Geoscience Canada

Mantle Studies

John N. Ludden and Don Francis

Volume 20, Number 3, September 1993

URI: https://id.erudit.org/iderudit/geocan20_3icg03

See table of contents

Publisher(s)

The Geological Association of Canada

ISSN

0315-0941 (print)
1911-4850 (digital)

Explore this journal

Cite this article

Ludden, J. N. & Francis, D. (1993). Mantle Studies. *Geoscience Canada*, *20*(3), 95–100.

Article abstract

Convection in the Earth's mantle provides the driving force for plate-tectonic processes and the heat source for fluid transport in the Earth's crust. Understanding the relationships between mantle composition and convection and its interaction with continental and oceanic crust provide a major challenge to modern petrologists and geochemists. This challenge can only be re-solved by indirect studies, such as tomography and geochemical inversionson mantle-derived products, or by direct studies on rarely sampled upper mantle products in mantle xenolith suites and the barely accessible in situ outcrops on mantle in oceanic fracture zones.

Mantle Studies

John N. Ludden [1]
Départment de Géologie
Université de Montréal
Box 6128 Station A
Montreal, Quebec H3C 3J7

Don Francis [1]
Department of Earth and
Planetary Sciences
McGill University
3450 University Avenue
Montreal, Quebec H3A 2A7

ABSTRACT

Convection in the Earth's mantle provides the driving force for plate-tectonic processes and the heat source for fluid transport in the Earth's crust. Understanding the relationships between mantle composition and convection and its interaction with continental and oceanic crust provide a major challenge to modern petrologists and geochemists. This challenge can only be resolved by indirect studies, such as tomography and geochemical inversions on mantle-derived products, or by direct studies on rarely sampled upper mantle products in mantle xenolith suites and the barely accessible *in situ* outcrops on mantle in oceanic fracture zones.

RÉSUMÉ

La convection qui a lieu dans le manteau de la Terre assure la force motrice derrière la tectonique de plaques et constitue la source de chaleur nécessaire aux déplacements se produisant dans la croûte terrestre. Comprendre les relations qui existent entre la composition du manteau et la convection, ainsi que son interaction avec la croûte continentale ou océanique constitue un défi de taille pour les pétrographes et les géochimistes. Ce défi ne peut être relevé que par des études indirectes telles la tomographie et des interprétations géochimiques à partir d'études sur des échantillons issus de processus mantéliques, ou par des études directes sur de rares échantillons issus du manteau supérieur provenant de suites de xénolites du manteau ainsi que d'échantillons difficilement accessibles d'affleurements *in situ* du manteau dans des zones de fractures.

INTRODUCTION

The ultimate challenge to many research scientists is to understand something that they cannot feel or see: the ocean deeps, distant space, the interior of the atom, and, for geoscientists, the Earth's core and mantle. The mantle is hottest at the bottom, but, probably, the most ductile part of the mantle is at the top where the pressure is the least. It is now accepted that the soft upper layer of the mantle, the asthenosphere, convects and transports the rigid lithosphere which, in turn, carries the continents. It is only through seismic imaging (tomography) and gravity and heat flow models that we can infer the structure and the convective processes in the mantle below the asthenosphere. Laboratory experiments using diamond anvil apparatus have allowed geologists to synthesize probable mantle materials and define phase changes in crystalline silicates of iron and magnesium, which indicate that the mantle is layered in a crude sense. In special cases, however, the mantle can be directly sampled: asthenospheric mantle may outcrop in deep oceanic fracture zones, enigmatic fragments of lithospheric mantle are exposed as tectonic slices in ophiolites and alpine thrust sequences, and mantle xenoliths are brought to the surface by alkaline magmas in both continental and oceanic settings.

The mantle plays a pivotal role in the Earth's evolution. The Earth's crust has formed by solidification of mantle-derived ultramafic and mafic magma. However, the andesitic nature of continental crust requires that accreted mafic crust is later reworked, a result of heat provided by mantle-derived magma and due to partial melting of crust in response to tectonic events. It is there-

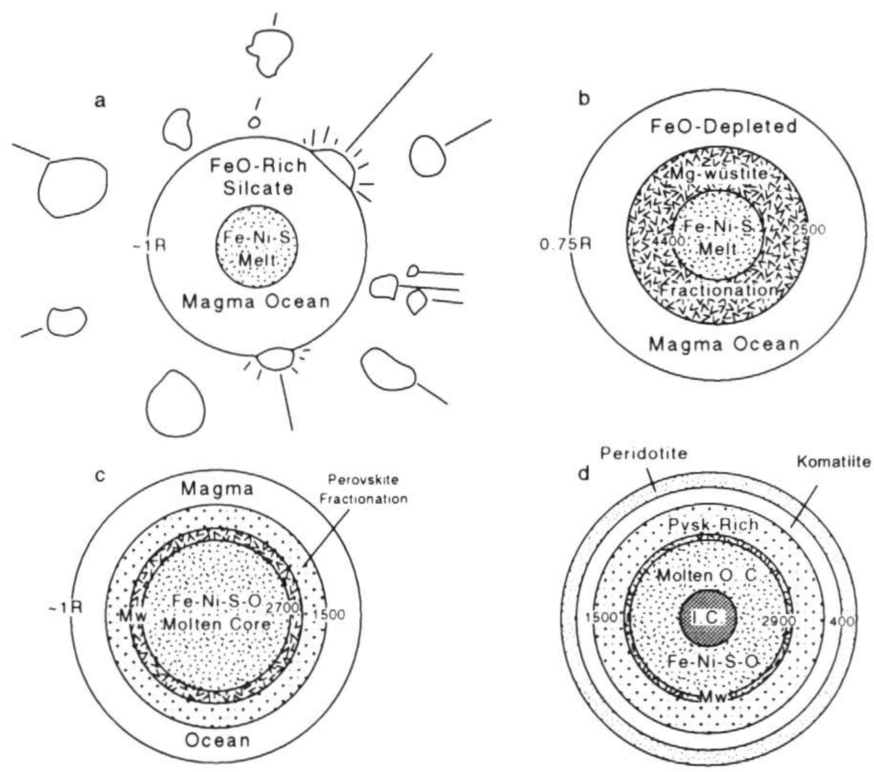


Figure 1 *Highly idealized model for early Earth differentiation from Agee (1990), showing crystallization and segregation of Mg-wustite and perovskite, with the development of a magma ocean and its subsequent differentiation to peridotite and komatiite.*

[1] *GEOSONDE, Terrestrial Magmatism Research Project*

fore increasingly relevant to consider the mantle and the crust as a holistic system in which magmas react with both the mantle and the crust, transferring heat into the crust, driving hydrothermal convection, and inducing regional metamorphism and anatexis.

EARLY EARTH EVOLUTION

One of the most challenging aspects of mantle studies, which is particularly relevant to Canadian geoscience, is the early evolution of Earth. Canada is the home of the oldest dated continental rock on Earth (Bowring *et al.*, 1989) and its landmass includes some of the largest Archean continental terranes on Earth. Although isotopic data indicate that Earth's differentiation had occurred by 4000 Ma, we know little about the process that formed the Earth's core, mantle and crust.

Carbonaceous chondrite meteorites are widely accepted as indicators of the primary composition of the Earth prior to its differentiation (Fig. 1). Multi anvil experiments on carbonaceous chondrites at 24-26.6 GPa by Agee (1990) indicate that initial FeO-rich magnesiowustite fractionation in the early molten Earth may have depleted the initial FeO content of the primitive chondritic mantle and "fed" a growing core (Fig. 1). Mg-perovskite would have crystallized as a later phase and accumulated at its level of neutral buoyancy (approximately 1500 km). A komatiite magma ocean and crystalline phases such as olivine, clinoproxene and majorite (beta-phase) would reside above these depths.

These experiments are the key to understanding the early evolution of the Earth. The role of magnesiowustite and Mg-perovskite fractionation in early differentiation of the Earth, and the role of late meteorite bombardment in the destruction of early formed crust and in controlling the siderophile element in the upper mantle remain important areas of future research.

A knowledge of trace element partitioning during these early stages of Earth evolution is fundamental in constraining isotopic models of mantle differentiation. It is now well established that the mantle had undergone isotopic differentiation by the Late Archean. However, there are indications that mantle reservoirs had time-integrated isotopic depletions, which represent a mantle that was far more depleted than that now sampled by oceanic volcanic rocks (McCulloch and Bennett, 1992; Smith and Ludden, 1989). These arguments, however, are based on ^{143}Nd/^{144}Nd-isotope studies of rocks that have been metamorphosed. Small variations in the ratio of ^{147}Sm/^{144}Nd due to alteration and metamorphism may have led to incorrect intial ^{143}Nd/^{144}Nd values and, thus, false conclusions concerning the differentiation of the early-Earth mantle. The short half-life of ^{142}Nd (103 Ma), which is produced by the decay of ^{146}Sm, offers a powerful new isotopic tool with which geochemists can model the early differentiation of the Earth. Positive ε^{142}Nd anomalies relative to chondritic values would have been produced in the first 500 m.y. of Earth's evolution had extreme mantle differentiation taken place in the earliest part of Earth's history (Fig. 2). The search for a ^{142}Nd anomaly has yielded contradictory results on similar materials (Goldstein and Galer, 1992; Harper and Jacobsen, 1992; McCulloch and Bennett, 1992). Nevertheless, this application of Nd-isotope studies, if successful in proving the existence of depleted mantle prior to 4000 Ma, will provide an important tool for understanding not only mantle differentiation, but also the stabilization and formation of the Earth's continental crust.

MAJOR IGNEOUS EVENTS

In its recent past (*i.e.*, in the Phanerozoic geological record), the Earth has produced major outpourings of mafic magma associated with mantle-plumes. For example, the Cretaceous-age Deccan Traps and Reunion hot

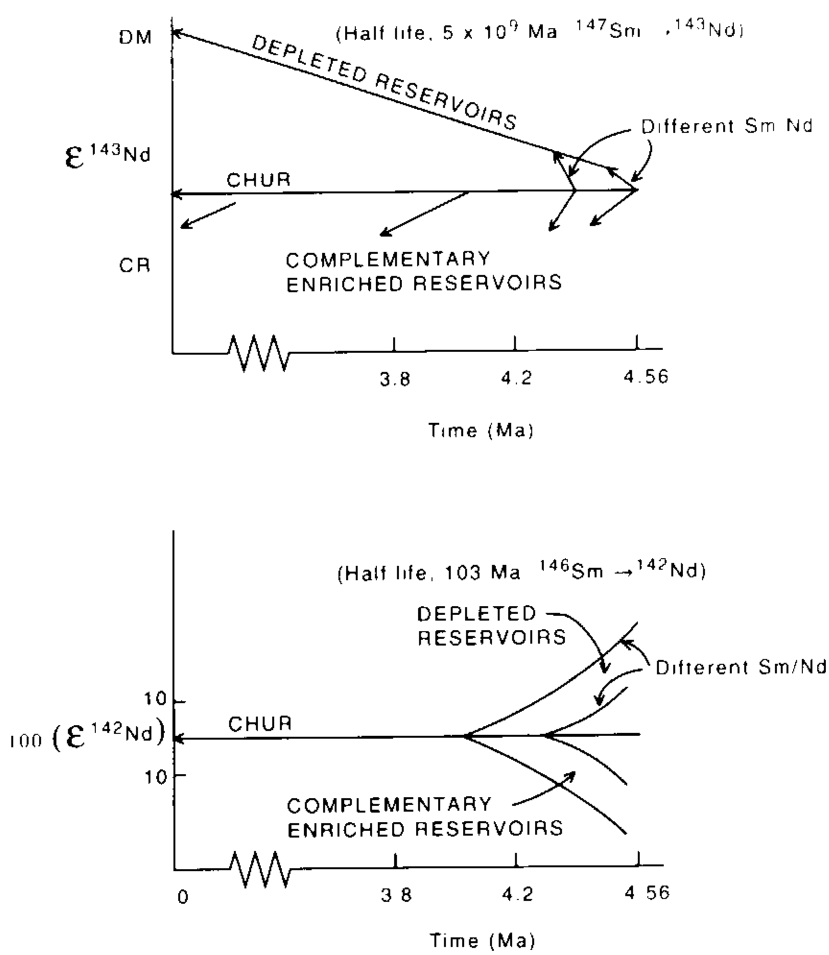


Figure 2 *Isotope evolution models for Sm-Nd systems. ^{143}Nd, the product of the long half-life ^{147}Sm, is progressively depleted in mantle reservoirs, with crust developing as a complementary enriched reservoir. In contrast, ^{142}Nd, the product of the short half-life ^{146}Sm, is rapidly depleted in mantle reservoirs. Any 3900 Ma crust extracted from the highly depleted mantle should show an anomaly in ^{142}Nd (a value of 10 parts per million represents the approximate detection limit). A complementary enriched crust should be formed, but must remain isolated through geological time.*

spot, the Rajmahal Traps and the Kerguelen hot spot, and the Ontong-Java plateau, have all produced 20-50 million cubic metres of basaltic crust (Fig. 3). These anomalous magmatic episodes may be related to chaotic convection in the outer-core convection (Larsen, 1991), or remelted recycled oceanic crust (Hofmann and White, 1982). These events seem to be tied to the production of anomalously thick oceanic crust produced elsewhere during long periods of stability in the Earth's magnetic field (*i.e.*, the Cretaceous superchron; Larson, 1991).

Griffith and Campbell (1991) modelled the dynamics of a hot, buoyant mantle plume rising from the deep mantle and argue that plumes grow in size as they rise and entrain upper mantle melts. Eventual ponding of the plumes below continental crust and divergence ofplume heads around ancient lithospheric roots may lead to continental breakup (Hill, 1991). However, there are enough examples of major igneous provinces that are not associated with ocean basins (Siberian traps, Karoo, Columbia River) to argue that plumes alone do not initiate continental breakup.

Campbell *et al.* (1989) and Hill *et al.* (1992) suggest that the widespread occurrence of high MgO-komatiite in the Archean can only be explained by melting in the high-temperature axis of a mantle plume. Modern, plume-related magmas are rich in FeO and high-field strength (HFS) incompatible elements compared to mid-ocean ridge basalts (MORB) at a similar MgO level (Fig. 4). In marked contrast, island-arc magmas are poor in FeO and commonly extremely depleted in HFS incompatible trace elements. If Archean komatiites are to be interpreted as the products of ancient mantle plumes, their geochemistry is enigmatic; their FeO contents are comparable to modern plume magmas, while their HFS incompatible trace elements are highly depleted and, therefore, more comparable to modern ocean-ridge and island arc magmas. The higher FeO contents of komatiites may reflect a greater depth of melt generation in Archean rift systems or a temporal evolution of the composition of their mantle source regions.

To solve the outstanding questions of plume-generation and their role in major igneous events throughout Earth's history, it is important to build links between geophysics and petrology. The causes of the superchrons in the Paleozoic and the relationship between core-dynamics and plume generation is a key element in the Earth's evolution. Whether mafic volcanism is cyclical through Earth's history, or whether only volcanic products in specific tectonic environments are preserved in the geological record may be addressed through a compilation of U/Pb zircon ages in the sedimentary record. New geochemical techniques, such as inductively coupled plasma-mass spectrometry (ICP-MS), secondary-ion mass spectrometry, and Re-Os isotope analysis, will allow greater analytical sensitivity and resolution of geochemical signatures of mafic and ultramafic sequences, leading to significant breakthroughs in the study of large igneous provinces in the future.

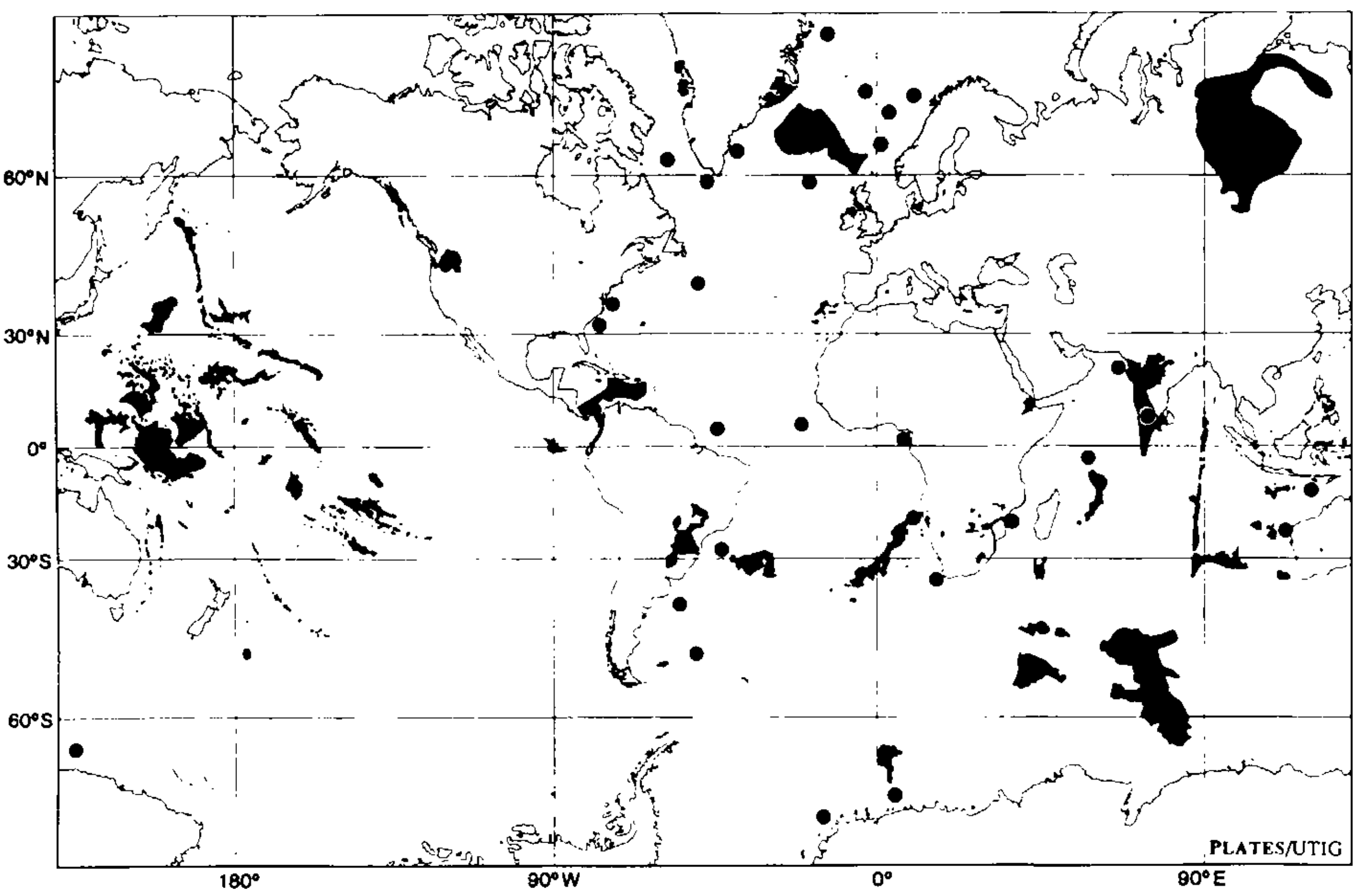


Figure 3 *Large igneous provinces (shaded regions) and plume locations (dark spots) in the present plate-tectonic context (from Coffin and Eldholm, 1990).*

CRUST-MANTLE RECYCLING AND MANTLE MELTING

It is widely accepted that plate-tectonics has operated in some form since at least the Late Archean. The injection of oceanic crust back into the mantle during the plate tectonic cycle has a fundamental role in fertilizing the mantle with fluids subducted in sediments and in metamorphic minerals. Mass balance estimates indicate that the mantle has turned itself inside out at least once during the past 3000 m.y. (Fyfe, 1992). Understanding the ultimate fate of the subducted oceanic crust is important in constraining magma genesis in subduction zones (Nicholls and Ringwood, 1973) and, potentially, in both continental and oceanic intraplate environments (Hofmann and White, 1982; Ringwood, 1990). Studies of the recycling process require close collaboration between geochemists and geophysicists. Tomographic studies aimed at imaging the mantle as it is penetrated by the cool oceanic plate (Shearer and Masters, 1992) suggest a correlation between regional depressions in the 660 km discontinuity and the location of subduction zones. This result is more consistent with deflection of the subducting plate than with slab penetration into the deep mantle. Ringwood (1990) argues that such a process would produce a thick layer of garnetite (former basaltic crust) at 550-650 km, which might provide a fertile (low solidus temperature) region in the mantle that may be the ultimate source for hot-spot volcanism.

It should be possible to differentiate between plumes derived from mantle melts at the core-mantle boundary and those derived from recycled basaltic crust (referred to, respectively, as thermal plumes and chemical plumes by Zindler and Hart, 1986) by using geochemical massbalance calculations. Such studies can only be achieved by establishing the bulk composition of the subducted crust (*e.g.*, Plank and Ludden, 1992), and mantle mineral-liquid partition coefficients for HFS elements such as Nb, the rare earth elements, and large ion lithophile elements such as Rb, K and Na. Figure 5 indicates that, of the major upper mantle phases, only amphibole is capable of explaining the large-ion lithophile and rare earth element systematics of mantle-derived magmas other than MORB. The accurate construction of such diagrams, however, depends on the high-preci-

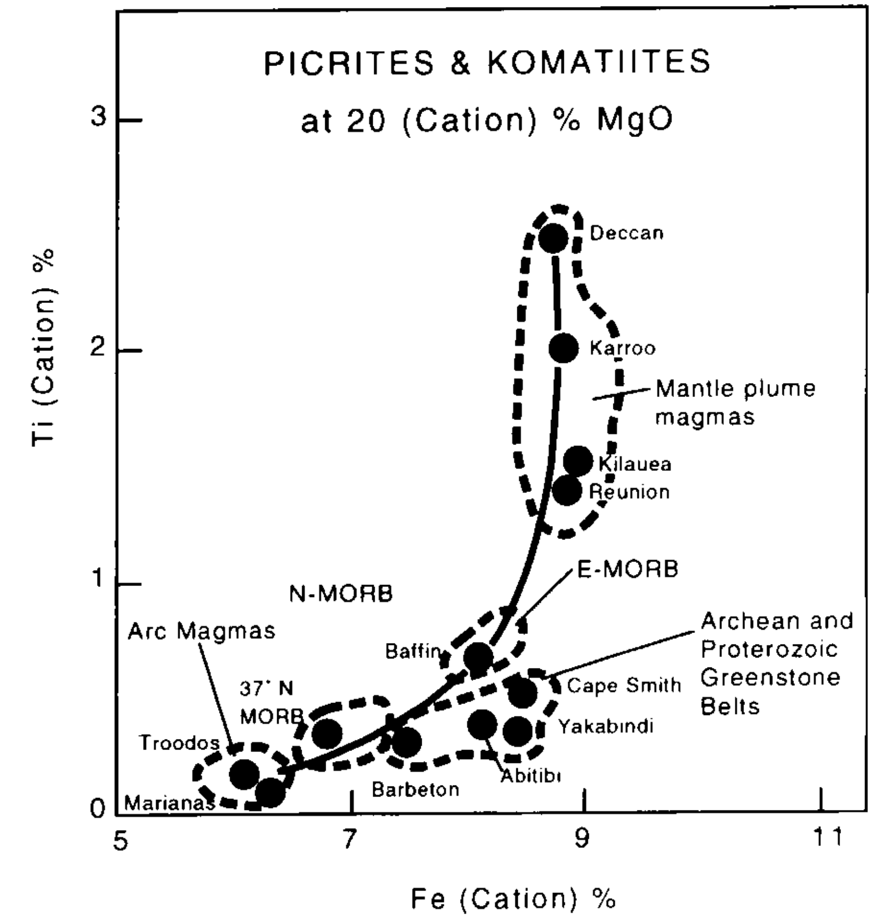


Figure 4 *Fe-Ti (cations) for mafic and ultramafic magmas compared at a constant MgO content of 20 cation%. The diagram demonstrates the high-iron and low incompatible element nature of mafic rocks in Archean and Proterozoic greenstone belts and significant differences between modern plume, arc and MORB magmas.*

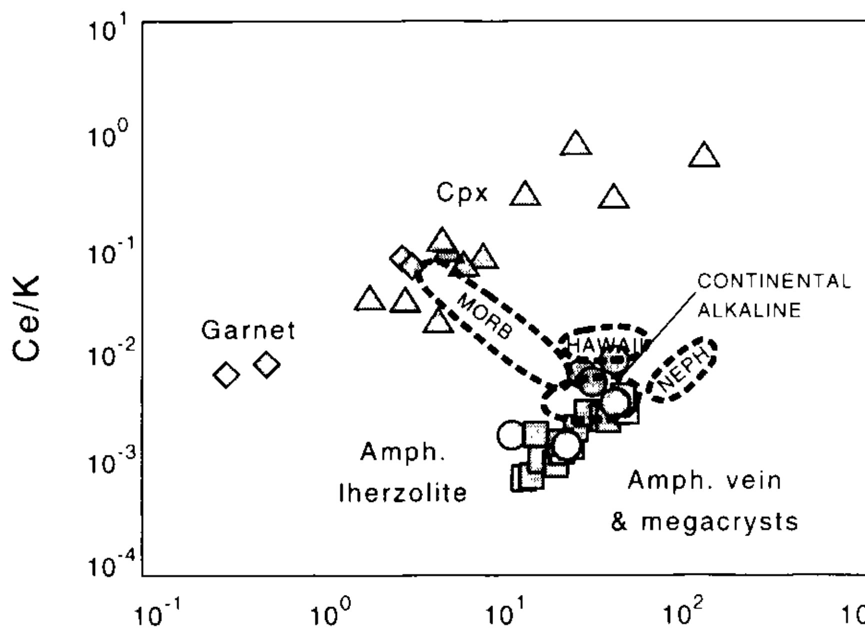


Figure 5 *Ce/K versus Ce for mantle minerals and melts (>8 wt.% MgO), indicating the importance of minor phases, such as amphibole, in mantle-melting processes.*

sion determination of trace element partition coefficients and abundances in both natural and experimental systems. These partition coefficient data will become increasingly available with the advent of high-sensitivity microbeam techniques, such as the ion microprobe, high-energy proton induced x-ray beams, synchatron x-ray excitation, and ICP-MS laser analysis.

The majority of models applied to basalt genesis involve forward modelling based on assumed mineral proportions in the mantle source region and in the fractionating assemblage during differentiation (*e.g.*, Francis and Ludden, 1990). The availability of high-quality abundance and partition coefficient data will provide increased constraints on inversion modelling of petrogenetic data (Minster and Allegre, 1978; Albarede, 1983; Mackenzie and Onions, 1991), permitting a more quantitative approach to understanding magma genesis.

CRUST MANTLE SYSTEMS AND OROGENESIS

It is increasingly relevant to consider the mantle and crust as a holistic system involving magma transport and solidification. Sinton and Detrick (1992) have demonstrated that our understanding of the formation of oceanic crust is well advanced. The rates of mantle upwelling, the depths of melting, and the composition of crust and mantle are reasonably well established (Fig. 6). For continental crust, the effects of magma migration are less well constrained. The densities of mantle-derived magmas generally exceed those of the lower crust, and such magmas will pond and fractionate at the base of crust (Cox, 1988). Different thermal regimes would result from magmatic underplating of newly accreted (*i.e.*, hot, wet fusible crust) *versus* older refractory crust (Fyfe, 1992, summarized in Fig. 6). In the earliest stages of continental rifting, dense magmas may rise through uplifted and fractured crust. At more advanced stages, when the lower crust is hotter, underplating of newly accreted crust will be dominant, while toward the end of a tectonic cycle, dense magmatic underplates may delaminate, resulting in renewed mantle upwelling with underplating and intrusion (intraplate) of the lower crust.

All stages of mantle-crust interaction in both the continental and oceanic regimes are responsible for ore deposit formation, either as magmatic sulphide deposits in crustal rifting environments or as deposits related to hydrothermal systems. Synvolcanic Cu and Zn massive sulphide ores formed in oceanic rift-zones are formed by direct heating of crust by magma intrusion. Mesothermal Au-deposits in late-stage hydrothermal systems may relate to less direct processes such as magmatic underplating and prograde metamorphic reactions. A more tenuous, but intriguing relationship between thermal plumes, the associated sea-level highstands, and hydrocarbon production (Larson, 1991) makes the holistic approach of mantle-crust dynamics increasingly relevant.

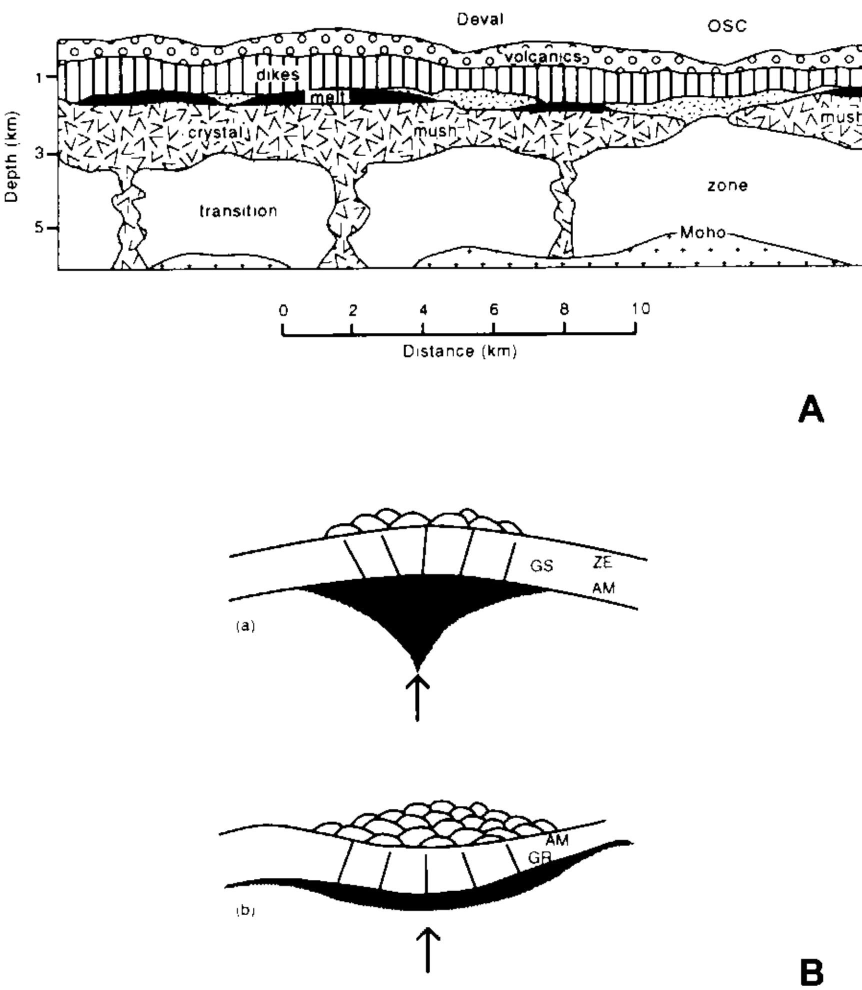


Figure 6 *Models of crust-mantle interaction, depicting the interplay of mantle-derived magma in crust formation, fluid regime, and, ultimately, in ore deposit genesis.* (**A**) *Along-axis views of magmatic evolution in an oceanic spread centre (from Sinton and Detrick, 1992).* (**B**) *Effects of underplating continental crust by mafic magma (from Fyfe, 1992).*

CONCLUSION

Mantle studies are entering a decade wherein the interaction between geophysics, petrology and geochemistry will be strengthened. To understand deep-seated geological processes it is imperative to define the chemical and physical properties of minerals under mantle P-T-*f* conditions. Experimental petrology will simulate greater P-T regimes in more complicated systems and improve our knowledge of distribution coefficients and abundances in mantle minerals. Petrophysics studies will assess the implications of mantle anisotropy and constrain geophysical images of upper mantle obtained by new LITHOPROBE initiatives aimed at the mantle lithosphere. Crustal studies can no longer be fully understood without evaluating the role of the mantle in metamorphic, uplift history, and metallogenesis and hydrocarbon production in orogenic and anorogenic zones.

ACKNOWLEDGEMENTS

The authors acknowledge the Natural Sciences and Engineering Research Council, FCAR (Quebec), EMR and LITHOPROBE for research funding. Field work in the Yukon, Ungava, Grenville and Abitibi was aided by funding from the Geological Survey of Canada (GSC). The authors acknowledge the fundamental role of GSC scientists such as W. Baragar and N. Irvine in pioneering studies of mantle-derived rocks in Canada.

REFERENCES

Agee, C.B., 1990, A new look at differentiation of the Earth from melting experiments on Allende meteorite: Nature, v. 346, p. 834-837.

Albarede, F., 1983, Inversion of batch melting equations and the trace element pattern on the mantle: Journal of Geophysical Research, v. 88, p. 10573-10583.

Bowring, S.A., Williams, I.S. and Compston, W., 1989, 3.96 Ga gneiss from the Slave Province, Northwest Territories, Canada: Geology, v. 17, p. 971-975.

Campbell, I.H., Griffith, R.W. and Hill, R.I., 1989, Melting in an Archean mantle plume: heads it's basalts, tails it's komatiites: Nature, v. 339, p. 697-699.

Coffin, M.F. and Eldholm, O., eds., 1990, Large Igneous Provinces, JOI/USSAC Workshop report: The University of Texas at Austin Institute for Geophysics, Technical Report 114, p. 79.

Cox, K.G., 1988, The Karoo Province *in* Macdougall, J.D., ed., Continental Flood Basalts: Kluwer Academic Publishers, Hingham, v. A, p. 239-271.

Francis, D. and Ludden, J.N., 1990, The petrogenesis of Alkaline magma series at Fort Selkirk, Yukon, Canada: Journal of Petrology, v. 13, p. 371-400.

Fyfe, W.S., 1992, Magma underplating of continental crust: Journal of Volcanology and Geothermal Research, v. 50, p. 33-40.

Goldstein, S.L. and Galer, S.J.G., 1992, On the trail of early mantle differentiation: $^{142}Nd/^{144}Nd$ ratios of early Archean rocks: EOS, v. 73, p. 323.

Griffith, R.W. and Campbell, I.H., 1991, On the dynamics of long-lived plume conduits in the convecting mantle: Earth and Planetary Science Letters, v. 103, p. 214-227.

Harper, C.L., Jr. and Jackobsen, S.B., 1992, Lost terrains of the early Earth: isotopic evidence from $^{142}Nd/^{144}Nd$ in the 3.8 Ga Isua supracrustals, West Greenland: EOS, v. 73, p. 323.

Hill, R., 1991, Starting plumes and continental break-up: Earth and Planetary Science Letters, v. 104, p. 398-416.

Hill, R.I., Campbell, I.H., Davies, G.F. and Griffith, R.W., 1992, Mantle plumes and continental tectonics: Science, v. 256, p. 186-193.

Hofmann, A.W. and White, W.M., 1982, Mantle plumes from ancient oceanic crust: Earth and Planetary Science Letters, v. 57, p. 421-436.

Larson, R.L., 1991, Geological consequences of superplumes: Geology, v. 19, p. 963-966.

McCulloch, M.T. and Bennett, V.C., 1992, Progressive growth of the Earth's crust and depleted mantle: constraints from ^{143}Nd-^{142}Nd isotope systematics: Evolving Earth Symposium, Proceedings, Okazaki, Japan, p. 55-64.

McKenzie, D. and Onions, R.K., 1991, Partial melt distributions from inversion of rare earth element concentrations: Journal of Petrology, v. 2, p. 1021-1091.

Minster, J.F. and Allegre, C.J., 1978, Systematic use of trace elements in igneous processes. Part III: inverse problem of batch partial melting in volcanic suites: Contributions to Mineralogy and Petrology, v. 69, p. 37-52.

Nicholls, I.A. and Ringwood, A.E., 1973, Effect of water on olivine stability in tholeiites and the production of SiO_2-saturated magmas in the island arc environment: Journal of Geology, v. 81, p. 285-300.

Plank, T. and Ludden, J.N., 1992, Geochemistry of sediments in the Argo Abyssal Plain at ODP site 765: A continental margin reference section for sediment recycling in Subduction Zones, *in* Gradstein, F.M., *et al.*, Ocean Drilling Program, Proceedings, Leg 123, p. 167-189.

Ringwood, A.E., 1990, Slab-mantle interactions: 3. Petrogenesis of intraplate magmas and the structure of the upper mantle: Chemical Geology, v. 82, p. 187-207.

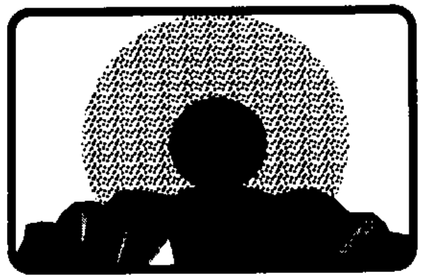
Shearer, P.M. and Masters, T.G., 1992, Global mapping of topography on the 660-km discontinuity: Nature, v. 355, p. 791-796.

Smith, A. and Ludden, J.N., 1989, Nd-isotope evolution of the Archaean Mantle: Earth and Planetary Science Letters, v. 93, p. 14-22.

Sinton, J. and Detrick, R.S., 1992, Mid-Ocean Ridge Magma Chambers: Journal of Geophysical Research, v. 97, p. 196-216.

Zindler, A. and Hart, S.R., 1986, Chemical geodynamics: Annual Review of Earth and Planetary Sciences, v. 14, p. 493-571.

Accepted 1 September 1993.



The Earth's Core

David Crossley
Department of Earth and Planetary Sciences
McGill University
3450 University Street
Montreal, Quebec H3A 2A7

ABSTRACT

The current status of knowledge of the Earth's inner and outer cores is reviewed from the standpoints of seismology, gravity, Earth rotation, and the geomagnetic field. Because of the remoteness of the deep interior, geophysicists have used great ingenuity in processing and interpreting surface data that is contaminated by many local (surficial and crustal) sources. Despite the lack of direct data from the deep Earth, there has been a rapid growth in knowledge in the last decade due to advances in instrumentation and the blossoming of interdisciplinary studies.

Of major interest at the present time is the interaction between the mantle and core, each of which contains a major convective regime, powering, in one case, plate tectonics and, in the other, the geodynamo. These regimes meet at the core-mantle boundary (CMB), which has provided a tempting target for seismology, magnetism, geodesy and high-pressure physics; much has been learned from the interchange between geophysicists in these disciplines. In this review, it is suggested that the predominant themes for the next decade, growing naturally out of existing trends, are 1) improvements in the quality and coverage of global data sets, particularly those in geomagnetism, geodesy and seismology, 2) increased international co-operation through participation in interdisciplinary studies such as SEDI (Study of the Earth's Deep Interior), and 3) exploration of the non-