Whole mantle convective model interpretation of oceanic basalt compositions: Are the geodynamical inferences of this model realistic?

M. Loubet

Université Paul Sabatier, UMR 5563, Laboratoire de Géochimie, 38 rue des 36 Ponts, 31400 Toulouse, France

The geochemical composition of oceanic basalts should represent a very interesting tool to discuss this problem (Hofmann, 1997). It can actually be thought that distinct geochemical characteristics should characterize oceanic basalts derived from mantle reservoirs evolving either through a layered or a whole mantle convective mode. In the large scale mantle convective mode for example, the time span from one convective turn to another would be rather large. According to present day plate velocities, and taking into account the generally admitted increase of mantle viscosity with depth, time span should be quite elevated and could reach half a billion year. Consecutively, in this convective mode, mixing of mantle materials within each convective cell and between convective cells will be minimized, allowing large scale mantle heterogeneities to persist. Mantle materials magmatically differentiated along the convective turns, such as the oceanic crust and complementary residual mantle could remain close one to another along several periods. If mid oceanic ridge basalts (MORB) and oceanic island basalts (OIB) form in the same convective cell from such magmatically differentiated sources, relationships between MORB and OIB compositions can be expected. The differentiation ages of the mantle sources indicated by the basalts compositions could be significantly old reaching possibly several billion years for differentiated sources which realized several convective turns without being involved in new differentiation processes.

The geochemical approach, however, presents difficulties. Interpretations of the oceanic basalts data can be numerous depending on the assumed nature of their sources. Furthermore within a model frame, expected compositions can extend on a large range, depending, for example, on melt tapping processes and more generally mantle geodynamics. These factors remain nowadays a matter of debate. To check the plausibility of a model, an interesting work is ultimately to discuss the geodynamical constrains used in the modelling or obtained from it.

Oceanic basalts database and whole convective mantle modelling

To discuss this mantle convective problem on a geochemical basis, two types of analysis were developed: (1) First a comprehensive data base of oceanic basalt compositions using literature data was created. Analysis of Sr, Nd and Pb isotopic and of incompatible trace element ratio data allows us to identify five distinct large scale oceanic domains, (Atlantic-East Pacific(AEP), Indian (I), Kerguelen-South Atlantic (KSA), Hawaii (H) and South Central Pacific (SCP)). (2) Secondly a simple comprehensive modelling, assuming whole mantle convection was developed. In this model, the heterogeneous mantle material composed mainly of recycled oceanic crust and residual mantle is, through the convecting process, subject to two main differentiation processes (a) partial melting during uprising giving rise in a first step to oceanic island type basalts (OIB) through a selective melting of the heterogeneous mantle source, and in a second step to mid-oceanic ridge basalts (MORB) through subsequent melting of the mantle sources. Consistent with present day observations, the plume/OIB and MORB type magmas concur to generate the oceanic crust. In the developed model OIB sources represent only 15–35% of the total mantle segment, and the MORB sources represent 70–75% of the total mantle segment. (b) CC differentiation during the lithospheric history of the oceanic crust and /or its recycling at subduction zones. It is assumed that the subducted oceanic crust is not isolated from the residual mantle during successive convective cycles. During subsequent uprisings, differentiated mantle segments melt again generating new oceanic crust. Along the successive cycles, mantle sources thus remain fertile allowing magma genesis to occur. The probability of melting a particular mantle segment during each overturn depends on its position in the convective cell and the lithospheric thickness above this cell. This variable melting probability leads to the distinct compositions and oceanic domains residual states, as well as to old differentiation ages of the oceanic basalts sources.

In a practical way, modelling is realized in a discrete way, and computes the composition of a mantle segment included in a convective cell through various cycles along through the Earth's history. Using classical sets of parameters, modelling takes into account the effects on the partial melting processes of a decrease of the Earth mantle temperature with time. Results were reported in two trace element ratios diagrams (Th/La,Ta/La), and (Th/U,Ta/U) and three isotope ratio diagrams ($^{87}Sr/^{86}Sr$,$^{143}Nd/^{144}Nd$), ($^{206}Pb/^{204}Pb$,$^{207}Pb/^{204}Pb$), and ($^{206}Pb/^{204}Pb$,$^{208}Pb/^{204}Pb$).

Consistency of the modelling results with oceanic basalts compositions

Modelling results obtained show that the geochemical basalt characteristics can be well fitted in such a whole convective model frame. Whole mantle convection satisfactorily explains the existence of: (1) large scale mantle heterogeneities (oceanic domains); (2) multiple mid-oceanic ridge basalts (MORB) and oceanic island basalts (OIB) sources; (3) relationships between OIB and MORB in each domain; (4) the old differentiation ages implied by both lead and osmium isotopic data. Furthermore, modelling shows that geochemical features which were presumed to support a two layer convective mode such as the uniform composition of the MORB are also consistent with whole mantle convection. In addition, in contrast to 2-layer mantle convection models; the single layer convection model can readily explain the apparent discrepancy between $^{208}Pb/^{204}Pb$ and Th/U ratios in the MORB, the apparent discrepancy between $^{143}Nd/^{144}Nd$ and Sm/Nd ratios in the MORB, and the elevated Nd isotopic composition of Archaean rocks.

Another interesting aspect of these results concerns the nature of the mantle sources inferred by this model. Modelling shows that material sources could be mainly composed by recycled oceanic crust segments differentiated at different periods of time associated with residual mantle. The oceanic domains distinguished are characterized by their distinct residual state and their last age of differentiation, shown to be indicated approximately in the ($^{206}Pb/^{204}Pb$,$^{207}Pb/^{204}Pb$) diagram.

Geodynamical inferences of the model: are they realistic?

The inferences of this model on melt tapping processes and mantle geodynamics should be analysed. Some of the geodynamical inferences may appear unrealistic, and then put severe restrictions on the advanced model. On the other hand, if they are valid, they will support the model. In the following we argue that most geodynamical implications of this model could be consistent with some present day observations.

(1) One first inference of this model is that MORBs should be generated from mantle sources depleted after OIB extraction. This implies that OIB extraction should occur at a very large scale. Most hot spot tracks are no more than 200–400 km wide suggesting that upwelling regions are often relatively narrow features, of the order of few hundred kms or less.

A number of geophysical observations, such as geoid and topographic anomalies and seismic topography studies indicate, however, that at least the upper portion of upwelling regions can be significantly larger. Large scale upwelling (2500 km wide) with OIB extraction have been shown for example in the Atlantic and western and Central Europe (Hoernle *et al.*, 1995). (2) The percentage of mantle which experienced CC differentiation is a strong constraint on the chemical mantle composition. Evaluation of this percentage is subject to large uncertainties in determining the relative mass of each domain within the mantle, or due to the uncertainties on the estimated CC composition. This percentage is constrained to be between the values obtained for the most residual oceanic domains (estimated 2.2% differentiated CC for the NAEP and H domains) and the values obtained for the less residual domains (estimated 0.8% differentiated CC for the KSA domain). This range only partly agrees with the 0.7% to 1.0% estimated range for the relative mass of the CC by Taylor and McLennan (1985). This may indicate that domains with low residual characteristics or primitive compositions remain hidden inside convective cells.

A mantle with convective cells keeping inside their structure mantle materials during long periods of time, preserving them from further partial melting and differentiation processes may appear unrealistic. However, according to some geophysical observations and modelling results mantle convection could be driven by recycled lithospheric slabs (Ricard *et al.*,1993). In these conditions, a mantle structure such as the one described previously may take place.

(3) Recycling time periods estimates can be deduced from the differentiation ages of mantle derived magmas deduced from analysis of the Pb isotopic data in the ($^{206}Pb/^{204}Pb$,$^{207}Pb/^{204}Pb$) diagram.