previous wholerock Nd isotopic data [22] for predominantly U-type cumulates (one sample was from A-type, MBS anorthosite) suggested Nd isotopic homogeneity of the intrusion. However, Nd isotopic data for anorthosites and troctolites of this study lie above the mineral isochron (OBZ's in Fig. 1). Three sulfide-rich cumulates from the UMS collected near footwall hornfels and a chromitite collected in close proximity to an alaskite sill in the LBS lie below the isochron (Fig. 1). These four rocks were contaminated locally with Nd from less radiogenic Archean crustal rocks that had ε_{Nd} values at 2701 Ma of -3 to -6 [22]. If the Nd isotopic systematics of the rocks analysed in this study have not been disturbed following crystallization at 2701 Ma, these new data preclude formation of the complex from one isotopically homogeneous magma. If, however, the samples are grouped according to their A-type or U-type magmatic affinities, uncontaminated U-type cumulates have initial ε_{Nd} = -1.8 to -2.2 and A-type cumulates have initial ε_{Nd} = -1.5 to +0.55 (Fig. 1). Deviation of ε_{Nd} from +2 (similar to mantle-derived rocks of the Superior Province) to -2 could be accounted for by assimilation of ~ 35% by weight of a material similar to footwall hornfels (20 ppm Nd, ε_{Nd} = -5), 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), < 25% contamination is required. However, the Nd isotopic homogeneity observed in all but three 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 with exposed country rocks could not have occurred *in situ*. The first major change in ε_{Nd} occurs over a 4 ft interval at the base of TAZ I near the J-M Reef, from ε_{Nd} = -1.9 in U-type norite of the footwall ore zone to ε_{Nd} = -0.3 to -0.5 in A-type anorthosite/troctolite of the basal and main ore zones. The change in crystallization order, REE ratios, and ε_{Nd} across this stratigraphic boundary is consistent with the introduction of a geochemically-distinct magma into the chamber. The formation of the J-M Reef may, then, have been a direct result of mixing of magmas with contrasting major element, precious metal, and sulfur abundances [4], as well as contrasting trace element and isotopic composition.

Re-Os isotopic results: Wholerock isotopic data (Fig. 2) exhibit a very large spread in $^{187}Re/^{186}Os$ (0.511-997) and define an isochron with an age of 2708 $\pm$ 68 Ma (MSWD=1.02),

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using the ^{187}Re decay constant of 1.59 x 10^{-11} [24]. This suggests the Re-Os isotopic systematics for these portions of the Stillwater Complex have not been disturbed, unlike the Rb-Sr isotopic systematics. This large, apparently primary range in Re/Os has broad applications in the geochronology of mafic-ultramafic rocks and magmatic ore deposits. Samples from the A chromitite, the alaskite chromitite, and sulfides from the J-M Reef define an initial Os isotopic composition of 1.11, which is 23% enriched relative to a chondritic mantle reservoir (0.90) of the same age (Fig. 3). Analyses of samples from the G chromitite from higher in the UMS do not lie along this isochron but lie within analytical uncertainty of a 2700 Ma reference isochron with a chondritic initial isotopic composition (Fig. 3). This suggests Os isotopic heterogeneity existed in the Stillwater magma chamber below the J-M Reef, in contrast to the apparent initial Nd isotopic homogeneity in most U-type cumulates analyzed in this study. The elevated initial Os isotopic composition occurs in samples which also have $\varepsilon_{Nd} \sim 0$ and therefore likely have an A-type magmatic affinity. The Nd and Os isotopic data are consistent with either derivation of A-type magmas by partial melting of relatively young (<100 Ma) tholeiitic crust at high pressure [6,25] or contamination of mantle-derived tholeiitic magmas with older Archean rocks which had crustal residence times of ~500 Ma. Os isotopic systematics preclude derivation of A-type magmas from subcontinental mantle to which crustal components had been added [23]. However, U-type magmas, as represented by the chondritic Os isotopic compositions for G chromitites and the below chondritic Nd isotopic compositions ($\varepsilon_{Nd} = -1.8$ to -2.2) for rocks of the UMS and LBS, would be consistent with either the involvement of a subcontinental mantle source enriched in crustal components [23] or contamination of komatiitic magmas with older Archean crust. The extreme light-REE enrichment of U-type parental magmas (including footwall sills and dikes [6]) is more easily achieved by introduction of crustal materials into the mantle sources prior to melting than by in situ crustal contamination of a komatiitic parental magma. The REE, Nd, and Os isotopic data of this study, therefore, are more consistent with the involvement of two isotopically distinct sources for the Stillwater magmas, one tholeiitic and a second enriched mantle source.

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MAGMA EVOLUTION IN THE STILLWATER COMPLEX
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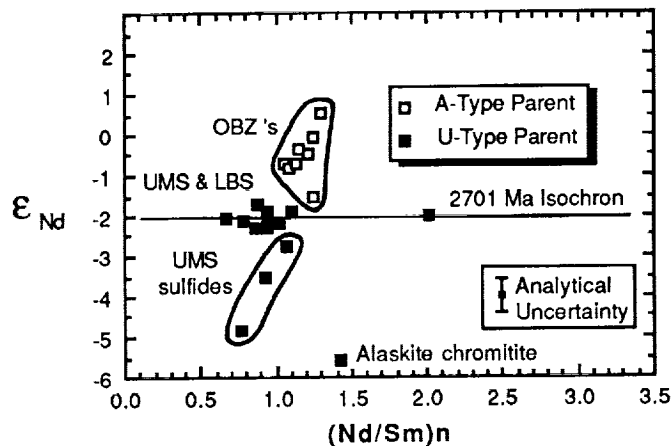
Figure 1. Initial Nd isotopic composition vs. chondrite-normalized Nd/Sm for wholerocks and minerals from the Stillwater Complex. Samples have been divided based on magmatic affinity. UMS = Ultramafic series, LBS = Lower Banded series, OBZ = Olivine-bearing zones. Mineral isochron of reference 22 is shown.
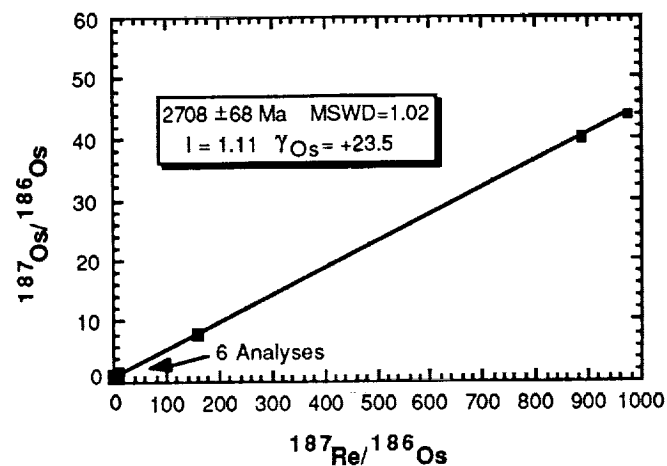
Figure 2. Re-Os isochron diagram for samples from the Stillwater Complex, Montana. Model 1 regression parameters were calculated using analyses of eight PGE-enriched wholerock samples. Errors at the 95% confidence level lie entirely within each symbol.
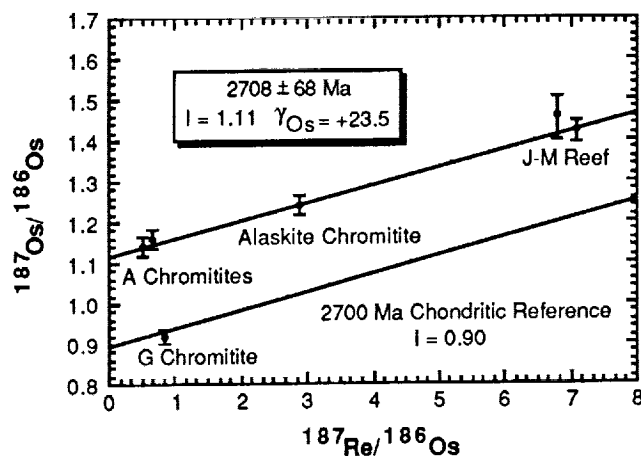
Figure 3. Re-Os isochron diagram for six samples with $^{187}Re/^{186}Os < 8$. The one analysis of the G chromitite was not included in the regression. Error bars are 95% confidence intervals for $^{187}Os/^{186}Os$.

ARCHEAN SEDIMENTARY ROCKS AND THE ARCHEAN MANTLE;   Scott M.
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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 plot 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 ($Gd_N/Yb_N<2.0$).

ARCHEAN SEDIMENTARY ROCKS

McLennan, S. M.

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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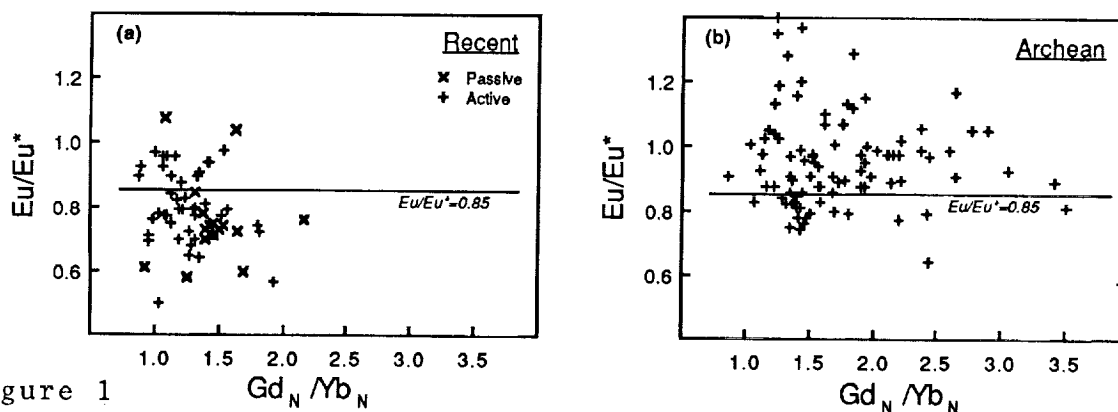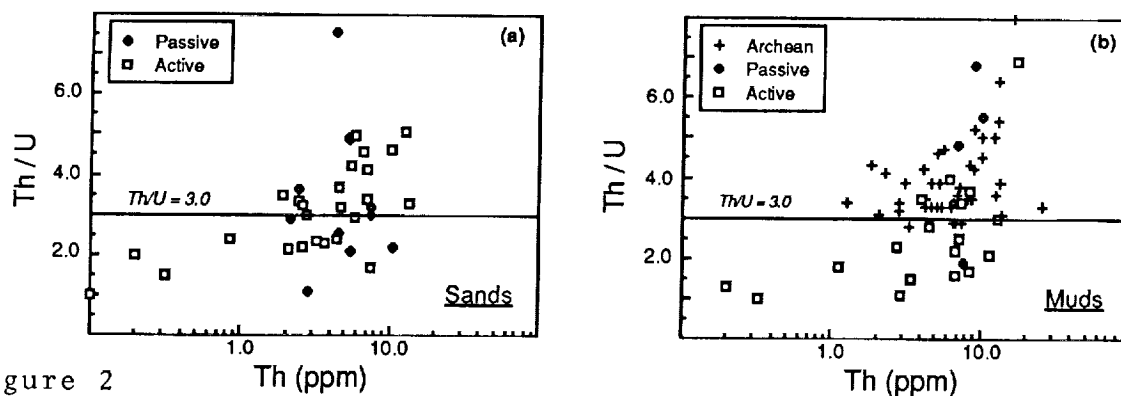

Figure 1

Figure 2

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

Paul Morgan, Geology Department, Box 6030, Northern Arizona University, Flagstaff, AZ 86011-6030, USA.

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:

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

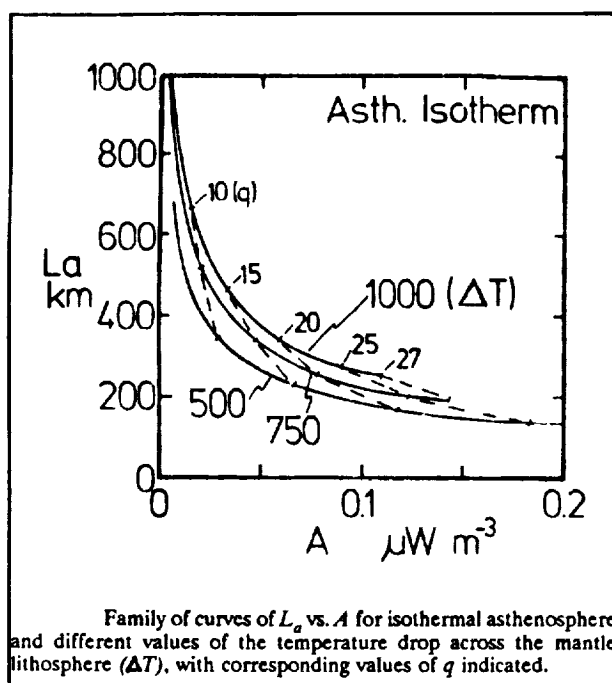Both models yield suitable geotherms with reasonable choices of parameters, as shown in Figures 1-3,

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.

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.

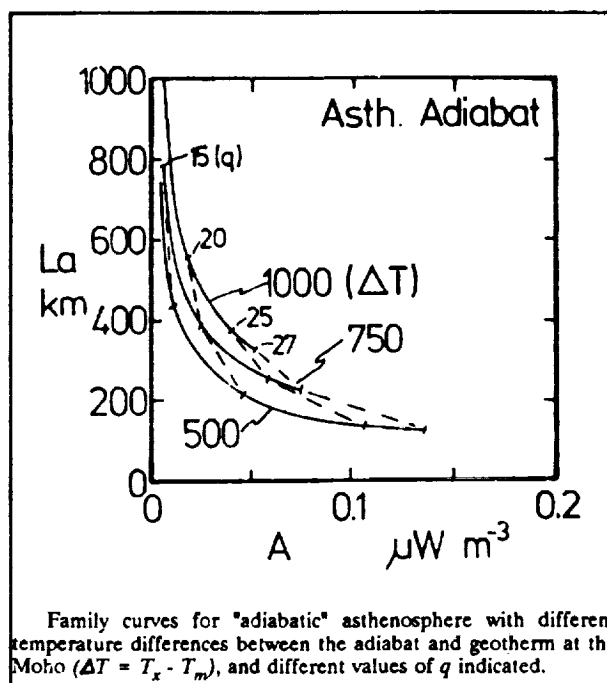**Figure 1:** Isothermal Asthenosphere L_a vs. A.

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
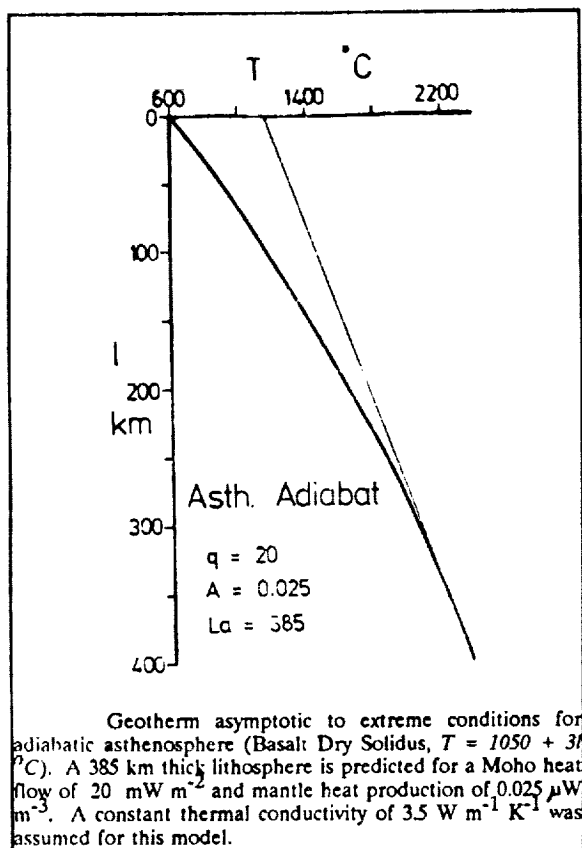
DIAMOND-KOMATIITE PARADOX
P. Morgan

Geotherm asymptotic to extreme conditions for adiabatic asthenosphere (Basalt Dry Solidus, $T = 1050 + 3P$°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 μW 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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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 heterogeneties 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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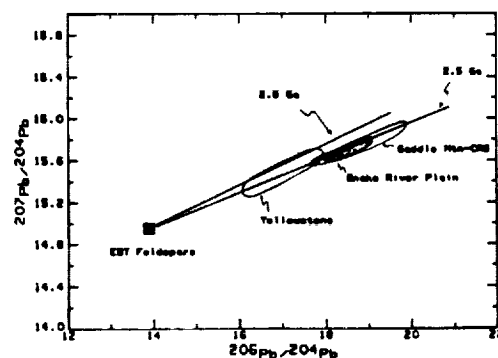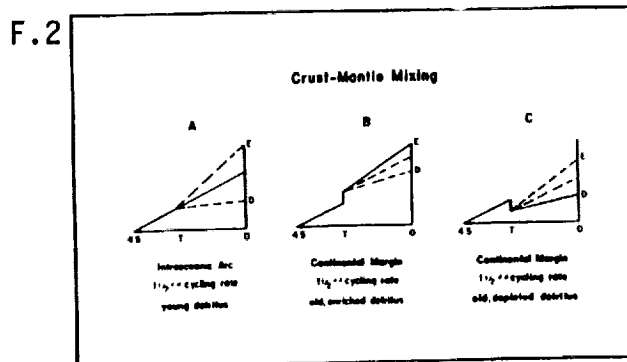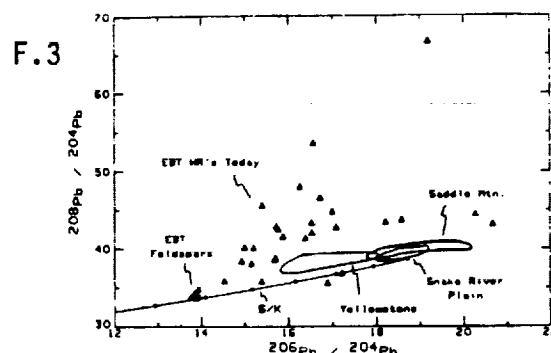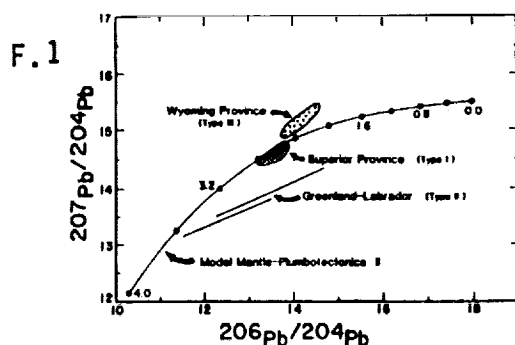
EVIDENCE FOR A DIFFERENTIATED MANTLE AND PLATE TECTONICS DURING THE LATE ARCHEAN DEDUCED FROM ECLOGITE XENOLITHS IN THE BELLSBANK KIMBERLITE.

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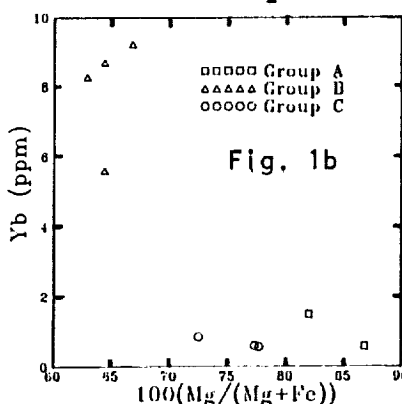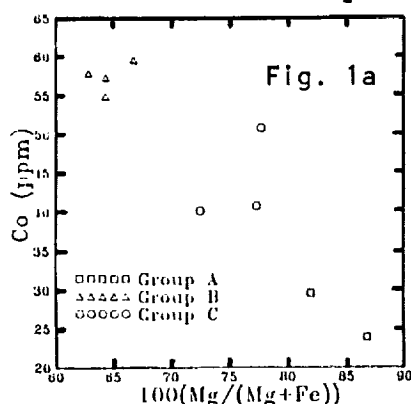
A suite of eclogites from the Bellsbank kimberlite (DeBruyn and Martin Mine) were studied in order to determine their petrogenesis. Three groups have been defined on the basis of major and trace elements, isotopes, and mineral chemistry. Ultrapure mineral separates were prepared for isotope and REE analyses.

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

Group B: moderate jadeite moles in cpx; Fe-rich garnets; extremely high ϵ Nd (+120 to 235), LREE-depleted cpxs; low $\delta^{18}O$ (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.

Group C: high jadeite moles in cpx; CaO-rich garnets; positive Eu_{18} anomaly in both garnet and cpx REE; Al_2O_3-rich whole-rock composition; low $\delta^{18}O$ (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

Fig. 1a

Fig. 1b

□□□□□ Group A
△△△△△ Group B
○○○○○ Group C

(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.

Fig. 2
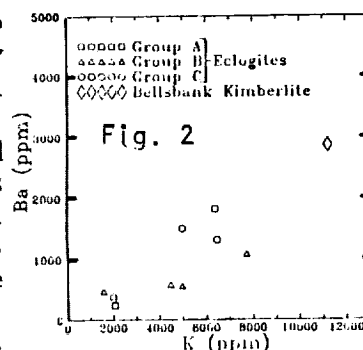
        Group A eclogites are defined as mantle cumulates
because of: their high MG#; minor amounts of orthopyroxene and olivine are
present; mantle oxygen and Sr isotope values; and the fact that Group A
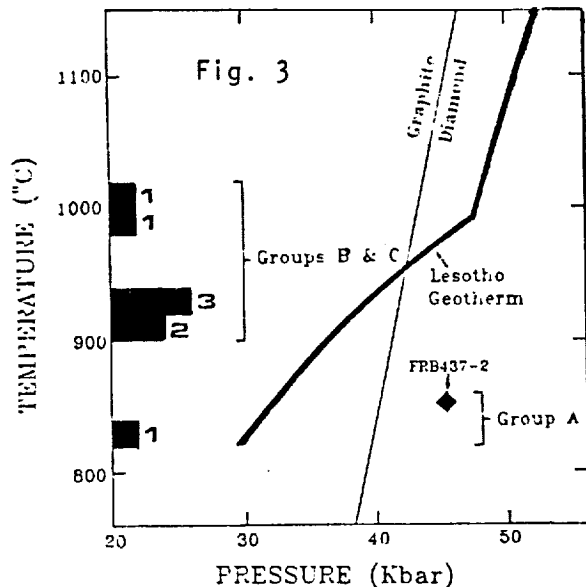eclogites are the only group which exhibit garnet/cpx mineral Kd's consistent
with fractionation from a basaltic magma (e.g., [17]). Group B eclogites have
compositions consistent with the seawater-altered basaltic portion of oceanic
crust (LREE-depleted signature; low $\delta^{18}O$; radiogenic $^{87}Sr/^{86}Sr$). 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
($\cong$ 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

Fig. 3

(Figure: plot of TEMPERATURE (°C) on vertical axis from 800 to 1100, versus PRESSURE (Kbar) from 20 to 50 on horizontal axis. Curves labeled Graphite/Diamond, Lesotho Geotherm, with bars labeled Groups B & C, Group A, and point FRB437-2.)

PRESSURE (Kbar)

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 ε 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

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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)

(1) E. J. Krogstad et. al., 1988, J. Geol. Soc. India, 31, 60-63
(2) D. K. Mukhopadhyay, 1988, ibid, 94-97
(3) S. Balakrishnan et. al., 1988, ibid, 31, 9-11
(4) S. Balakrishnan et. al., in prep.
(5) V. Rajamani et. al., 1985, J. Petrol. 26, 92-123
(6) S. Balakrishnan et. al., 1989, this volume
(7) V. Rajamani et. al., 1989, J. Geol., in press.
(8) S. Balakrishnan and V. Rajamani, 1987, J. Geol., 95, 219-240
(9) E. J. Krogstad et. al., in prep.

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 $50\text{-}100^{\circ}\text{C}$ 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.

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

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The isotopic composition of garnet inclusion in diamonds (1) provides direct evidence for the development of a thick, major element-depleted but trace element enriched (2) lithospheric mantle keel beneath the Kapvaal craton prior to 3.0 Ga. In contrast, there is little isotopic evidence for the antiquity of this depletion in the more abundant garnet lherzolite xenoliths from S. African kimberlites, all of which have been affected by later metasomatic enrichment. It has been known for some time, however, that these xenoliths provide a mantle sample that is distinct in terms of major element composition from other sources of mantle rocks (3). Notably, they are strongly depleted in FeO (an average of 6.5% FeO compared with 8% FeO in spinel lherzolites) in addition to having the usual CaO, Al_2O_3 and TiO_2 depletions commonly observed in other lherzolite suites. Such variations cannot be interpreted in terms of basalt extraction since primary basaltic magmas are too poor in FeO to account for this iron depletion. Instead it is necessary to invoke depletion through komatiite extraction since these are the only known primary mantle melts with sufficiently high FeO_{Tot}. However, since komatiite production was largely restricted to Archaean times, this implies that the Fe-depleted garnet lherzolites were also produced during the Archaean, a conclusion supported by Os isotope data presented in this volume (4). Furthermore, the frequent occurrence of garnet lherzolite xenoliths in Cretaceous kimberlites throughout the Kapvaal craton implies that the Archaean lithospheric keel was developed on a regional scale, is still largely present beneath southern Africa and may have a controlling influence on the stabilisation of the craton at ~3.0 Ga.

Given this model of crust-mantle structure, it is surprising that the earliest craton cover sequences such as the Dominion Group (DG) and the later Ventersdorp Supergroup, contain voluminous basaltic lavas of mantle origin. The DG 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 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 from borehole samples on the basis of Ti, V, and Zr 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 (5) and continental flood basalts (6) 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, an alternative interpretation 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 (7, 8). 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 (Fig. 1) 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 Nd/Y vs. Nd/Nb, (Fig. 2) the DG basalts define a flat-lying trend with constant Nd/Y and variable Nd/Nb and while the Nd/Y values are intermediate between those for crustal melts (as exemplified by the porphyries) and magmas derived from a chondritic or depleted mantle source, the Nd/Nb ratios are higher than both. Thus the TE abundances preclude an origin involving mixing between komatiite and crustal melts and are interpreted to reflect trace element enrichment processes operating in the basalt source region.

Key element ratios in the DG basalts, notably Ti/Yb and Ta/Yb are close to chondritic values while Al/Ti and Ti/V ratios are similar to those in the Onverwacht komatiites. Since none of these elements are mobilised by modern subduction-related processes, it is suggested that their relative abundances reflect the fertile nature of the DG source prior to trace element enrichment. In addition, Nd isotope ratios corrected to 3.0 Ga, give ϵ_{Nd} of 0 ± 0.5 with one sample at +1.2. They imply chondritic or slightly depleted time integrated REE characteristics, and are distinct from the diamond inclusion evolution curves which, at 3.0 Ga, lie between ϵ_{Nd} values of -2 to -3.8, reflecting a time-integrated LREE enrichment.

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Thus the trace element and isotope characteristics of the DG basalts cannot be related to the strongly depleted but possibly trace element enriched early Archaean lithospheric mantle and clearly demonstrate the marked chemical heterogeneity in the sub-cratonic mantle at 3.0 Ga. This observation implies either that komatiite extraction was not a regional phenomenon or that the D.G. source was not related to the lithospheric mantle. The former model seems unlikely because of the craton-wide distribution of iron-depleted garnet lherzolites. The preferred model involves intrusion of the lithosphere by a fertile diapir of asthenospheric material in response to extension. This probably took place in a supra-subduction zone (possibly back-arc) enrivonment as suggested by the trace element characteristics of both the D.G. and later Ventersdorp volcanics and is consistent with the recent model of Burke et al., (9) which interprets the Witwatersrand basin as developing in response to continental collision at a convergent plate boundary to the north.

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Fig. 1   Plot of TiO_2 vs V for the Dominion Group basalts and porphyries emphasising the difference in Ti/V between the two and the similarity between the basalts and Barberton (Onverwacht) komatiites. The cross denote the average compositon of the Archaean Upper Crust.

Fig. 2   Plot of Nd/Y vs Nd/Nb for the Dominion Group basalts (filled dots) compared with a mixing line between average porphyry and a model komatiite with 10x chondritic abundances of Nd, Nb and Y. The arrow marked 40% illustrates the effect of 40% clinopyroxene fractionation, DM = depleted mantle and AUC, Archaean Upper Crust. Variations in these elemental ratios in the D.G. basalts cannot be related to interaction between crust and komatiite.

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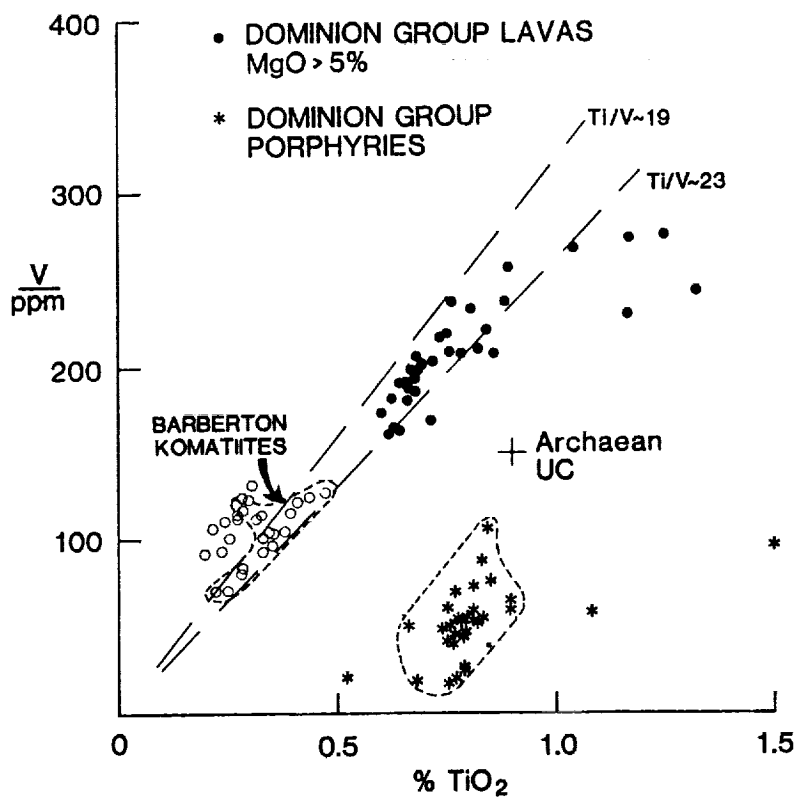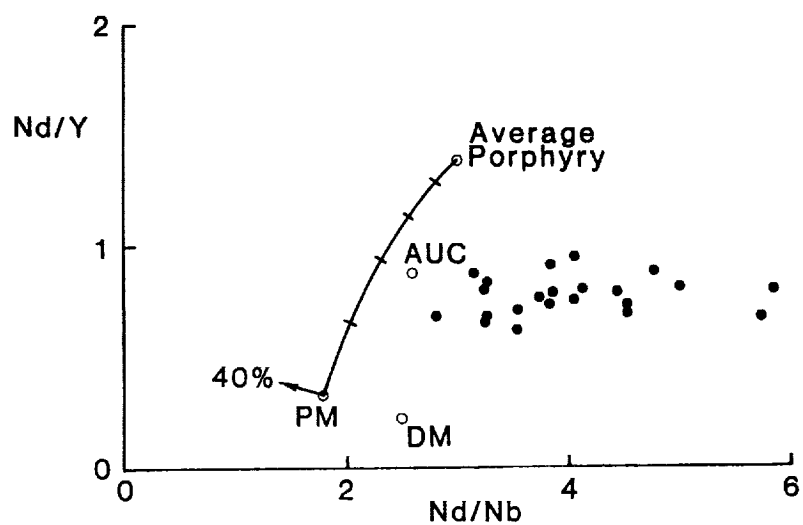N. W. Rogers and J. S. Marsh

Figure 1

Figure 2

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

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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

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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 re-cycled 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 con-vection 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 es-pecially 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]

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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 $\sim$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 μ_1 = 8.3; Baltic, Pilbara, Yilgarn Craton's μ_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.

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(FIG. 1)

(FIG. 2)

(FIG. 3)
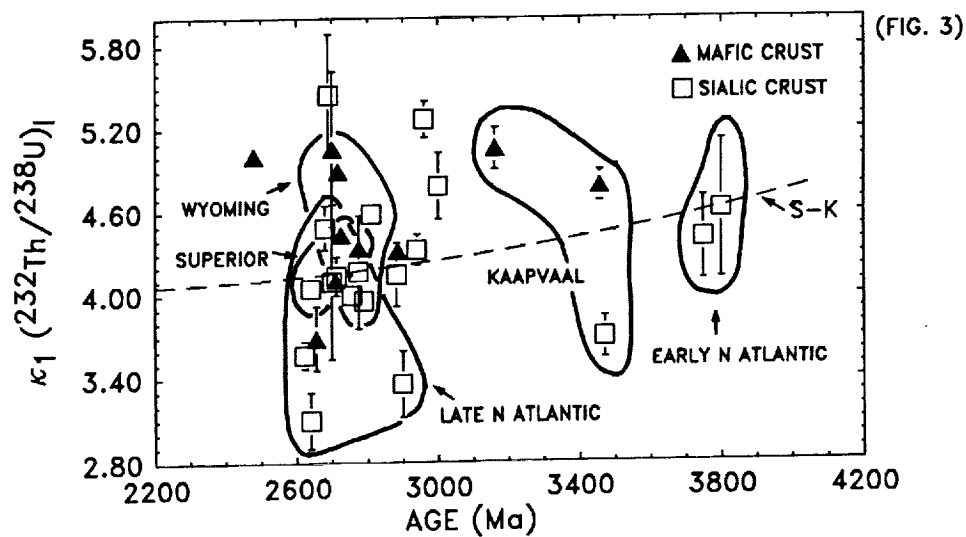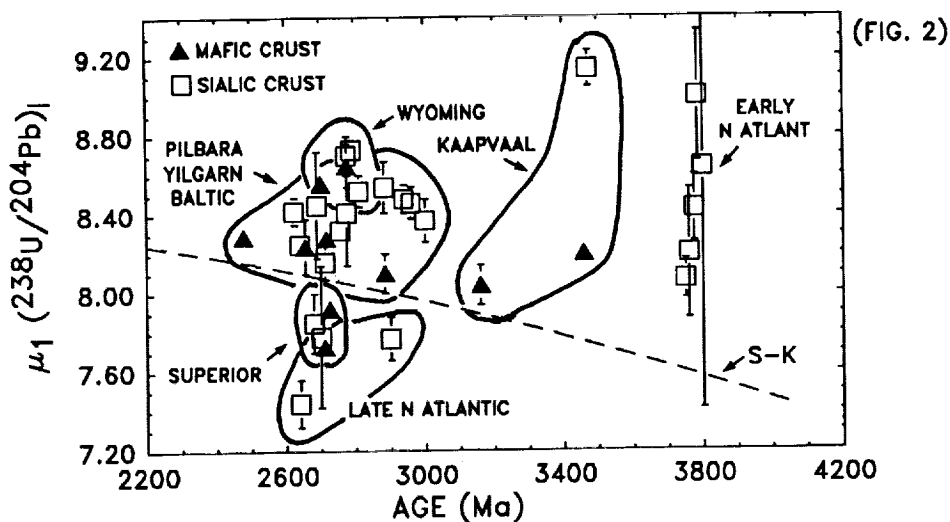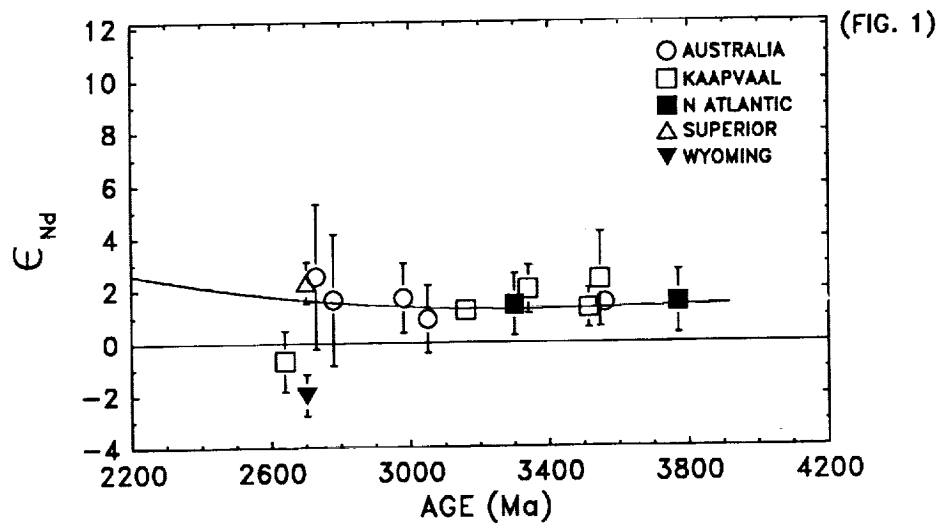
ABUNDANCES OF AS, SB, W, AND MO IN EARLY ARCHEAN AND PHANEROZOIC MANTLE-DERIVED AND CONTINENTAL CRUSTAL ROCKS;

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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

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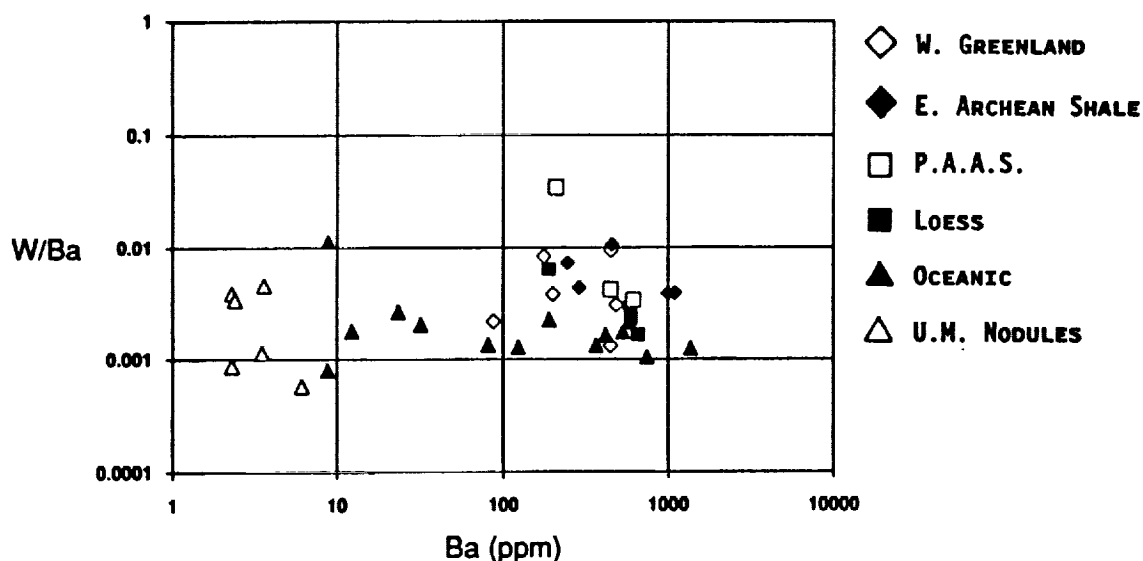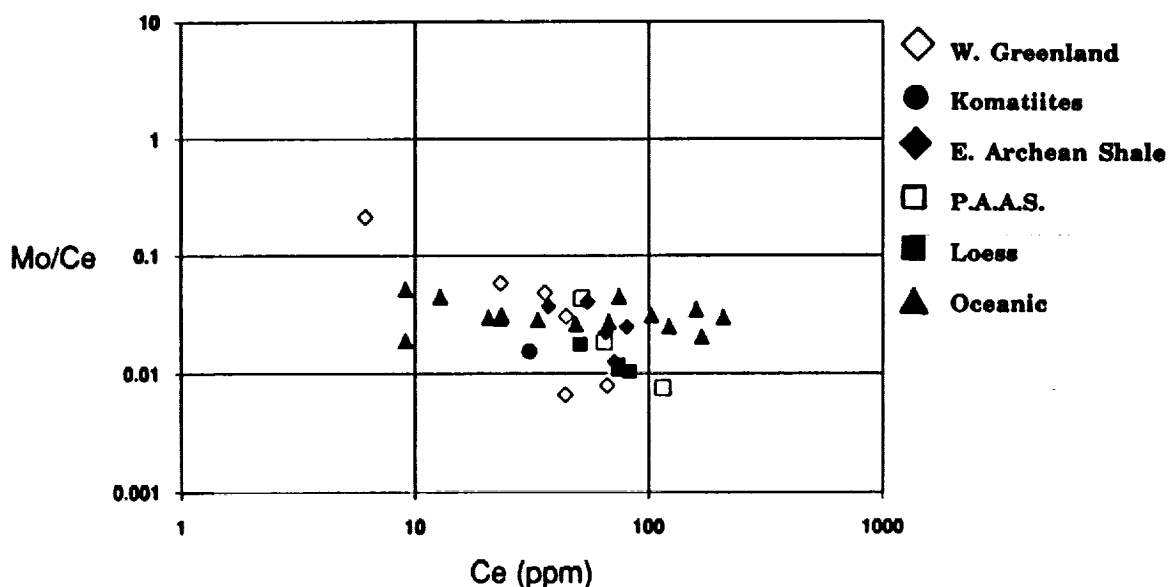
Figs. 1 & 2. Data for Mo and W from this study. Nodule data from refs. 13, 14 and 15.

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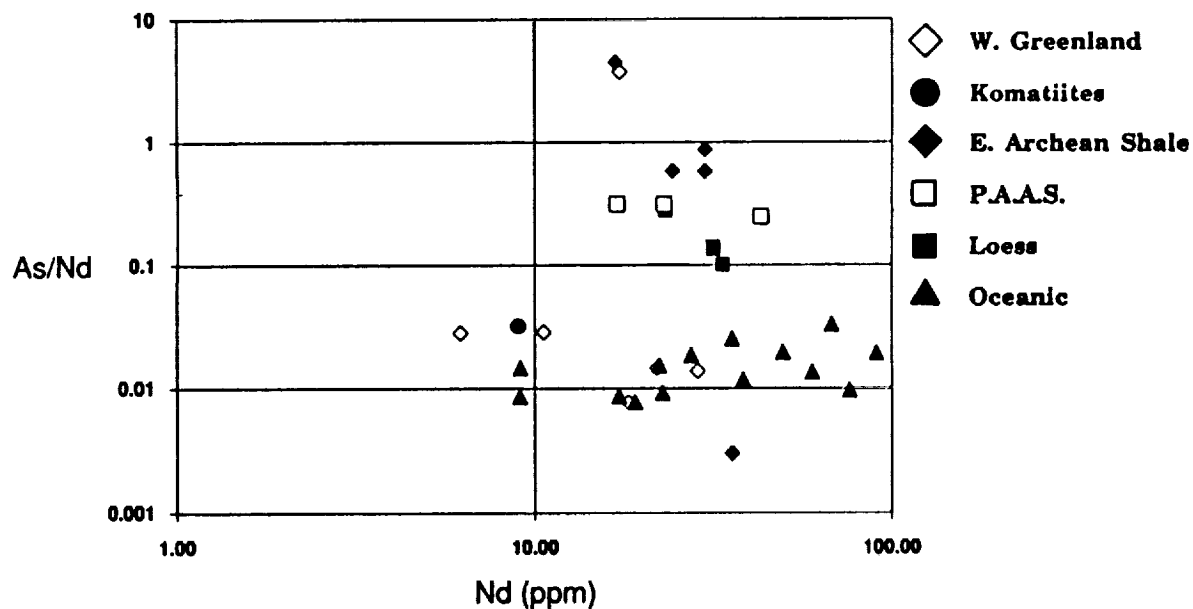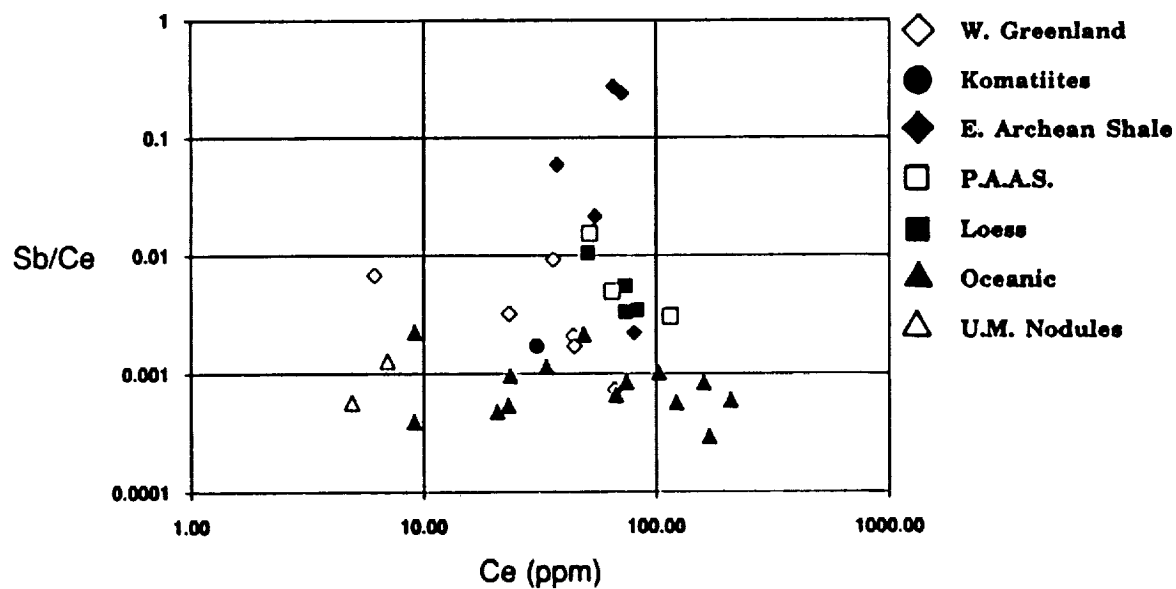
Figs. 3 & 4. Data for Sb and As from this study. Nodule data from refs. 13, 14, and 15.

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

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With the exception of the garnet-amphibolite and a Mg-rich
basalt, the major and trace element compositions of the tholei-
tes are close to those of other Archean tholeiites. The REE sys-
tematics 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 komatiites, 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 koma-
tiites. These rocks were probably derived from partial melting
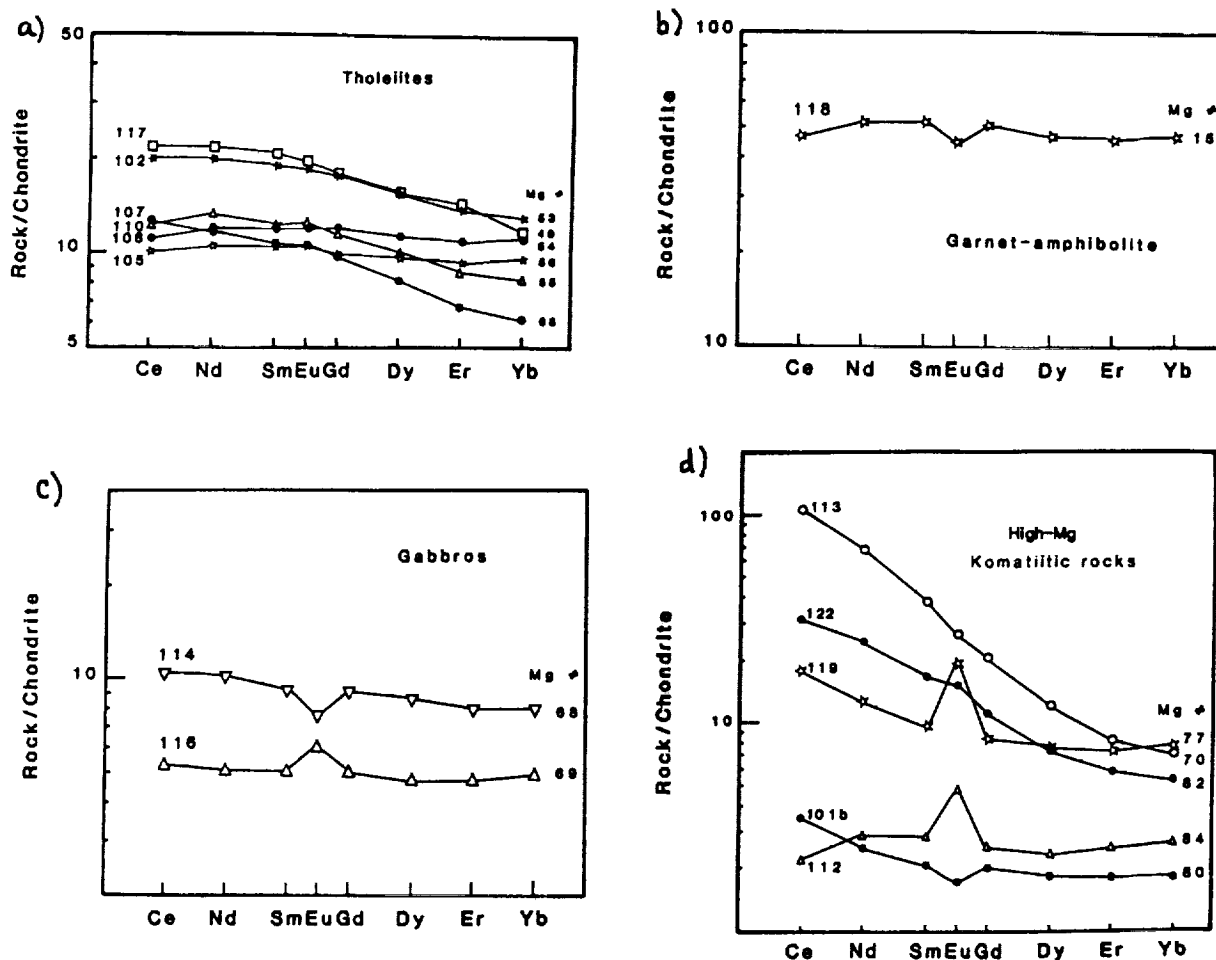of a garnet-bearing source.

Figure 1.

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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 during 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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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). Comparable growth rates are inferred only for the source of some Lunar basalts which have $\varepsilon_{Nd}(3200Ma)$ 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

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for tholeiites and komatiites, indicates some compositional
layering of the terrestrial mantle during the Early Archaean.
Partitioning data for high pressure mineral phases (7) 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 $\mathcal{E}_{Nd}$
+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 (8), is
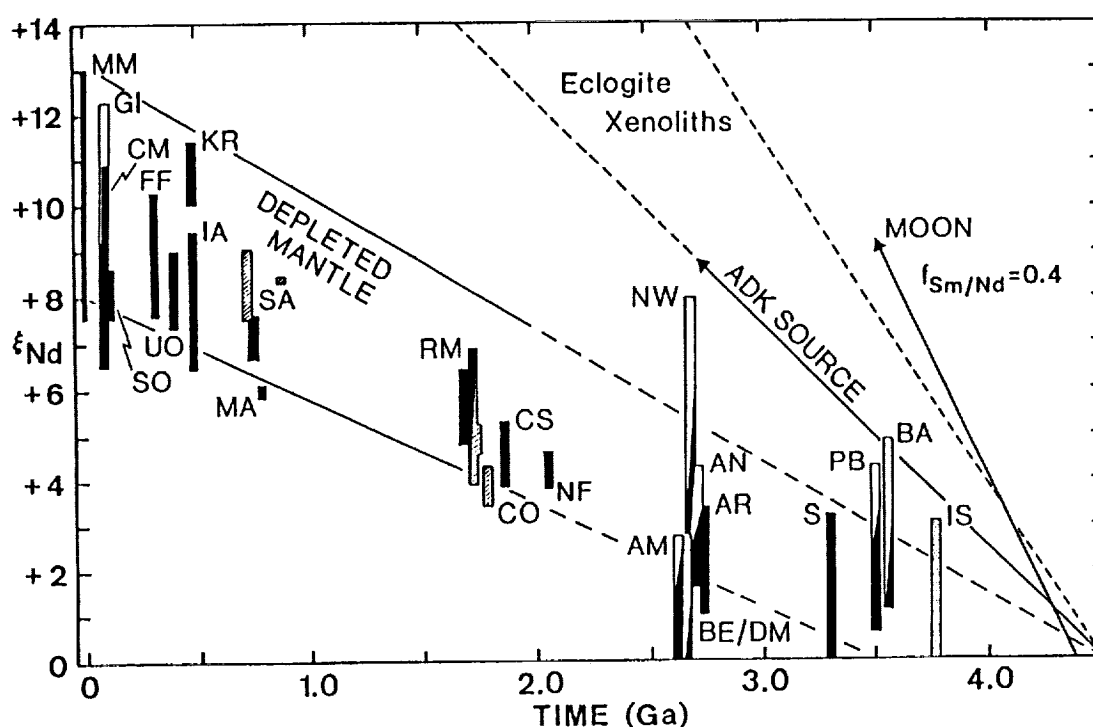considered more plausible.

Figure 1. Variation in $\mathcal{E}_{Nd}$ 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.

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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 $\varepsilon_{Nd}(T)$ (9). 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).
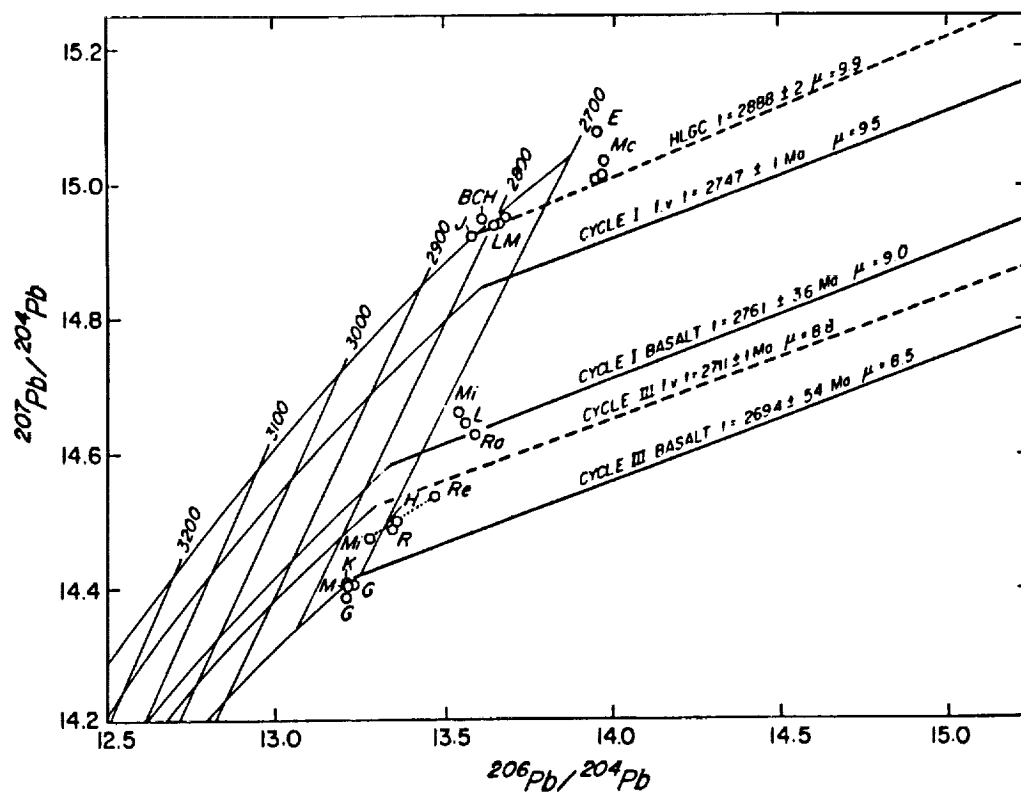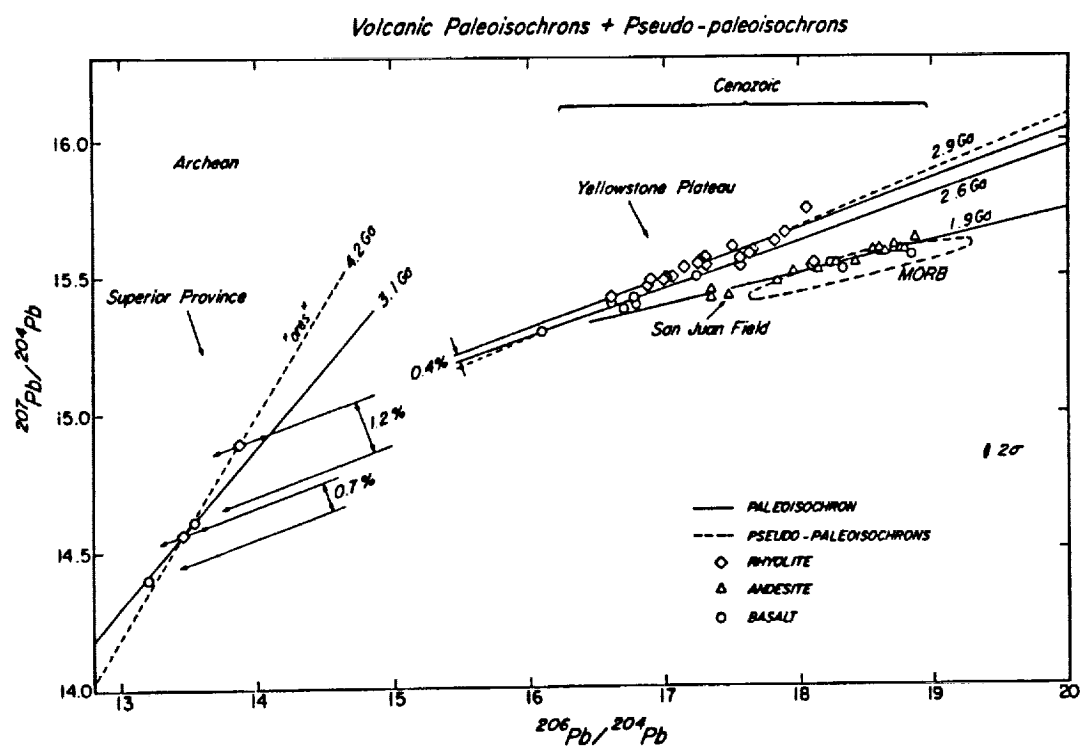
Fig. 1

Volcanic Paleoisochrons + Pseudo-paleoisochrons

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 with 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 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, thus 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 lamprophyres, but, in general, the lamprophyres cannot be parental to the sanukitoids due to their similar or lower Mg#'s, and MgO, Ni, and Cr contents. The sanukitoids cannot be explained by crustal contamination of komatiitic melts (5) because crustal contaminants would have had lower LILE contents than the sanukitoids.

Modelling of the geochemical data set for the sanukitoids in southwestern Superior Province supports their mantle origin. Such an origin is consistent with their primitive FeO-MgO systematics, their high transition metal contents, experimental melting studies upon high-Mg andesites (3) and peridotite at low pressures (6), 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 from 7.4 to 8.0 (7, 8, 9).

C - 2

The extremely high LILE contents and steeply fractionated REE patterns of the sanukitoids (Ce_n/Yb_n = 7 - 40) relative to primitive mantle are consistent with melting of LILE-enriched sources. Modelling of the REE's suggests that regardless of the residue mineralogy, low extents of melting of a source with chondritic REE ratios cannot explain the LREE enrichment of the sanukitoids. A LREE-enriched mantle source region is required. The HREE depletion for some of the sanukitoids are also difficult to explain by melting of a source with chondritic HREE ratios leaving garnet in the residue. The data seem to require a mantle source which was both LREE-enriched and which had variable HREE depletion. Thus, although garnet cannot be ruled out entirely by the geochemical data, the source for some of the sanukitoids must have had a fractionated REE pattern even if garnet were present. Since the experimental data suggest that garnet would not be in the residue at pressures less than 15 kbar (10), the source probably had a REE pattern subparallel to that of the sanukitoids.

The variation of about 2 cation mole % FeO in the sanukitoids may reflect heterogeneities in the Mg# of the mantle source region. Such variation cannot be a result of fractional crystallization of a common parental magma. An interesting observation is that the sanukitoids with lowest FeO content are also those with the steepest REE patterns. This relationship may indicate that the part of the source with the highest Mg# (yielding the sanukitoids with lowest FeO) was also that part of the source with the greatest LREE enrichment. Such a relationship is similar to that of metasomatised mantle nodule suites (e.g. 11). The negative correlation between FeO and LREE enrichment is opposite to that predicted for metasomatism of the source by basaltic melts. One possibility is that fluids or siliceous melts enriched a mantle source which was already heterogeneous in its Mg#, perhaps a result of previous melt extraction or addition.

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 parental magmas. 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 of LILE enriched, mafic to ultramafic sources. An intriguing question is whether LILE enrichment is necessary in the source regions of other rocks in the crust, and thus a requirement of crustal stabilization.

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Re-Os ISOTOPIC CONSTRAINTS ON THE CHEMICAL EVOLUTION OF THE ARCHEAN MANTLE;

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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

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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]).
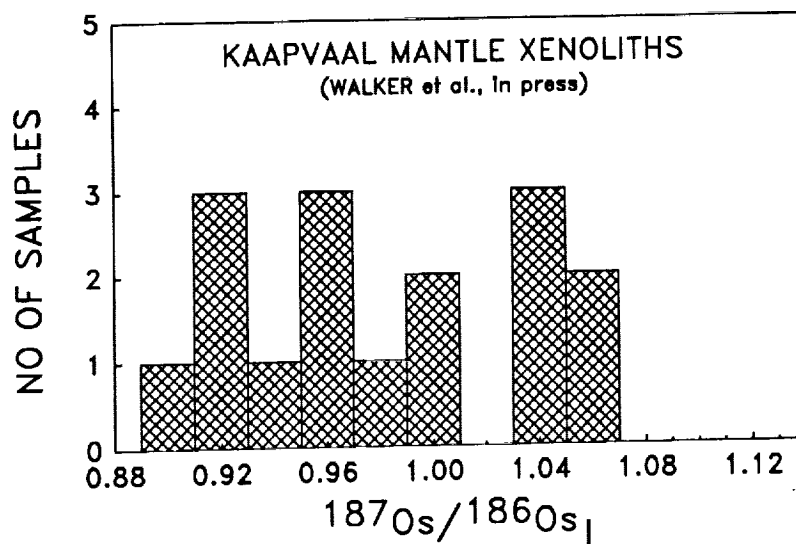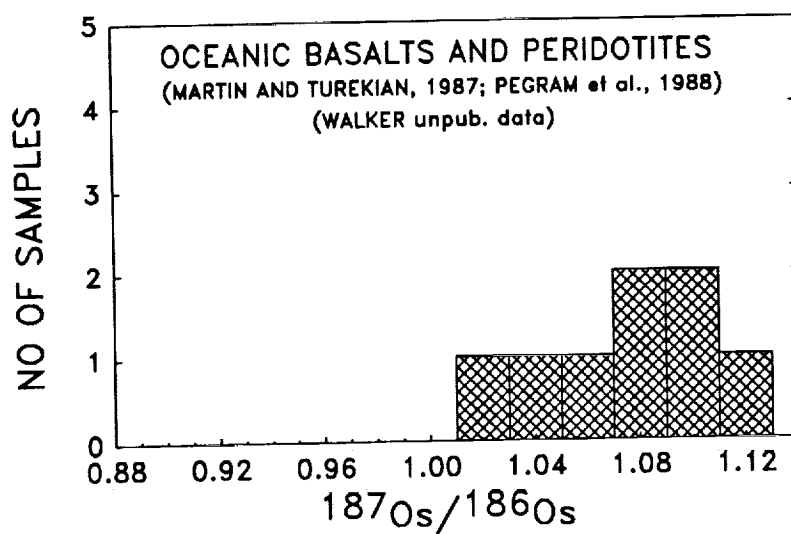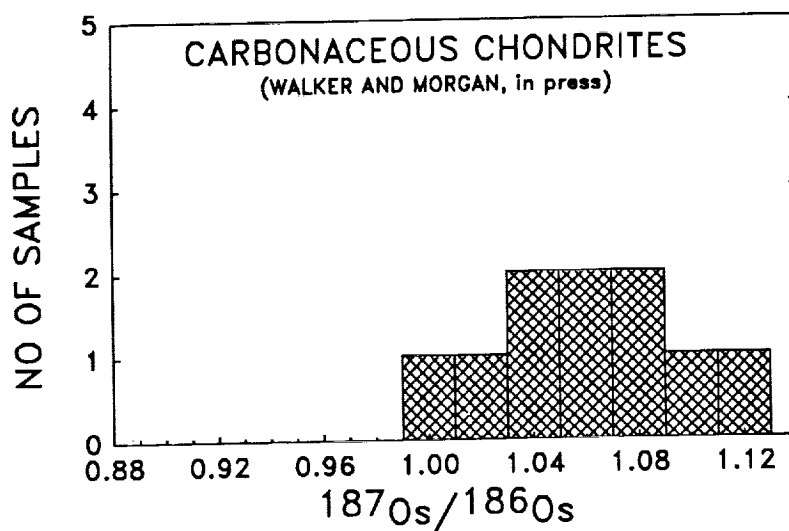
Deviations from "chondritic" Re-Os evolution in portions of the mantle are now documented [11,16]. During mantle melting, Re is an incompatible element and Os is compatible. Thus, melting events that produce crust from the mantle lead to major depletions of Re relative to Os in the resulting mantle residue. 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.

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CARBONACEOUS CHONDRITES
(WALKER AND MORGAN, in press)

OCEANIC BASALTS AND PERIDOTITES
(MARTIN AND TUREKIAN, 1987; PEGRAM et al., 1988)
(WALKER unpub. data)

KAAPVAAL MANTLE XENOLITHS
(WALKER et al., in press)

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