A Composite Diapir Model for Extensive Basaltic Volcanism
Magmas from Subducted Oceanic Crust Entrained within Mantle Plumes

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Abstract: A composite diapir model for extensive basaltic volcanism is proposed on the basis of the melting phase relations of subducted oceanic crust in the mantle. Ascending peridotitic diapir across 660 km discontinuity drags fragments of subducted oceanic crust stagnating there into the diapir and forms a “composite diapir”. Because of the differential melting between peridotite and oceanic crust, ascent of such a composite diapir can produce voluminous basaltic magma by melting of subducted oceanic crust, capsulated in solid peridotite. Release of the voluminous basalt magma would be triggered by partial melting of diapir-forming peridotite in the shallow upper mantle. Physical and chemical properties of the resulting hybrid magma can explain most features of continental flood basalt.

Key words: Composite diapir; continental flood basalts; hybrid magma.

Introduction. Subducted oceanic crust has potential to form chemically distinct magma source because of its evolved feature and its vast volume during the long history of plate subduction. Therefore, the fate of subducted oceanic crust is fundamental in understanding the evolution of the earth’s crust-mantle system. Recent experimental study¹ on the melting temperature of a MORB at high pressure suggests a unique melting behavior of subducted oceanic crust in the mantle. In this paper, we discuss the production of magma from subducted oceanic crust on the basis of its melting behavior in the mantle. Seismological and experimental observations suggest the stagnation of subducted oceanic crust at the boundary layer between the upper and lower mantle.²⁻⁷ Therefore, contrary to the previous studies discussing the recycling of subducted oceanic crust starting from the core-mantle boundary,²⁻⁷ we focus on the magma production originated from subducted oceanic crust trapped at the boundary layer between the upper and lower mantle. Physical and chemical properties of the resulting magma are inferred and are compared with the characteristics of a voluminous type of basaltic magmatism, continental flood basalts.

Melting phase relations of subducted oceanic crust and mantle peridotite. Melting curves of oceanic crust are shown in Fig. 1(a), compared with melting curves of mantle peridotite⁸⁻¹⁰ and with a mantle geotherm.¹⁰ There are two important features on the melting curves. First, the solidus temperature of the oceanic crust (labeled ‘BS’ in Fig. 1(a)) is much higher, by 600°C, than the predicted geotherm at the base of the upper mantle. This difference will ensure the long-term survival of subducted oceanic crust that has stagnated at the boundary between the upper and lower mantle because solid-state chemical diffusion is considered to be too slow to destroy the chemical heterogeneity. Unless mechanical mixing is very effective, continuous subduction of oceanic crust by plate tectonics will result in the formation of chemically distinct regions characterized by a basaltic composition at some depths within the mantle. Second, the liquidus temperature of oceanic crust (labeled ‘BL’ in Fig. 1(a)) is lower than the solidus temperature of peridotite in the pressure range between 3 and 11 GPa. This melting relationship is quite important to the composition of magma generated in an ascending diapir containing basaltic material.¹¹

Fig. 1(b) is a cartoon showing the “composite diapir”, i.e., upward migration of fragments of subducted oceanic crust enclosed within a peridotitic diapir. Supposing that a composite diapir with an excess temperature of 200°C, for
example, migrates upward from the base of the upper mantle along an adiabatic gradient, it will cross the solidus of oceanic crust at about 170 km depth (point S in Fig. 1) and the melt fraction will increase with ascent of the diapir. However, the temperature of the composite diapir is still lower than the peridotite solidus at this stage. Therefore the resulting basaltic melt would be capsulated in solid peridotite within the composite diapir consisting mostly of peridotite. Surrounding peridotite would hardly be assimilated because its melting temperature is much higher and orthopyroxene reaction zone formed at the boundary between basaltic magma and peridotite would prevent further reaction. The major-element composition of the basaltic melt would, therefore, be affected little by the surrounding peridotite. As the composite diapir containing melt pockets continues to ascend, it will cross the mantle peridotite solidus at about 70 km (point T in Fig. 1), and a small degree of partial melting of surrounding peridotite will occur. At the initiation of partial melting of peridotite, the molten fragments of oceanic crust initially isolated each other will connect and the resulting hybrid magma, a mixture of the molten oceanic crust and the incipient melt of surrounding peridotite, will rapidly segregate from the diapir because the density of the magma is smaller than that of the surrounding peridotite in this pressure range. \textsuperscript{12}

**Chemistry and physical properties of the magma derived from the composite diapir.** Concentrations of major and trace elements in the hybrid magma are calculated using batch melting model in the following three cases when the segregated magma consists of: (case 1) 100% melt of oceanic crust + 1% melt of peridotite; (case 2) 80% melt of oceanic crust (residual phase is clinopyroxene) + 1% melt of peridotite; (case 3) 75% melt of oceanic crust (residual phases are 20% of clinopyroxene and 5% of garnet) + 1% melting of peridotite. Table I shows the major element compositions of the hybrid magmas. In comparison with the case 1, high Fe/Mg ratio, enrichment of Ti and Na are attained in the cases 2 and 3 because of the existence of the residual phases. Even in the case 3, however, the composition of the magma is still basaltic. Addition of 1% of partial melt of peridotite does not significantly affect the major element concentrations because it has much smaller amount than the melt derived from oceanic crust. On the other hand, its effect on changing the concentrations of trace elements in the magma is remarkable. Since the partition coefficients of some light rare earth elements (LREEs) between peridotite-forming minerals and liquid are much less than unity (<0.001), a small fraction of liquid derived from peridotite strongly concentrates those elements. The influence of residual clinopyroxene and garnet on the concentrations of those elements within the hybrid magma is also large. The concentrations of LREEs in the magma are up to several times as much as those of the normal
MORB and around 20 times larger than those of C1 chondrite.

Temperature is one of the most important factors controlling the behavior of the magma because it affects density and viscosity. As a consequence of the composite diapir model, the initial temperature of the resulting magma when it segregates from the diapir is fairly higher (>50°C) than that of basaltic magma generated by peridotite melting. Its exact value depends both on the excess temperature present at the bottom of the upper mantle and on the fraction of oceanic crust within the composite diapir. It may be observed as a super-heated lava flow at eruption. Because of its high temperature, the viscosity of the magma will be low. After the calculation by Shaw, such a super-heated magma at the surface is about one order of magnitude less viscous than that observed in present-day ordinary basaltic eruptions.

A comparison with CFB. Hybrid magma derived from a composite diapir containing subducted oceanic crust possesses several distinctive features similar to those of continental flood basalt (CFB). CFB has many unique features. e.g. 1) Although the Fe/Mg ratio, Ti and K contents of CFB are usually higher than those of normal MORB, the other major element concentration is almost similar to normal MORB. 2) In terms of trace elements composition, CFB is more akin to enriched MORB and ocean-island basalt. Compared with normal MORB, incompatible elements, including LREE, are relatively enriched in CFB. 3) Vast amounts of CFB lava, ~10^6 km^3, have been produced within a short time span of several Myrs. 4) The aspect ratio of CFB flow, i.e. the ratio of lateral extent to thickness, is generally extremely large. For example, one flow unit of Columbia River Plateau traveled as far as several hundreds kilometers, whereas the average thickness of the lava flow is between 15 and 35 m. This feature can be ascribed both to high fluidity and to large effusion rate. 5) In terms of Nd and Sr isotopes, the isotopic composition of relatively uncontaminated CFB often lies between the most depleted region represented by normal MORB and the bulk earth composition (e.g. Deccan and Columbia River). 6) An apparent connection of CFB with hotspot activity is widely observed.

Most of these features of CFB can be readily explained by the composite diapir. As mentioned above, the major element composition of the magma derived from a composite diapir is not greatly deviated from normal MORB, but shows evolved nature in terms of Fe, Mg, Ti, Na and K as a result of residual clinopyroxene and garnet during melting.

The incompatible trace element concentrations in the above mentioned hybrid magma also agree with CFBs. Calculated REE pattern of the hybrid magma lies in the relatively unenriched area of the CFB field. Because the density of the magma is comparable to that of upper crust and because the temperature of magma is high, the involvement of the crustal material in the course of eruption is more or less inevitable. It will result in further enrichment of incompatible elements. Thus the diversity of the REE chemistry of CFB may be acquired by the reaction between parental basaltic magma derived from the composite diapir and crustal wall rocks.

Huge amount of CFB magma is also compatible with the composite diapir. Possible production rate of basaltic magma from a composite diapir can be roughly estimated using Stokes’ law. It is ~1.4 km^3/year when the excess temperature, fraction of oceanic crust, the viscosity of upper mantle, the diameter of diapir and the diameter of oceanic crust fragments are assumed to be 200°C, 15 wt%, 4 x 10^20 Pa s, 400 km and 5 km, respectively. The total volume of the magma is 4 x 10^6 km^3 during 2.9 Myrs. The ascent velocity of diapir is ~14 cm/year, and this figure is realistic based upon the velocity of material transport in the mantle expected from the present spreading rate of ocean floors. The exact production rate of CFB is difficult to evaluate because little is known about the span of CFB activity, but the rate is considered to be large. For example, the eruption volume is estimated to be 200,000 km^3 during 1.5 Myrs (0.13 km^3/year) for the Columbia River flood basalts and 1,500,000 km^3 during <3 Myrs (>0.5 km^3/year) for the Deccan Traps. These volumes are thought to be minimums because some magma must have stayed within the crust as either sills or solidified dykes. Therefore, the estimation of magma.

Table I. Major element compositions of magmas derived from the composite diapir

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<tr>
<td>SiO₂</td>
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<td>50.63</td>
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<tr>
<td>TiO₂</td>
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<td>1.66</td>
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<td>Al₂O₃</td>
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<td>MgO</td>
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<td>7.43</td>
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<td>CaO</td>
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<td>Na₂O</td>
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<tr>
<td>K₂O</td>
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<td>0.25</td>
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<tr>
<td>FeO/MgO</td>
<td>1.22</td>
<td>1.52</td>
<td>1.55</td>
<td>1.27</td>
</tr>
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</table>

(1) 100% melt of oceanic crust + 1% melt of peridotite;
(2) 80% melt of oceanic crust + 1% melt of peridotite;
(3) 75% melt of oceanic crust + 1% melt of peridotite;
(4) Composition of original MORB.
volume from the composite diapir is consistent with the observations on CFB.

The large aspect ratio of CFB flows also can be easily explained by the composite diapir model. The large effusion rate of the magma is important factor in causing a large aspect ratio of the lava flow.\(^{15}\) Although the present model cannot readily predict a high effusion rate within a short time span, a composite diapir has a potential to cause a eruption with high effusion rate. When the eruption is triggered by the disruption of the peridotitic capsule caused by partial melting of peridotite, a large volume of basaltic magma already exists in the diapir. Magma transport to the surface is assured by its relatively low density, and the existence of a large volume of melt will result in eruption with a high effusion rate.

As to the isotopic characteristics of the magma, a detailed discussion is not intended here because it is rather complicated. There are many factors which affect the isotopic composition of the magma erupting from a composite diapir. The age of subducted oceanic crust, its initial ratios of radiogenic to stable isotopes, possible chemical exchange with seawater, disturbance of parent and daughter element concentrations both by the dehydration process and by contamination of crustal components during subduction, etc. will affect initial isotopic ratios of the magma formed in the composite diapir.

The apparent connection between CFB and hotspot was first implied by Morgan\(^{20}\) and supported by many recent studies.\(^{17}\) In these studies, CFB is considered as the first volcanic expression after initiation of a hotspot by a mantle plume. The model proposed in the present study also considers a mantle plume as a heat source of the composite diapir. Therefore, the connection between CFB and hotspot is indispensable in the present model. Furthermore, once the basaltic fragments are exhausted to form CFB magma, further magma produced from the plume would be magmas which are equilibrated with mantle peridotite. This is consistent with the well-known observation that CFB is observed only at the initiation stage of the hotspot track.\(^{17}\)

In this paper, we focused on the fate of subducted oceanic crust trapped at the boundary between the upper and lower mantle, and discussed the possible involvement of subducted oceanic crust in the genesis of continental flood basalts. The behavior of subducted oceanic crust returned from deeper regions in the mantle is another interesting problem, but physical properties of both subducted oceanic crust and mantle material at higher pressures must be clarified first. However, even in this case, we would like to stress that the constraints from the melting behavior of composite diapir at shallow upper mantle depths are still applicable to diapirs which contain fragments of ancient oceanic crust. Since the entrainment of fragments of subducted oceanic crust into a plume is independent of surface lithospheric conditions, magma generated from composite diapir must be observed also in oceanic regions. We believe oceanic plateau is suitable province to test the model because contamination of the crustal materials might be minimal in such areas.

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References