

mental crust relative to the oceanic crust is attributable to the addition of alkalis to the ocean in the vicinity of rifts, the removal of potassium by clays, and the involvement of sodium-rich formation water during granitization. The sources of hydrothermal ore deposits are heavy metals and sulphur previously concentrated by sedimentary processes. Further, hydrothermal wall rock alteration may explain some of the mineral and rock assemblages observed in rift zones (for example, greenstones and greenschists).

Seawater began as a carbonate solution rich in magnesium. It gradually evolved to a sodium chloride dominance by a series of mineral equilibria. The excess in CO₂ was removed by carbonate deposition and inorganic and biological CO₂ reduction. Steady state conditions were probably established at the end of the Precambrian, at which time organisms began to form a carbonate shell.

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LETTERS TO NATURE

PHYSICAL SCIENCES

Non-Primary Magmas and Dubious Mantle Plume beneath Iceland

BASALT lavas dredged from the mid-Atlantic ridge south of Iceland exhibit a conspicuous correlation of minor element chemistry with distance from Iceland¹. This also happens to be a correlation with altitude, those lavas which contain the higher concentration of incompatible elements (and the higher Fe/Mg and Na/Ca ratios) being collected from greater heights above the general level of the ocean floor. The lavas are predominantly quartz-normative and most contain phenocrysts of olivine, augite and plagioclase.

Schilling¹ has rejected differing degrees of fractional crystallization as an explanation of these relationships. He prefers a process of mixing of two primary magmas, the one generated by partial melting of depleted upper mantle spreading from the ridge, and the other generated by partial melting of undepleted deeper mantle rising as a plume beneath Iceland.

Here I summarize the evidence that these lavas are not primary magmas, but may have suffered extensive low and high pressure fractional crystallization. I re-examine the proposition that a varying degree of fractional crystallization is responsible for the variation in lava chemistry and offer an alternative interpretation of the observations, without recourse to mantle plumes, in terms of a hypothesis of magma genesis at the upper mantle-transition zone boundary.

Experimental petrology of quartz-normative basalts² has shown that they are not in equilibrium with olivine at pressures greater than 2 to 5 kbar. They cannot, therefore, be primary magmas derived from a peridotite upper mantle at greater pressures because olivine (and enstatite) will be resi-

dually crystalline phases in that material when the partial melting occurred. Olivine and calcic plagioclase are, moreover, not stable together at pressures greater than 8 to 10 kbar (ref. 3) so the phenocryst assemblage cannot be explained as residual from the source mantle. This point has been made previously with respect to ocean floor tholeiite⁴ when I pointed out that olivine would not be present at the liquidus of the more siliceous of such rocks beyond ~2 kbar or the more basic beyond ~7 kbar. This has been confirmed recently by experiment⁵ and enstatite does not appear at the liquidus of these rocks at any pressure (the pigeonite which appears transiently in one sample investigated by Kushiro and Thompson has an Mg/(Fe+Mg)=0.845, much more iron-rich than presently suggested for residual upper mantle mineral compositions).

The values of M ($=100 \text{ Mg}/(\text{Mg} + \text{Fe})$) in the lavas change in such a way on passing northwards along the ridge that they would be in equilibrium with an olivine with $M=83$ to 78 (if all iron is present as FeO) or 86 to 81.5 (if 20% of all iron is present as Fe₂O₃) assuming the Roeder-Emslie⁶ empirical relationship to hold. These indicated olivines are approximately twice as ferriferous as the olivines of postulated fertile upper mantle ($M=88$ to 92) in the case of iron-rich basalts allegedly derived from the undepleted mantle plume, and also iron-rich relative to the olivines of postulated⁷ depleted upper mantle ($M=96$ to 94). In simple terms, these basalts are too rich in iron relative to magnesium to represent primary magmas from likely upper mantle compositions and an interval of olivine fractionation is indicated in order to decrease their M values relative to the true primary magmas⁴.

A true primary magma derived by substantial partial melting at pressures of 10 to 25 kbar as suggested by Schilling (ref. 1, Fig. 4) should be at a temperature above its liquidus on arrival at low pressure and, moreover, its composition

should bear no special relationship to that of a liquid in simultaneous cotectic equilibrium with several crystalline phases at low pressures. Yet it is clear that most of the basalts under discussion were erupted with phenocrysts of olivine, augite and plagioclase present. They seem to have had the temperature and composition of liquids in cotectic equilibrium with these three crystal species at low pressures and this has been confirmed experimentally in the case of the 1783 Lakagigar fissure eruption⁸ which seems to belong to the same petrographic group. Such relationships are a mandatory consequence if low pressure fractional crystallization had modified the magma compositions.

Nevertheless, basaltic liquids can be in equilibrium with olivine, augite and plagioclase over a considerable temperature range. It would be expected that those lavas erupted at the higher levels, which have higher Na/Ca and Fe/Mg ratios and higher Ti, K, P and REE than those erupted at lower levels, would have the lower liquidus temperatures and must, therefore, have been erupted at lower temperatures in order to contain the observed phenocrysts. This can easily be verified by experiment. Such a relationship accords with a model in which greater amounts of low pressure fractional crystallization affect those magmas which have to rise to higher levels before eruption. The temperature relationship is the reverse of that predicted by the plume model (ref. 1, Fig. 4).

The way in which the erupted magmas might be related to the true primary magmas has been explored from the theoretical point of view^{2,4} and substantiated by studies of an actual province⁹. Once olivine, augite and plagioclase are fractionating together at low pressure, or when eclogite fractionates at high pressure, large reductions in the residual liquid volume are possible without dramatic changes in the character of the residual magma, except with respect to its concentration of incompatible elements. The basalts under discussion seem to have been erupted from the condition of olivine-augite-plagioclase fractionation, but the basalts richest in the rare earth elements do not show the relative depletion in the lighter rare earth elements which is expected when significant fractionation of clinopyroxene has occurred.

The $(La/Yb)_{EF}$ ratio in the basalts poor in incompatible elements and collected south of 61° N (ref. 1, Table 1) is 0.28, indicating very substantial enrichment of heavy REE in these magmas relative to chondritic ratios. In the basalts rich in incompatible elements and collected north of 63° 50' N, the $(La/Yb)_{EF}$ ratio is 2.04, indicating massive relative and even absolute depletion of the heavy rare earth elements simultaneous with an approximately four-fold increase in the light REE.

Light REE depletion in the more primitive looking, potassium and titanium-poor basalts from the southern part of the ridge may be ascribed either to clinopyroxene fractionation, or better to derivation from the partial melting of a garnet-harzburgite source rock, which would represent a partially residual mantle^{4,7} after the prior elimination of clinopyroxene from the assemblage. Only eclogite fractionation from such liquids appears capable of producing residual liquids with the extraordinary depletion of heavy REE, simultaneous with massive enrichment of other incompatible elements which the more northerly basalts display.

I now suggest that all these basalt magmas erupted between 60° N and 65° N on the mid-Atlantic ridge may be derived from a similar parental magma. The differences arise because the outflow of magma was persistently greater in the area of Iceland itself¹⁰ leading to a greater elevation of the superstructure above the ocean floor. Magmas rising through this thicker superstructure exert a higher hydrostatic pressure at the source region and take much longer periods between formation and the eruption of some of the magmas on the surface, allowing greater scope for fractional crystallization at all pressures during ascent. The remarkable abundance of acid differentiates in Iceland fits naturally into this model.

The relative enrichment of incompatible elements, such as K, P, Y, implies that those basalts erupted at the highest levels (on Iceland itself) represent the residual liquid after the crystallization as olivine-gabbros or eclogites of at least 75% of some parental liquid if fractional crystallization is the sole cause of the variations.

The ultimate source of the primary magmas might be postulated to be the base of the upper mantle, which is the most likely region for an intersection of the geotherm with the solidus. Such a process, which requires a substantial heat flow from the lower mantle, has side effects capable of explaining plate decoupling, ocean floor spreading, "convective" return within the upper mantle and the geochemical problems of magmatic provinces¹¹. It does not require the extensive flow of solid mantle which is required by the "plume" or simple convection hypothesis, but I concede that it is no more successful than any other interpretation at explaining why Iceland should be a point of enhanced magma flow.

The grounds on which Schilling¹ rejected fractional crystallization as the origin of the geochemical differences between the abyssal and subaerial lavas were the increased $^{87}Sr/^{86}Sr$ and $^{207}Pb/^{206}Pb$ values in those basalts enriched in incompatible elements. The assumption that these isotopes cannot be fractionated is implicit. In the face of the evidence for substantial low and high pressure fractional crystallization of these basalts, it may be necessary to re-examine the proposition that isotope ratios do not change during such a process. At least part of the geochemical differences commented on by Schilling¹ are due to low pressure fractional crystallization. Only after these effects have been carefully unravelled will it be possible to determine whether or not there is any residual evidence for mixing of magmas from two fundamentally different mantle sources, one of which might then be interpreted as a mantle plume.

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Wave-like Disturbances in the Ionosphere

BEER¹ has recently suggested that atmospheric gravity waves could be expected to exist in the ionosphere as a result of the supersonic motion of the terminator. He reached this conclusion by drawing an analogy between the proposed production of gravity waves by the supersonic motion of the Moon's shadow on the Earth's atmosphere during a solar eclipse², and the supersonic motion of the Earth's terminator. At the mesopause the extent of the terminator's supersonic motion can be as great as $\pm 55^\circ$ latitude.

We find Beer's suggestion particularly interesting in the light of our observations of the behaviour of ionosphere electron temperature and density measured by the Langmuir