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Models of earth structure inferred from neodymium and strontium isotopic abundances

(mantle/basalts/magma genesis)

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ABSTRACT A simplified model of earth structure based on the Nd and Sr isotopic characteristics of oceanic and continental tholeiitic flood basalts is presented, taking into account the motion of crustal plates and a chemical balance for trace elements. The resulting structure that is inferred consists of a lower mantle that is still essentially undifferentiated, overlain by an upper mantle that is the residue of the original source from which the continents were derived.

It has been noted that tholeiitic flood basalts from the midocean ridges and from the continents are distinctive in Nd isotopic composition (1, 2). These isotopic differences result from the decay of ^{147}Sm and changes in the relative abundance of the rare earth elements. The Nd isotopic composition (^{143}Nd/^{144}Nd) observed for young continental flood basalts (CFBs) appears close to the value expected from a parental source with Sm/Nd equal to the chondritic average over the age of the earth. The midocean ridge flood basalts (MORBs) have a higher ^{143}Nd/^{144}Nd, which reflects a parental source that had a high Sm/Nd ratio. The fractional differences in ^{143}Nd/^{144}Nd in parts per 10^4 relative to a reference reservoir with the ^{147}Sm/^{144}Nd ratio of chondrites is defined as

$$\epsilon_{Nd} = \left[\frac{(^{143}\text{Nd}/^{144}\text{Nd})}{(^{143}\text{Nd}/^{144}\text{Nd})_{\text{CHUR}}} - 1\right] \times 10^4,$$

in which CHUR is chondritic uniform reservoir. It may be shown that $\epsilon_{Nd} \approx Q_{Nd} f^*_{Sm/Nd} T^*$. Here T^* is the time in units of aeons (1 aeon = 10^9 yr) required to produce ϵ_{Nd} in a reservoir enriched in Sm/Nd by $f^*_{Sm/Nd}$, and Q_{Nd} is a constant that is proportional to the decay constant of ^{147}Sm and is equal to 24.7. The isotopic difference between typical MORBs ($\epsilon_{Nd} \approx +10$) and continental flood basalts ($\epsilon_{Nd} \approx 0$) corresponds to a time (T^*) of 1.5 aeons for $f^*_{Sm/Nd} \approx 0.3$. The small differences in ϵ_{Nd} therefore require lithic reservoirs with distinct enrichment factors that have persisted over a substantial fraction of the history of the earth.

Earth structure models: Considerations and precepts

In the present discussion we will first assume the rules (*i*) that $\epsilon_{Nd}^{MORB} = +10$, $\epsilon_{Nd}^{CFB} = 0$, (*ii*) that these magma types appear dominantly in oceanic and continental regions, respectively, and (*iii*) that they directly monitor the mantle source regions. We will then attempt to construct some simple earth structure models compatible with these rules. Following this, we will explain the considerable variability of ϵ_{Nd} found in actuality, and the intermediate values characteristic of ocean island basalts and some continental basalts by partial relaxation of the rules. It will be assumed that values of $\epsilon_{Nd} = 0$ identify magmas derived from an ancient unfractionated source. The approach follows that described in a cursory fashion by DePaolo and Wasserburg (2).

Earth models will be considered in which the structural elements are continental crust (CC), oceanic crust (OC), continental mantle (CM), oceanic mantle (OM), and intermediate and lower mantles (IM, LM). Layers that can produce basalt magmas will be defined as fertile, and those fertile layers actively producing magmas will be called fecund. Layers that cannot produce magmas are called sterile. It will be assumed that basalts are derived from underlying fertile mantle and have initial Nd isotopic compositions the same as the parent mantle reservoir. Acceptable arrangements of the structural elements will be those that logically result in flood basalts with $\epsilon_{Nd} = 0$ appearing predominantly on the continents and flood basalts with $\epsilon_{Nd} = +10$ appearing predominantly in oceans. Ancillary rules that are needed to maintain consistency will be identified and the physical plausibility of such rules will be assessed. Our emphasis will be on rationalizing the qualitative characteristics of Nd isotopic variations. The details of transport and interaction between reservoirs will not be addressed. The most satisfactory simple model will be expanded and modified in an attempt to construct an earth structure model that grossly is compatible with petrologic and geophysical data.

For a model to be acceptable, the chemical distinction between mantle reservoirs required by differences in ϵ_{Nd} must be preserved for times that are long in comparison to the time scales for continental drift and oceanic plate movements (≈0.1 aeon). The physically distinct units may be either (*i*) chemically isolated and isotopically evolving along divergent paths subsequent to the time of differentiation or (*ii*) communicating with one another by material exchange with the rate constants or residence times and enrichment factors in the transport process governing the isotopic differences. The reservoirs could be produced by gross planetary processes dating from near the time of formation of the earth (congenital reservoirs) or continuously evolving due to differentiation processes taking place over the long times involving crustal growth (evolving reservoirs). Because the continents must be allowed to drift, the depth to the bottom of the continental "plate" (CC ± attached underlying mantle) represents a logical point of distinction between "upper mantle" and "lower mantle." Clearly, any fertile reservoir in the "lower mantle" cannot be constrained to lie under either CC or OC for long times.

The conceptual units discussed here should correspond to actual physical segregations of matter, implying an inherent large-scale "immiscibility" between the units. They should also be related to the observed physical structure of the earth. The units may represent striking dynamical and temperature–

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Abbreviations: CFB, continental flood basalt; MORB, midocean ridge (flood) basalt; CC, continental crust; OC, oceanic crust; CM, continental mantle; OM, oceanic mantle; IM, intermediate mantle; LM, lower mantle.

pressure differences as well as major differences in chemical composition. For example, the CC is clearly an ancient chemical unit, but the OM may not differ from other parts of the mantle in chemical characteristics but only in physical or dynamical properties. A specific example may be the distinction between CM and OM. We may conceptualize this by imagining the tectonic behavior of the earth in the absence of continents. A global OM, strongly convecting and fertile, may simply represent a shallow facies of IM in the absence of continents. Superimposing a rigid CC on the mantle will depress the isotherm at its base and should inhibit fecundity and strong convective mixing in the underlying mantle, resulting in the distinctive behavior observed under the continents.

Differentiation from an initially homogeneous earth requires the segregation into reservoirs with complementary chemistry. Insofar as $\epsilon_{Nd} = 0$ is a sound estimate for the bulk earth, then ϵ_{Nd} of all reservoirs weighted by the number of Nd atoms they contain must sum to zero. If we consider the CC, which is highly enriched in Nd and today has distinctly negative ϵ_{Nd} (≈ -15) (2), then there must exist a complementary reservoir with positive ϵ_{Nd}. If this reservoir is depleted in Nd, then it must be of large volume. Mantle reservoirs with $\epsilon_{Nd} = +10$ are clearly candidates for such complementary reservoirs. We therefore will use this mass balance consideration as a qualitative basis for acceptance or rejection of models and will favor models that provide for a contiguous complementary reservoir for the continental crust. We note that magmatic activity in ocean basins is more intense than on continents. This implies that mantle magma sources for oceanic basalts, when overridden by continental masses, would yield intense volcanic contributions of an oceanic character on continental blocks.

Simple models

The requirement of continental drift leads to two basic classes of models (Figs. 1 and 2). The first class has OC and CC underlain by fertile layers with the appropriate isotopic composition to produce the values in oceanic and continental basalts. The second class differs in that one (or both) of OC and CC are underlain by both types of fertile mantle. The latter class of models requires an additional rule that the products of a given fertile mantle reservoir must be inhibited from reaching the surface in either oceanic or continental areas.

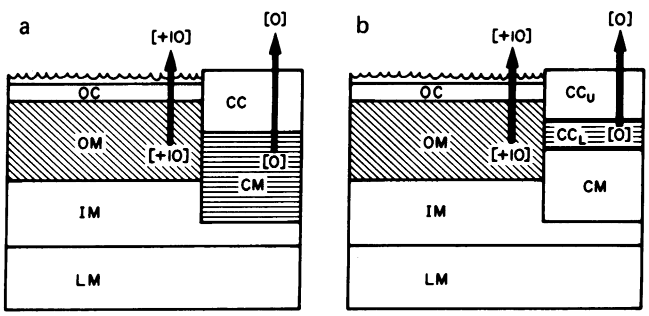

FIG. 1. Box model of a possible earth structure. The units are: OC, oceanic crust; OM, oceanic mantle; CC, continental crust; CM, continental mantle; IM, intermediate mantle; LM, lower mantle. The base of the continental block is in IM. Arrows indicate transport from the source region through the overlying layers. The source regions characterized by $\epsilon_{Nd} = +10$ and $\epsilon_{Nd} = 0$ are shown with a diagonal and a horizontal pattern, respectively. OC has $\epsilon_{Nd} \approx +10$ and average CC has $\epsilon_{Nd} \approx -15$. The total continental block is assumed to be coherent during displacements. (*a*) Model Ia. The fertile source regions for this model are OM and CM. IM and LM are sterile. (*b*) Model Ib. This model subdivides CC into upper crust (CC_U) and lower crust (CC_L). The fertile source regions are OM and CC_L; CM, IM, and LM are sterile.

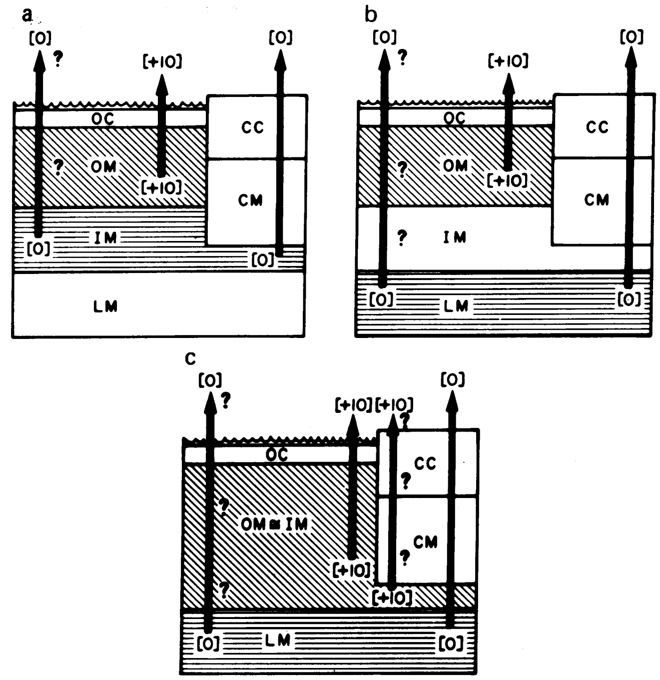

FIG. 2. (*a*) Model IIa. The source of magmas with $\epsilon_{Nd} = +10$ is taken as OM. The source of magmas with $\epsilon_{Nd} = 0$ is taken as IM. CM and LM are sterile. The base of the continental block rests in IM and below OM. This model yields $\epsilon_{Nd} = 0$ magmas in the ocean basins (note query) in violation of the simple rules. (*b*) Model IIb. The source of magmas with $\epsilon_{Nd} = 0$ resides in LM and magmas with $\epsilon_{Nd} = +10$ come from OM. The continental block, including CM, and IM here are sterile. This model yields magmas with $\epsilon_{Nd} = 0$ in the ocean basins. (*c*) Model IIc. This model removes the distinction between OM and IM. The source for magmas with $\epsilon_{Nd} = +10$ is in IM ($\approx$ OM) and for magmas with $\epsilon_{Nd} = 0$ is in LM. This violates the simple rules in oceanic *and* continental regions.

Fig. 1*a* shows the simplest arrangement (Model Ia) compatible with the rules. Here mantle sources for CFB are in CM and sources for MORB in OM. The IM and OM are here distinct units with IM considered as a passive inactive medium and with IM and LM taken as sterile. This arrangement requires that the two fertile sources OM and CM be attached to OC and CC, respectively; drift of crustal blocks involves coherent displacement of the corresponding mantle segment. This model is analogous to a stable, layered two-fluid medium on which the continental blocks float. Movements of the rigid continental blocks displace the upper fluid medium (OM). The continental blocks are thick enough so their bases lie within the lower fluid medium (IM and LM) such that CC + CM never override OM. Model Ib is similar to Ia, but the source for $\epsilon_{Nd} = 0$ lies in the lower CC rather than the mantle, removing the requirement that a chemically distinct CM exist as the source of $\epsilon_{Nd} = 0$ magmas. Any mantle keel to the continental crust must be sterile and would be required only insofar as the thickness of the total continental block must be greater than the thickness of OC + OM. This model demands that the lower continental crust be greatly different in relative abundances of rare earth elements as compared to the upper crust.

Fig. 2*a* shows Model IIa, in which the source for CFB is in the IM and the source for MORB is in the OM. CM is taken to be sterile. Displacements of CC and a coherent CM may be considered in terms of the two-layered fluid model for OM and IM discussed for Model I. Model IIa requires an additional rule that magmas from IM do not penetrate OM if the appearance of $\epsilon_{Nd} = 0$ is strictly forbidden in OC. Such a rule is difficult to justify because OM is very mobile and should therefore freely allow IM-derived material to pass through it. An alternative is to relax the strict rule and to permit IM magmas to penetrate OM, but with the stipulation that the rate of transport from IM be low in comparison to that from OM. This would be compatible with the much greater rate of basalt generation in oceanic regions as compared with the continents. Model IIb is a variant of IIa, with the source for CFB being LM. During continental drift OM is displaced by CC and CM, which are again coupled. The virtue of such a model in comparison to IIa is that the inert IM can provide a sufficiently large contiguous complementary reservoir for CC. In this model CM would be nonproductive but can be chemically the same as IM. However, CC cannot be displaced over OM, otherwise $\epsilon_{Nd} = +10$ in the ocean basins would again demand relaxation of the rule regarding $\epsilon_{Nd} = 0$ magmas. A third variant (Model IIc) is shown in Fig. 2*c*, where we have removed any distinction between OM and IM. This case takes OM and IM to be the same chemically *and* to have the same dynamic behavior, including a characteristic fecundity. The continental block CC + CM is again a coherent unit. LM is taken as the source for magmas with $\epsilon_{Nd} = 0$. In models of this type, a rule that magmas with $\epsilon_{Nd} = 0$ may not appear in ocean basins is not satisfied. However, in this model an *additional violation* occurs with regard to the transport of magmas derived from OM (or IM) through the continental crust. Because we here assumed total equivalence of OM and IM, it would be necessary to demand that IM magmas could not penetrate CC while LM magmas could penetrate IM and CC, which is not consistent.

Discussion of models

Each of the arrangements exhibited above could satisfy the basic rules, but all have need for additional requirements. Model Ia requires an undifferentiated continental keel that persists during plate motions and provides for no contiguous complementary reservoir for the crust, except possibly the thin OM. If we consider the CM not as a static unit but as a dynamical one in which matter from OM and CC are mixed in the proper proportions to maintain a composition of $\epsilon_{Nd} = 0$ under the continents, this arrangement might work. However, this would require a delicate balance if we assumed the rule of $\epsilon_{Nd} = 0$ were strictly true. Model Ib is difficult to justify because it requires the lower crust to be the magma source and to have peculiar rare earth element abundance characteristics. We reject Model IIa because it does not provide a contiguous complementary reservoir for CC. If we relax the requirement of a contiguous character, then it is possible to make the complementary reservoir LM. This requires an extra segregation of depleted reservoirs (OM, LM), which is difficult to defend. Model IIc has contiguous complementary reservoirs, but is unsatisfactory because of the need for a peculiar additional rule that permits LM magmas but not IM- (or OM)-derived magmas to penetrate CC.

On the basis of the preceding arguments, the only static model that appears plausible is IIb. We will take this as our preferred earth model and pursue the consequences.

A plausible physical characterization of CM and the nature of the distinction between OM and IM are the most obvious issues that require attention. IM and OM must be the depleted layers complementary to the continental blocks. However, as argued for model IIc, it is not possible to consider OM and IM as a single unit with the same magma productivity. The distinction must therefore be physical. One possibility is that OM is an interactive buffer regime, resembling IM chemically and isotopically, but productive due to fluxing with material from the continents, oceans, or both. Wherever the continents may be, they eliminate the interaction in the overridden regions of IM, causing the difference between OM and CM. Another alternative is that convection in OM is the regular behavior of the whole upper mantle without requiring the OM to be a specially activated boundary layer. In this case the rigid continental blocks may suppress convection at their base by depressing the isotherms to greater depths, thus inhibiting MORB-type magma generation in the fertile mantle that underlies them. The CM may then differ from OM and IM, not chemically but only in its physical [$T(P)$ and velocity field] state. Either of the above *ad hoc* explanations would be consistent with the isotopic constraints.

In this model we would interpret the ϵ_{Nd}–ϵ_{Sr} correlation for basaltic rocks (2, 3) to be a mixing line between two endmember mantle reservoirs (2, 4). The assignment of $\epsilon_{Nd} = 0$, $\epsilon_{Sr} = 0$ to LM and $\epsilon_{Nd} = +10$, $\epsilon_{Sr} = -30$ to OM and IM yields a self-consistent model that will yield a mixing line from blends of LM and IM or OM magmas. The rationalization of the Nd systematics will thus also apply to Sr for both oceanic and continental volcanics. The observed divergences from the correlation line require contamination with CC or ocean water and sediments (5).

A synthetic earth model

Our preferred earth model is shown in Fig. 3, which attempts to provide a geological context for Model IIb. This model integrates the geometrical arrangement of magma sources with a plausible mantle flow pattern and takes account of the range of ϵ_{Nd} found in both oceans and continents by allowing some magmas to be blends of material derived from two sources. The model is essentially one of a two-layered earth (excluding the core). The lower mantle is primitive material that has remained undifferentiated since near the time of formation of the earth, except for loss of Fe to the core and partial degassing. The intermediate and upper mantle, above ≈600–1000 km depth, and the crust and hydrosphere, together make up the upper layers, with a net composition similar to the lower mantle. The IM and upper mantle are chemically similar but distinct from the LM because they are depleted in those elements enriched in the CC. They are also essentially totally degassed of juvenile volatile elements. The boundary between IM and LM may be a gradational one over a substantial depth range. The continental crust continues to grow today by addition of igneous materials formed in subduction zones at continental margins and island arcs; some igneous material is added from the LM. The upper mantle and IM are convecting as shown in Fig. 3. The convection motion dies out or is greatly diminished at the boundary with LM. The LM may also convect at a low rate but is only loosely coupled with IM. The oceanic mantle represents a zone where pressure–temperature conditions are such that the constituent material is at or near its melting temperature, and may correspond to the low-velocity zone (6). The lower viscosity in the OM region results in more effective flow. The flow in OM and IM is envisaged as dominated by large-scale convective motion rather than vigorous small-cell convection. The continental mantle is considered as chemically similar to OM and IM, but due to lower temperatures at the corresponding depth, it is not near its melting point and thus is similar to IM in physical behavior. As the continent moves relative to the deep mantle, the cooler "shadow zone" beneath the CC moves also, but the same mantle material does not necessarily remain beneath the continent. CM′ illustrates the possibility that a limited mantle "keel" that is more permanently attached to the continental mass may exist beneath continents.

The basic feature of this model is that the upper mantle (OM + CM) and IM are differentiated, having been previously

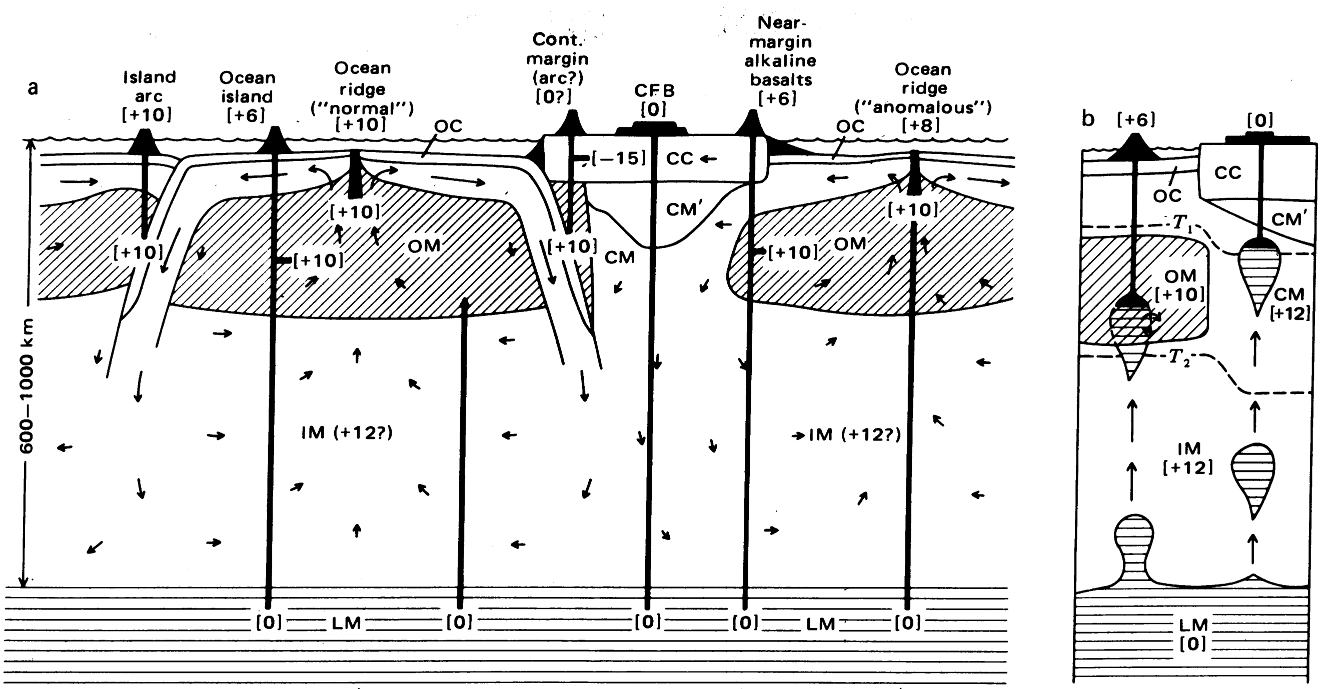

FIG. 3. (*a*) Earth structure model based on Nd isotopic data. Arrows show a plausible flow pattern for the mantle. IM, OM, and CM regions are chemically the same and matter is presumed to circulate between them. However, OM is fecund. Intermediate ϵ_{Nd} values result from mixing of LM-derived material with OM-derived magmas during transit through the fluid OM layer which is at or close to its melting point. (*b*) Difference between oceanic and continental regions. The partially molten state of OM ensures that any material passing through it will mix with OM magmas, resulting in blends. Due to the depressed isotherms (T_1, T_2) under continents, CM and IM are far from their melting temperatures and do not interact much with the LM-derived diapirs. CM′ represents mantle attached to CC over long times. Subducted slabs produce magmas similar in ϵ_{Nd} to MORB but with some continental and hydrospheric material added.

tapped of volatiles and low-melting constituents that are stored for long times in the continental crust, hydrosphere, and atmosphere. As a result they are relatively infertile and produce magmas only under special conditions that exist at plate boundaries. At mid-ocean ridges, where the planetary scale deep convective motion rises, the upwelling brings hot OM ($\approx$ IM) material up to extremely shallow depths where it is partially melted and the magma is emplaced passively during seafloor spreading. In subduction zones where materials have been cooled, H_2O and other agents are dragged down into the mantle, the OM is effectively "fluxed" and magmas are produced and erupted. Thus OM is directly sampled only at ocean ridges and subduction zones. In this model, all intraplate magmatic activity originates in the lower mantle, and in these regions OM is sampled only indirectly, acting as a diluent to the rising sources from the lower mantle.

The difference between oceanic and continental *intraplate* volcanism is illustrated in Fig. 3*b*. The ultimate sources of all the basaltic volcanism are diapirs originating in LM. The pods of material rising from LM may be (*i*) a "solid" mass that attains a lowered density, perhaps due to local heating caused by concentration of heat sources, (*ii*) a mass of material that has a lower density because it contains a small amount of melt, or (*iii*) magmas formed by melting in LM. For (*i*) or (*ii*) the "solid" diapiric plugs would rise until intersecting their melting curve, where the basaltic magma would be formed (7). For the latter case, it would be required that the lower mantle be close to its melting temperature. This is not currently thought likely, but quantitative knowledge of melting temperatures in the mantle at 200–300 kilobars (20–30 GPa) is still lacking (7). In continental regions these diapirs pass only through mantle material that is far from its melting point and therefore reach shallow depth with little or no interaction in the intermediate mantle, and retain their isotopic identity. In oceanic regions, however, the LM-derived diapirs encounter the fecund OM, where extensive mixing takes place between melts derived from the diapir and from the surrounding OM. Thus the magmas derived from LM diapirs that are erupted in oceanic regions differ from those in continental blocks in that they have been variously diluted with OM materials.

Fig. 3*a* shows schematically the sources of magmas in different tectonic settings. The MORBs are derived from OM. At so-called "normal" ridge segments the ϵ_{Nd} of the basalts directly reflects that of OM. At "anomalous" ridge segments there is some input from LM-derived material. CFB and intraplate oceanic island basalts are derived ultimately from LM, but ocean island basalts contain an admixture of OM-derived magma, resulting in ϵ_{Nd} values intermediate between MORBs and CFBs (shown as $\epsilon_{Nd} = +6$ in Fig. 3*a*). Similar mixtures may occur at continental margins, where OM may undercut the CC. Island arc magmas may come from either OM or subducted OC, with possibly some contributions from LM (5). Magma production at continental margin subduction zones may be more complicated, because there may be involvement of CC. There is as yet little data relating to this problem. In general, all magmas erupted through CC may be affected by contamination to some degree. The isotopic composition of CM′ is unspecified, being dependent on its detailed history, but because it is also cool, it is generally not considered to produce magmas. Some rare continental magmas of peculiar chemical and isotopic composition could be derived from such a region.

Because in this model LM-derived material with $\epsilon_{Nd} = 0$ passes through the IM with relatively little material exchange and in passing through OM is mixed with OM, the observed ϵ_{Nd}

value of about +10 attributed to OM may be slightly displaced toward zero as compared to the true ϵ_{Nd} value of IM. Accordingly we indicate on Fig. 3*a* that IM may have $\epsilon_{Nd} = +12$, which is about the highest value measured on a MORB. The rate of transport of material out of LM is assumed to be fairly low, but because it is the driving mechanism, it is disportionately represented in intraplate volcanism.

This model encounters no serious geometrical difficulties in tracing the evolution of this configuration back through time. The volume of OM + CM + IM must balance the continental crust such that the bulk ϵ_{Nd} of all the material above the IM–LM boundary is zero. We would expect that the isotopic differences between the different mantle and crustal units have generally increased through time. However, the detailed history of the evolution of ϵ_{Nd} in these reservoirs depends upon the rates of mass transfer between the reservoirs. For instance, if the crust has grown gradually, we would expect a different change of ϵ_{Nd} through time for each of the reservoirs than if the volume of the crust were constant through time with a significant amount of crustal recycling back into the mantle. Because LM is assumed to be undifferentiated, the transport of material out of LM required in the model implies that the depth to the IM–LM boundary has increased through time.

The model presented here is dominated by considerations of the Nd isotopic data and consequently is substantially different from earth models, such as that of Ringwood (7), deduced from petrologic considerations. It also is incompatible with the mantle flow patterns calculated by Hager and O'Connell (8). The model is consistent with the upper mantle model of Jordan (9) which recognizes a physical distinction between oceanic and continental mantle in much the same sense as postulated here. It is also fully consistent with the mantle plume hypothesis as originally advanced by Wilson (10) and Morgan (11). Our model is distinct from that of Brooks *et al.* (12), who propose the continental keel as the source of most continental magmas.

In Ringwood's models (7) it is proposed that material now appearing at midocean ridges represents previously undifferentiated mantle being displaced to shallow levels by depleted mantle sinking to great depths in subduction zones. However, the isotopic data show that MORBs come from *ancient* depleted mantle, in direct contrast with the assumption underlying the model of Ringwood. Furthermore, a contrast between oceanic and continental basalts is not recognized in major elements and was not incorporated into the model by Ringwood. The differences in our conclusions may be a result of the fact that the chemical distinction between "depleted" and "undifferentiated" material based on trace elements may correspond to only a subtle difference in the major elements. However, the primitive *undegassed* nature of oceanic mantle is an extremely important tenet of the Ringwood model, because pyrolite must contain H_2O in order to be partially molten in the low velocity zone. In this regard the trace elements considered in this work are clearly more likely to be related to degassing history than are major elements.

The Pb–U–Th data must also be integrated with the Nd results, although the contributions from continental materials may make a simple approach difficult. Significant efforts to understand the Pb isotopic systematics in oceanic ridges as related to the mixing of mantle plumes with a depleted upper mantle have been made by Sun *et al.* (13), following the binary mantle mixing model of Schilling (14). We believe that it is possible to bring the observations of all three isotopic systems into qualitative congruence with the "synthetic earth model" outlined above. A more serious attempt at constructing earth models will have to include the isotopic, petrogenetic, and geophysical considerations in a balanced and quantitative manner, which has not been done here.

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