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GEOLOGY
Paper: Metamorphic and Igneous Petrology
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Table of Content

1. **Basic Introduction**
2. **Concept of Mantle Metasomatism**
3. **Agent for Metasomatism**
4. **Enrichment of lithospheric peridotites.**

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GEOLOGY

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1. Basic Introduction

The term metasomatism was originally coined by C.F. Naumann in Lehrbuch der Mineralogie, published by Engelmann in Leipzig (1826); it comes from the Greek $\mu\epsilon\tau\alpha$ (meta=change) and $\sigma\acute{o}\mu\alpha$ (soma=body). Metasomatism is a metamorphic process that involves the subsolidus modification (introduction and/or removal) of chemical components of a rock or a portion of rock because of invasive percolating aqueous fluids. During this process, the rock is in a solid state and the volume remains constant (Harlov and Austrheim, 2013).

The lithospheric mantle is a palimpsest recording the multiple fluid events that have affected each domain since it formed. These events, involving different fluids and compositions, have repeatedly overprinted variably depleted original mantle wall rocks. This produces a complex, essentially ubiquitously metasomatised lithospheric mantle, heterogeneous on scale of microns to terranes and perhaps leaving little or no “primary” mantle wall rock. Decoding this complex record by identifying significant episodes and processes is a key to reconstructing lithosphere evolution and the nature and origin of the volatile flux from the deep earth through time. Metasomatism of the crust or upper mantle can cause profound changes in the composition of rocks. Even small amount of magmatic or aqueous fluids controls the rate of metamorphic reactions. Thereby, reaction between the fluid/melt and peridotite may modify the phase assemblages of the mantle peridotite. Two of the hallmarks of this process are the presence of hydrous and other incompatible element-rich phases that texturally appear to replace the primary phases, and the marked relative enrichment in the light rare earth elements (LREEs) and other incompatible trace elements. For example, many peridotite xenoliths in basalts exhibit these metasomatic hallmarks (M. F. Roden, 1987). Some highly alkaline mafic and ultramafic magmas, calcareous skarn etc. are some other few examples.

The productions of enriched magmas from other unenriched mantle sources are explained by various metasomatic processes. During such processes, the rocks adjust to new physical conditions that differ from those under which the rock originally formed. A geochemical study of such rocks that has undergone any such

metasomatic changes gives us the knowledge of various metasomatic processes. Some examples of metasomatism are: contact metamorphism, the changes in mineralogy due to chemical reaction (e.g. in the contact aureole at Crestmore, California); Na-metasomatism associated with ocean floor metamorphism (e.g. sulphide precipitation in black smoker); alkali metasomatism associated with carbonatites that produce fenites; mantle metasomatism; infiltration; and depletion of granulites etc. Thus, we can say that metasomatism best developed in such situations where rocks of highly contrasting characters are juxtaposed and elements move easily. Some of the common examples include:

1. Shallow plutons where siliceous magmas contact calcareous or ultramafic rocks and fluids are circulated through open fractures.
2. Layers, lenses and pods with contrasting composition in rocks undergoing metamorphism: ultramafic pods in pelite or carbonates, interbedded carbonate and polytuff sediments.
3. Veins where fluids equilibrate with one rock type and then migrate into a contrasting rock types along a fracture.

Metasomatic processes coupled with igneous and tectonic processes, played a major role in the formations of Earth's crust and the lithospheric mantle, their ongoing evolutionary history and consequent mutual relationships with one another. Metasomatic processes include alteration of oceanic lithosphere, ore mineralization, mass transport, fluid flow, alteration of subducted oceanic and continental crust, volatile storage in the lithospheric mantle etc. (Harlov and Austrheim, 2013). Metasomatic events can be dated from the metasomatic alteration of accessory minerals like zircon, monazite, xenotime, or apatite and major elements such as feldspar, amphibole and micas provides the chemistry of the responsible fluid. Serpentinization of the oceanic crust, formation such as skarns and greisens are few examples indicating the massive fluid flow and total alteration of the original rock. The high-pressure rocks such as granulite, eclogite and blueschist facies rocks also provide similar evidence of widespread metasomatism. Metasomatism involves the re-equilibration of mineral assemblages due to change in pressure, temperature and chemical environment. It also involves the transport of materials on different length

scales. A simple example of mineral zonation due to metasomatism in ultramafic pods in pelites in the Shetland Islands is illustrated in figure 1. Such type of zonation occurs commonly at the margins of the pod because of the sharp chemical contrast across the contact (between ultramafics and country rocks-pelites). The number of zones, thickness and mineralogy depend upon the stability of the minerals and the ability of the components to migrate. These, in turn depend upon the P-T conditions, the nature and mobility of fluid phase and the composition of the juxtaposed rocks (Winter, 2001).

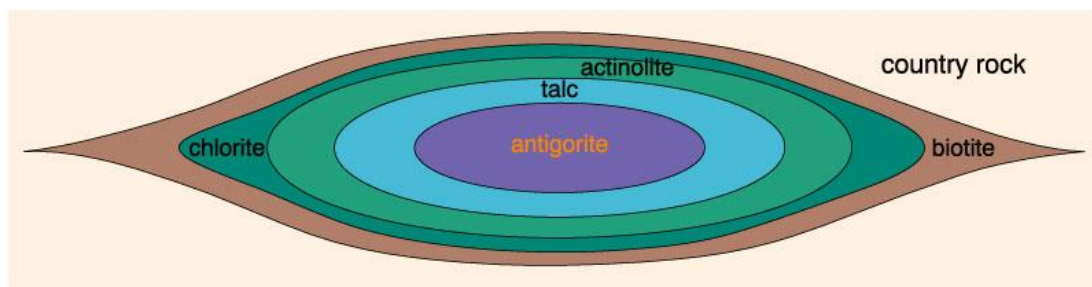


Figure 1. “Ideal” mineral zonation due to metasomatism in < 3-m long ultramafic pods in low-grade regionally metamorphosed pelites at Unst, Shetland Islands. Winter (2001).

2. Concept of Mantle Metasomatism

Mantle metasomatism has been widely accepted as one of the mechanisms by most of the workers to explain the enrichment patterns observed in various rock types. A critical, conceptual advance in understanding Earth’s geodynamic behavior is emerging from understanding the linkage between mantle metasomatism and the physical properties of mantle domains. So now let us study in detail the concept, agents of mantle metasomatism and the enrichment process of various incompatible trace elements.

Mantle metasomatism is a complex and diverse process in which the bulk composition and phase assemblages of a mantle peridotite are modified due to interaction with melt or fluid (Roden and Murthy 1985). It is the process of continuing chemical changes within the earth due to magmatic injection and the process of injection follows a specific chemical chronological order (early K

followed by Fe and Ti), as they are derived from increasingly low-pressure regimes over time (Wilshire).

Bailey (1970, 1972) explicitly introduced the idea of mantle metasomatism to explain certain features of the highly alkaline magmatism associated with uplifted and rifted continental regions. Since then numerous studies have carried out to study the metasomatic changes in mantle rocks. The process of both “infiltration” and “diffusion”, wherein the mobile components are transfer from one region to another, are brought forward while discussing mantle metasomatism. In such cases, the affected region can either be enriched or depleted depending on the addition or removal of the mobile components. However, mantle metasomatism refers only to the enrichment process whereby the abundances of incompatible trace elements are enriched relative to the presumed primitive or depleted mantle precursor. Specially, elements such as K, Rb, Sr, Ba, LREE, Ti, Nb, Zr, P, U and Th are enriched. Enrichment details depend on the nature of the liquid, partition coefficients between the metasomatizing liquid and the minerals in the wall rocks and the composition of the wall rock. Some metasomatism may be due to wall-rock alteration near magma bodies, but the evidence for metasomatism prior to melting opens the possibility that the process is a precursor to alkaline magmatism, giving the necessary source enrichment in lithophile elements. One example of metasomatic replacement or mantle replenishment process is identified in ultramafic xenoliths which are brought up in high-velocity alkaline eruptions. Metasomatism, as a large-scale process is indicated by the widespread distribution of alkaline magmatism in space and time: volatile flux through the lithosphere would then be the necessary precursor of metasomatism and magmatism. Thus, alkaline magmatism provides the best *prima facie* evidence of metasomatism and open-system conditions in the upper mantle (Bailey, 1987).

Two types of mantle metasomatism may be defined:

1. The first one is called **patent or modal metasomatism** in which the original minerals undergo textural recrystallization and are replaced by entirely new minerals within the mantle rocks. For example, an olivine-orthopyroxene

assemblage (harzburgite) may be modally metasomatized to a new mineral assemblage of amphibole and clinopyroxene. Here the melt or the fluid produces veining or secondary replacement and underwent mineralogical and chemical change in the rock as the growth of new minerals such as amphibole, apatite, carbonate, mica, ilmenite etc.

2. The second type is **cryptic metasomatism** where certain minor and trace elements are enriched by substitution in existing phases without textural changes or growth of new mineral. In short, cryptic metasomatism is related to change in chemical composition without obvious growth of new minerals. For example, original clinopyroxene may be made more Fe- rich, but the subtle chemical changes may not be obvious, hence the designation cryptic (hidden) metasomatism.

Obviously, these two types of metasomatism can develop simultaneously in same volume of rock; i.e. at some places, the original mineral composition are modified and at the same time another new one replace other unstable minerals.

Mantle metasomatism largely may occur at the Moho, where the density contrast between crustal rocks and mantle peridotite leads to the trapping and crystallization of alkaline basalts. Residual melts and fluids derived from these alkaline magmas are the agents of metasomatism. With time such metasomatised mantle will developed isotopic characteristic unlike most Na₂O rich alkaline basalts (but similar to some K₂O rich alkaline basalts). Consequently, it unlikely that old metasomatized mantle is the source of Na₂O rich alkaline basalts. The isotopic ratios of the peridotites from three examples (Nunivak, Kiama, St. Paul's Rocks), that are postulated to be metasomatised mantle show relatively low Rb/Sr and Sm/Nd ratios (M.F. Roden, 1987). Alkaline magmatism is the results of complex, multistage processes, and it occurs in a variety of settings. Mantle metasomatism is required for most alkali rocks, from kimberlites to comendites, but the alkalinity of much magma is also enhanced by fractionation and crustal assimilation. Moreover, hydrous phases such as phlogopite and amphibole are of great importance to mantle metasomatism. Hydrous peridotites contribute substantial LIL, Fe, Al and alkali enrichments, they

also provide H₂O, CO₂ and other essential volatile fluxes, thus are likely the source of alkali melts. Certainly, the increase in LREE/HREE in mantle clinopyroxenes correlates strongly with the development of hydrous phases in the peridotite host.

Overall, mantle metasomatism has been attributed to a variety of: (1) processes, (2) sources, and (3) melt–fluid compositions. Which factors dominate in creating specific metasomatic signatures in the continental lithospheric mantle remains widely debated. Another widely debated topic of mantle geochemistry is the provenance (sources) of melts and fluids responsible for metasomatism in the continental mantle. The metasomatic media (such as silicate and carbonate melts, water- and CO₂-rich fluids) originate within the lithospheric mantle, deep mantle plumes and convecting asthenosphere or subducted oceanic lithosphere that are derived from different sources (Beccaluva *et al.*, 2001; Downes, 2001 and references therein). The carbonate rich melts have a strong potential for enrichment of specific trace elements (Rudnick *et al.*, 1993). A simple illustrative diagrams showing the effect of metasomatism on mantle sulfides is shown in figure 2. Sulfides are sensitive to many processes, including melt removal and metasomatism (figure 2). Due to the low melting temperature of sulfide, the heating events and extensive melt/rock reaction trigger sulfur loss, while volatile-rich metasomatism may add significant amount of sulfide.

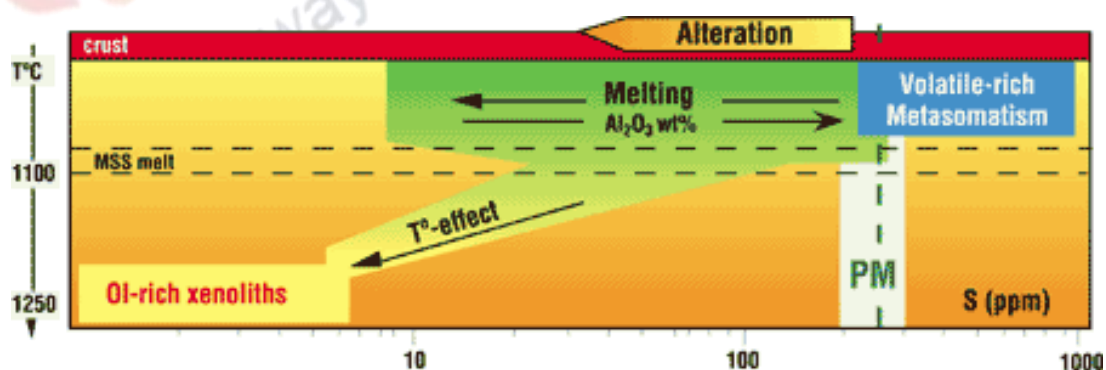


Figure 2: Effects of different processes on mantle sulfides.

3. Agent for metasomatism

The production of enriched magmas from otherwise unenriched mantle sources through mantle metasomatism has been explained in numbers of ways. In particular, metasomatism of a sub-continental lithospheric mantle is indicated as an important contributor to the elevated incompatible element enrichment of highly alkaline magmas. Some of the possible agents of metasomatism include:

1. Volatile primary magmas, such as kimberlite and carbonatites that stall at the resistant lithosphere or the solidus ledge where they solidify and released an enriched volatiles phase into the wall rocks.
2. Supercritical volatile fluids from the deep asthenosphere or subduction zones.
3. Silicate melts
4. H₂O or CO₂ fluid

Numerous authors include addition of melt such as dikes, lithospheric underplates and other stalled bodies under the general term “metasomatism”. However, such term should be restricted to additions by diffusions or pervasively infiltrating fluids. Such melts may add material by injection or may alter the adjacent rocks if they are volatile-rich by metasomatic fluid emanations. Melts may nonetheless be an important agent for enriching the upper mantle. On a small scale (such as a vein network) the melt/fluid distinction becomes difficult, and lax terminology is understandable. Any or all of the agents above may produce enriched zones or veins in mantle peridotites, so it is not a matter of finding some universally correct process (Winter, 2001).

Metasomatic fluids or vapors invade rock volumes by infiltration along cracks and grain boundaries. These processes are well demonstrated in some types of ore deposits (Lindgren, 1928), where evidence suggests that metasomatizing agents were introduced by intrusions. Fluid-aided mass transfer and subsequent mineral re-equilibration are the two defining features of metasomatism in a silicate rocks and must be present in order for metamorphism to occur. Taking into account geological

time scales, the amount of fluid required need not be great (considerably less than 0.01 % of the total volume of the rock) nor even in continuous flow but the fluid must be able to actively flow along grain boundaries and be chemically reactive with respect to the minerals it encounters such that efficient mass transfer is promoted. If the fluids are quite chemically reactive, the possibility exists of fluid flow through the minerals themselves in the form of migrating fluid inclusion or porosity. Lack of fluids generally means lack of re-equilibration between minerals and consequently a lack of information regarding the true P-T-X history of rock ((Harlov and Austrheim, 2013). The distribution of fluid depends upon the quantity of fluid present and the dihedral angle (Θ) of fluid-mineral triple point (Figure 3). The distribution of fluid of a single grain at $\Theta < 60^\circ$ and $\Theta > 60^\circ$ and the intersection of the grain at $\Theta = 60^\circ$ is display in figure 3. When $\Theta < 60^\circ$, means when the dihedral angle is low, the fluid forms a continuous grain boundary network or a network of interconnected tubes at the edges of grain whilst when $\Theta > 60^\circ$, the tubes pinch off and the fluid beads up as an isolated pocket at grain-edge intersections (Figure 3, Winter, 2001). Mantle metasomatism involves an enormous variety of fluid types. These includes silicate melts ranging from mafic to ultramafic; carbonatite melts; sulphide melts; C-O-H fluids ranging from water to CH_4 and CO_2 ; dense brines and hydrosilicic fluids and hydrocarbon bearing fluids. Under some environmental condition, some of them appear to be miscible to one another while others are immiscible. In addition, coexistence and interaction of different fluid types within single volumes of the mantle on short time scales are evident (Harlov and Austrheim, 2013).

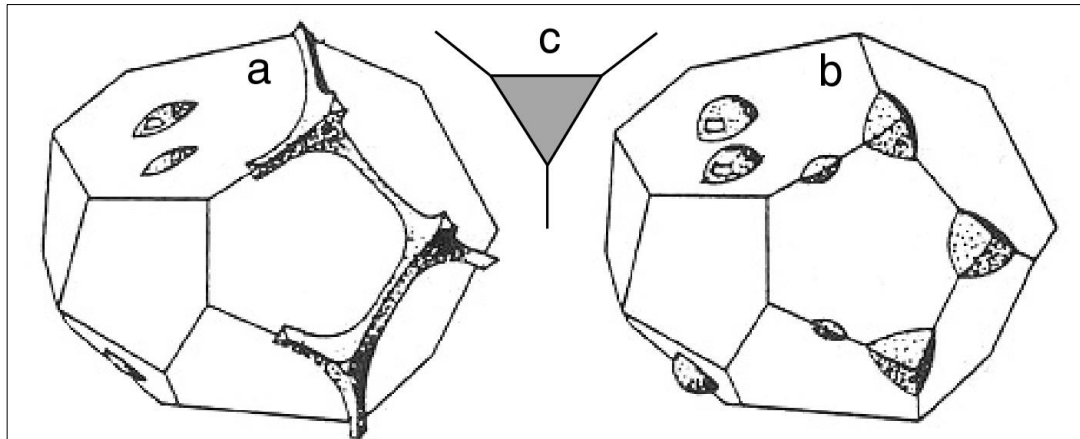


Figure 3. Three-dimensional distribution of fluid about a single grain at $q < 60^\circ$ (left) and $q > 60^\circ$ (right). In the center is a cross section through a fluid tube at the intersection of three mineral grains for which $q = 60^\circ$. After Brennan (1991).

Alkaline silicate melts are found associated with the formation of carbonatites by partial melting in the lherzolite-C-O-H system. Some alkaline silicate melts can dissolve 10 to 20 wt.% carbonate (Wyllie, 1989), and fractional crystallization of non-carbonate phases from a carbonated Ne-normative magma could concentrate CO₂ in the remaining liquid to the point of carbonate saturation, resulting in a residual carbonatitic liquid (Lee and Wyllie, 1994). Carbonatite are igneous rocks and are produced by melting of the mantle. Fractional crystallization, liquid immiscibility and direct partial melting of hydrous-carbonated lherzolite can produce carbonatite rich melts. Peter Wyllie proposed a simple model for the genesis of carbonatites which is shown in figure 4. In this figure, at point 2 melting occur as rising lherzolite exceeds solidus temperature when sufficient CO₂ and H₂O are available in a rising asthenospheric mantle plume along the geotherm. And at point 1, accumulation of primary carbonatite melts at the lithosphere-asthenosphere boundary. They began to solidify at sub-solidus temperature at point 3 when encounter the solidus. The released volatile resulted in metasomatism of the adjacent mantle wall rock. The rising asthenospheric plume resulted higher degree of partial melting producing alkaline silicate melts such as nephelinites, carbonatites and kimberlites. The melt rises adiabatically and reach point 4, where again they crystallize releasing volatiles, metasomatizing, and fracturing the wall rocks. The

melts that rise from point 4 reached the crust and form large bodies that are capable of differentiating. The asthenosphere remains the main contributors of carbonatite magmas, and volatile driven plume or hot-spot play a major role during their genesis. Thus, carbonatite derives from each of the above processes reach the surface at one location or another (Winter 2001).

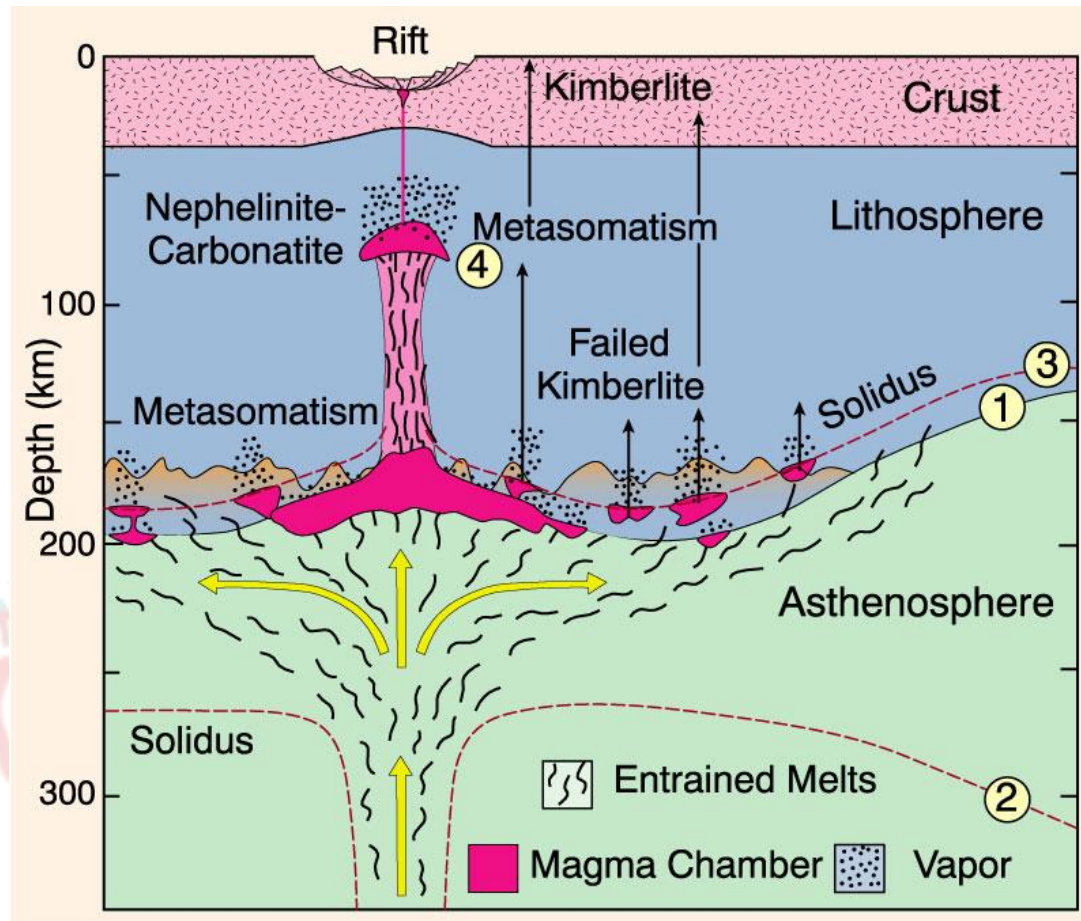


Figure 4. Schematic cross section of an asthenospheric mantle plume beneath a continental rift environment, and the genesis of nephelinite-carbonatites and kimberlite-carbonatites. (From Winter, 2001 and references therein).

Subduction zone metasomatism initiated at a shallow level. As oceanic slabs enter the trenches, they bend and are potentially infiltrated by seawater, and a sedimentary section begins their journey into fore arcs resulting in extensive physical compaction, fluids expulsion and diagenetic alteration (Figure 5). Experiment studies predict dramatical changes in the physicochemical properties and

metasomatic capabilities of subduction zone fluids as a function of depth. Moreover, the mobility of the fluids at scales up to tens of km, lead to myriad metasomatic effects in subduction zones, with larger-scale manifestation including the metasomatism related to mass flux leading to arc magmatism and convergent margin volatiles cycling (Harlov and Austrheim, 2013).

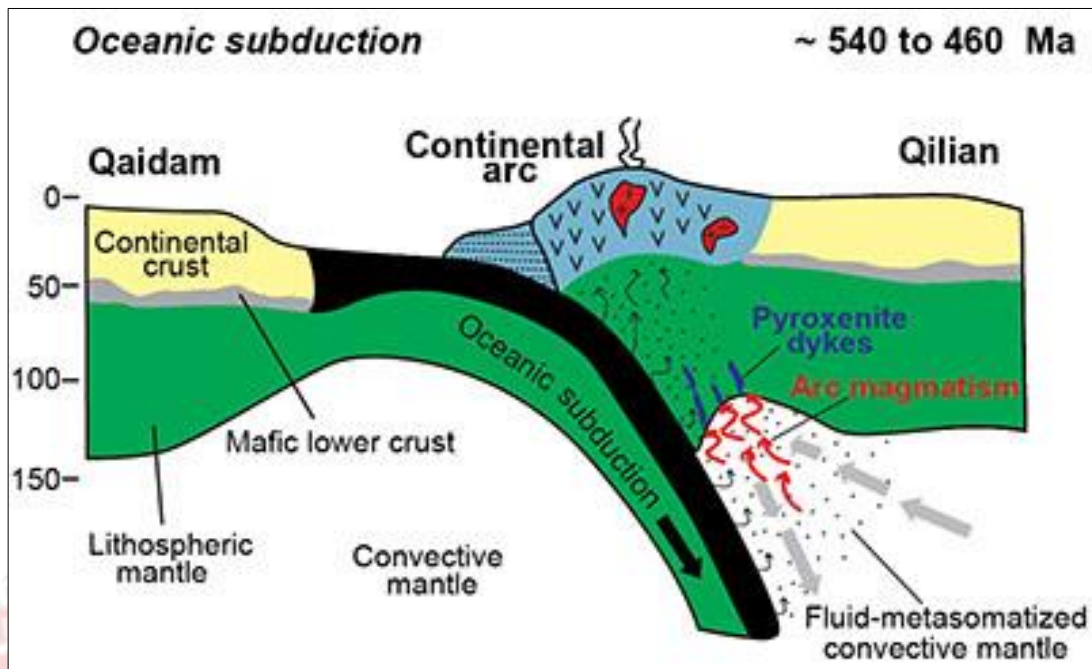


Figure 5: A model example of metasomatism in subduction zones of subducted oceanic slabs.

Another model is displayed for the formation of metasomatic veins (Figure 6, Pilet et al 2011). In this figure, the starting point is the generation of liquids by low degrees of partial melting at high pressures upwelling of the asthenosphere beneath rifting lithosphere. These low-degree melts then ascend into the lithosphere, metasomatizing it as they interact chemically with their surroundings. They form veins below a parcel of lithosphere. This could occur in a variety of environments (Figure 6) including small degrees of “wet” melting during normal upwelling beneath a mid-oceanic ridge at the periphery of an ascending plume beneath continental or oceanic lithosphere or during by precipitation of the phases that crystallize from them progressively as they cool. Alkaline melts are then formed by melting of the assemblage of veins and metasomatized peridotite (Pilet et al 2011).

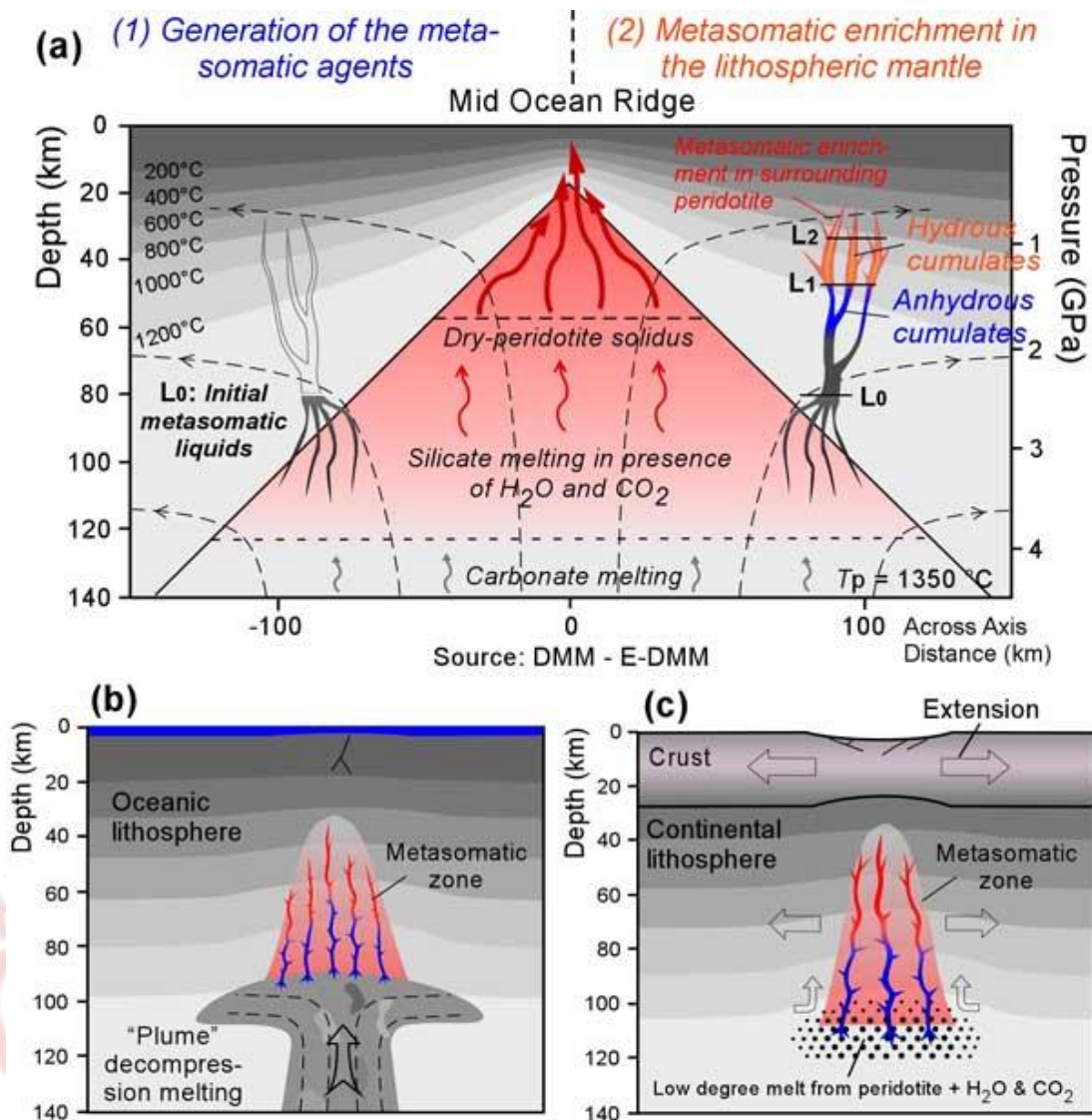


Figure 6 (a) Schematic model for lithospheric metasomatism at the periphery of a mid-oceanic ridge. (b) Schematic model for the metasomatism of oceanic lithosphere induced by a mantle plume. (c) Schematic model for the metasomatism of the continental lithosphere (*Pilet et al 2011*).

In Figure 6(a), model for lithospheric metasomatism at the periphery of a mid-oceanic ridge is shown. This model assumes that near-solidus liquids produced at depth in the melting column are not collected to form MORB, but percolate across the cooling lithosphere and generate anhydrous and hydrous cumulate veins plus cryptic and modal metasomatic enrichment in the adjacent peridotite. The geometry and thermal structure of the cooling lithosphere is based on the model published by

Shaw et al. (2010) for the Gakkel Ridge. Again, Figure 6(b) display a schematic model for the metasomatism of oceanic lithosphere induced by a mantle plume. In this model, some of the melts produced by plume upwelling do not reach the surface but percolate through and differentiate within the oceanic lithosphere producing anhydrous and hydrous cumulates plus metasomatic enrichment in the lithospheric peridotite surrounding these cumulates (Halliday et al.,1995). In the model display in figure 6 (c), the generation of asthenospheric melts responsible for the formation of metasomatic veins and cryptic and modal metasomatism in adjacent peridotite surrounding the veins is due to upwelling of the asthenosphere beneath rifting lithosphere or to ‘finger-like’ plumes ((Pilet et al 2011 and references therein).

4. Enrichment of mantle peridotites

Peridotite is a coarse grained, dense ultramafic rock consisting mostly of olivine and pyroxene and usually silica less than 45%. Peridotite is derived either as crystal accumulated from magmas, or as solid blocks and fragments from the Earth’s mantle. Mantle rocks appear to be dominantly spinel or garnet- bearing Mg and Cr-rich peridotites. Nearly ubiquitously, peridotites found associated with mafic rocks types of lesser abundance, we can name dikes as one examples (Nielson and Noller, 1987). Lithospheric mantle comprises of many rocks type, some of them are defined as: 1) Peridotite mantle wall rock (over 95% by volume) are ultramafic (olivine dominated) in composition and may contain orthopyroxene (Harzburgites), clinopyroxene (wehrlites), or orthopyroxene+ clinopyroxene (Iherzolites) as well as aluminous phase (garnet, spinel or plagioclase depending on the pressure-temperature environment; garnet and chromite may co-exist); 2) Eclogites are clinopyroxene+garnet rocks, mafic in bulk composition and equilibrated under high-pressure and low geo-thermal gradient conditions in the lithospheric mantle; they may represent subducted crustal material or igneous intrusions. 3) Pyroxenites are mafic in composition and represent frozen basaltic magmas, cumulates, and fractionates, most commonly intruded into young (Phanerozoic) mantle domains (Harlov and Austrheim, 2013).

Enrichment of the mantle peridotites is quite an example of metasomatized mantle. The enrichment of incompatible trace elements (LREE) of metasomatised rocks (Kimberlites, orangeites and Lamproites) are displayed in figure 7 with typical OIB and MORB (Winter, 2001). Available geochemical and isotopic data from peridotite xenoliths show the evidence of metasomatism characterized by enrichment of LREE relative to HREE in the bulk whole rock and clinopyroxene and the indication of the presence of secondary hydrous minerals. Such enrichment could be caused by the intrusion of mafic melt. Clinopyroxene may become enriched in LREE at the same time that hydrous minerals are deposited and minerals of the peridotite wall rock are enriched in Fe-Ti and Al by reaction with volatile-rich fluid from a dike (Fe-Ti metasomatism) (Nielson and Noller, 1987).

Direct evidence for metasomatic processes in the subcontinental lithospheric mantle (SCLM) is provided by mantle rocks in two very different geological situations. The first comprises xenoliths and xenocrysts entrained in a spectrum of magmatic rocks. Example: Kimberlitic and alkali basalts while the other type of occurrence such as ultramafic massif, ophiolites and ocean floor peridotites comprises fragments of upper mantle that have been tectonically exposed and emplaced into the crust (Harlov and Austrheim, 2013). Ultramafic massifs have the advantage of exposing large volumes of upper mantle material from which one can define the rock-type relationships, intrusive magmatic (dikes, veins) relationships and the effects of fluid infiltration whereas xenoliths and xenocryst are smaller samples thus relationship between the rock types are easily visible.

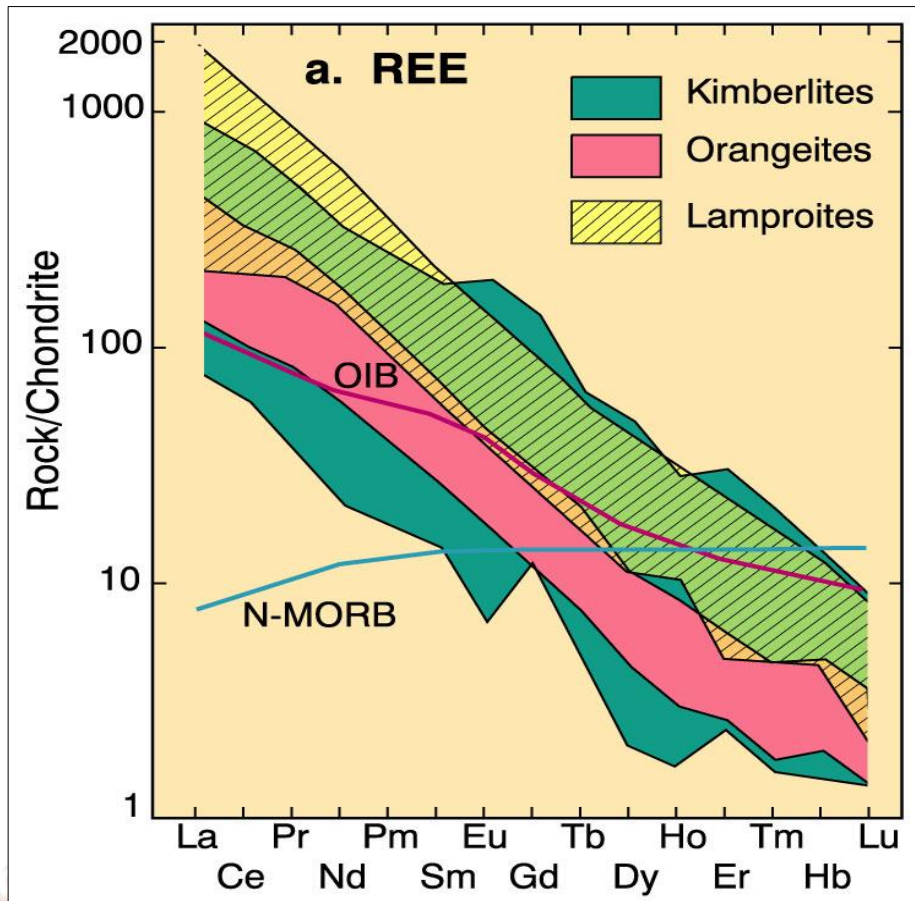


Figure 7. Chondrite-normalized REE diagram for kimberlites, unevolved orangeites, and phlogopite lamproites (with typical OIB and MORB), Winter (2001).

Microscopic solid and fluid inclusions in the peridotite xenoliths are the sources of incompatible elements. The distribution pattern of such inclusion observed in the composite xenoliths indicates that mantle fluids can add them. The enrichment of LREE/HREE in peridotite xenoliths in the bulk rock is controlled by olivine rather than by pyroxene, which may be due to enriched LREE inclusions in olivine and other minerals that do not accommodate REE in structural sites. Such evidence of the enrichment proposes that mantle metasomatism consequences from reaction between fluids differentiate of mafic melts and peridotite wall rocks. Differences of initial melt compositions, degrees of melt differentiation, and ratios of peridotite to melt all impact the LREE and isotopic compositions of metasomatized mantle rocks.

In the past few decades, mantle metasomatism has attracted considerable interest. We have seen several examples in which a metasomatized source was essential in order to model effectively the high incompatible trace element concentrations or isotopic enrichment of diverse mantle origin alkaline rocks. Minerals such as K-richrichterite, phlogopite, diopside, LIL-titanites, calcite and zircon added to previously depleted harzburgite to generate lamproites, orangeites, etc. Some of the volatile-enhanced sources such as hydrated and carbonated lherzolites can also derived highly alkaline melts. Therefore, in order to explain the enrichment process, numerous models and experiments for mantle metasomatism proposed. In one of the experiment (Meen et al., 1989), demonstrate in what ways the volatile alkaline melts interact with peridotites beneath carbonatite-alkaline silicate rock complexes, dissolving olivine and orthopyroxene and precipitating Ca-rich clinopyroxene, and perhaps accompanied by carbonate or amphibole in vein networks of clinopyroxene or wehrlite (Winter, 2001).

All of the methods above have the air of assumption without some hard evidence, for example, sample of metasomatized mantle. Although a variety of magma types are known to bring ultramafic xenoliths to the surface, most are cognate (typically cumulates) or refractory residua. Kimberlite and orangeites, on the other hand, perhaps to their more rapid rise, have delivered the most varied and extensive collection of crustal and mantle xenoliths of any magma type. The deep-seated inclusions include garnet peridotite, spinel peridotite, dunite, harzburgite, websterite, and eclogite, as we might expect (Winter, 2001). Most of these deep-seated inclusions appear to be pristine and relatively unaltered throughout their transport to the surface. Some, however, contain minor amounts of amphibole or mica. Such mantle samples are valuable natural mantle specimens provided to experimental petrologists that help them construct a mantle model system and its derivative magmas to test against the natural phenomena. In addition to the “typical” mantle samples, kimberlite and orangeites contain a host of enriched and metasomatized ultramafic samples, including phlogopite clinopyroxenites, “glimmerites” (phlogopite rich rocks), apatite-amphibole pyroxenites, and the “MARID” suites

(Mica-Amphibole-Rutile-Illmenite-Diopside rocks, Dawson and Smith, 1977, Winter 2001). Some patent-metasomatized xenoliths in alkaline-volcanic and kimberlites also exhibit veins with amphibole, mica, diopside, carbonates, and/or REE-rich titanite pegmatites. In some peridotite xenoliths, the magmatic dikelets of K-rich magma have added K, Fe, OH, and REE metasomatically to previously depleted wall rocks. The evidence for carbonatitic melts enriching depleted mantle xenoliths is also reported (Rudnick et al 1993, Winter, 2001).

Frequently Asked Questions-

- Q1.** What are the two main types of mantle metasomatism? Give one examples of each types?
- Q2.** Name some of the few lithophile elements that are added or enriched due to metasomatism process?
- Q3.** What are the defining features of metasomatism in a silicate rocks?
- Q4.** Explain the role of fluids as an metasomatic agents?
- Q5.** Explain the enrichment process of mantle peridotite by different metasomatic processes?

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