GEOLOGICAL SOCIETY OF AUSTRALIA (W.A. DIVISION)

SPECIAL INVITED LECTURE

The constitution and evolution of the mantle A.E. Ringwood

Professor Ringwood's lecture will be delivered on 11 August 1986 at a special meeting of the Western Australian Division of the Geological Society of Australia, held in conjunction with the Fourth International Kimberlite Conference.

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COMPOSITION

The bulk chemical composition of the upper mantle beneath the ocean basins can be estimated on the basis of petrological relationships between various classes of basaltic magmas and residual peridotites, interpreted in the light of geochemical and experimental petrology data. Several techniques of deriving this composition, 'pyrolite', have been employed. These include the complementary relationships between MORBs, komatiites and their residual harzburgites and dunites. Another approach is based upon the recognition of particular peridotites which have experienced only minor losses of magmatic liquids and which remain geochemically fertile in their capacity to produce basaltic magmas by more advanced degrees of partial melting.

Estimates of the pyrolite composition obtained by these methods are in good agreement. They are characterized by near-chondritic ratios of many lithophile involatile elements such as Ca, Al, Ti, Zr, Hf, Sc, Y, heavy and intermediate REE. Highly incompatible elements such as light REE, U, Th, and Ba are substantially depleted compared to chondritic abundances. These depletions are believed to have arisen via the extraction from pyrolite throughout geological time of small amounts of highly alkalic liquids strongly enriched in incompatible elements. It seems possible that at an early stage of the Earth's history, these incompatible elements were originally present in pyrolite in chondritic relative abundances. The pyrolite composition in turn can be related to the primordial abundances of elements as displayed by Cl chondrites, via processes which involve loss of volatiles and partial reduction of oxidised iron and nickel to the metallic state. Significant amounts of silica must also be removed in order to preserve this close relationship. Alternative interpretations propose that silica was removed as a volatile species in the solar nebula prior to accretion, or that the silica deficit in the upper mantle is compensated by excess silica in the lower mantle, so that the Mg/Si ratio of the bulk mantle is similar to that of Cl chondrites.

The pyrolite bulk composition prevails in the upper mantle beneath ocean basins. However the upper mantle layer immediately underlying stable continental regions differs from pyrolite in several important respects. Its composition is obtained from analyses of mantle xenoliths brought to the surface in kimberlites and alkali basalts and is characterised by marked depletions in Ca, Al, Na and Fe as compared to pyrolite. These depletions were caused by previous extraction of basaltic magmas. The distribution of incompatible elements in this layer is extremely heterogeneous, testifying to a complex, multi-stage history of prior melt extractions, melt additions and metasomatism. Many localised regions are enriched in incompatible elements and are capable of yielding specialised varieties of basaltic magmas when subjected to small degrees of partial melting. The sub-continental mantle is significantly less dense than pyrolite under equivalent P,T conditions and hence is gravitationally stabilized, forming a long-lived chemical boundary layer. The thickness of this layer varies widely, but probably extends at least to 200 km in some regions. When continents and sub-continental lithosphere are rifted to form new ocean basins, MORB basalts are erupted along the new oceanic ridges, strongly implying that upper mantle of pyrolite composition extends continuously beneath the 'depleted' sub-continental chemical boundary layer.

The copious volumes of MORBs and komatiites which have been erupted during and since the Archaean implies that the pyrolite composition has predominated in basaltic source regions of the upper mantle throughout geological time. The near-chondritic ratios of many involatile lithophile elements in pyrolite provide an important boundary condition for geochemical earth models and place severe limitations upon hypotheses which invoke large-scale melting of the mantle early in the Earth's history. If large-scale melting did occur, subsequent mixing processes via solid state convection must have been extraordinarily effective in re-establishing the degree of homogeniety in pyrolite (over scales of a few kilometers) which is recognized today. Recent high pressure experiments have shown that the temperature interval between the solidus and liquidus of pyrolite narrows considerably at pressures of 12-15 GPa. This has been interpreted to imply that upper mantle pyrolite was itself produced by partial melting of more primitive material at greater depths. However, the thermodynamic basis for this inference is non-unique. Experimental studies show that majorite garnet would be the principal residual phase in the source region where partial melting is inferred to have occurred (400-600 km). This would probably have caused substantial relative fractionations of Ca, Al, Ti, Zr, Sc and heavy REE to a degree which makes it very difficult to explain the near-chondritic relative abundances of these elements in pyrolite.

CONSTITUTION

The phase transformations which are experienced by pyrolite and other relevant mantle compositions such as harzburgite and eclogite are reviewed in some detail. The olivine component of pyrolite transforms sharply to the β -Mg₂SiO₄ structure near 400 km, whilst pyroxene dissolves in the garnet structure over a broad interval between 350-450 km. At a depth of about 550 km, the beta phase transforms to spinel and so the stable mineral assemblage between 550-670 km consists of spinel + garnet. Near 670 km, spinel disproportionates to MgSiO₃ perovskite + magnesiowUstite, whilst the transformation of garnet, mainly to perovskite-related phases, occurs over a broad depth interval between 500-670 km. The phase transformations experienced by harzburgite between 500-670 km are substantially different to those of pyrolite because of the lower Ca and Al contents of harzburgite. These differences have significant geodynamic implications and are discussed later. Basaltic compositions transform successively from basalt/amphibolite to eclogite to garnetite and finally to perovskitie. Recent experimental data show that the transition of eclogite to garnetite is complete by 450 km and contradict arguments that the mantle between 450-600 km is composed of 'piclogite'.

Despite many decades of effort by seismologists, appreciable uncertainties remain in the distributions of P and S wave velocities with depth. It is important that these uncertainties be considered when attempts are made to use seismic velocity distributions as constraints on petrological models. There is a clearly-defined low velocity zone beneath ocean basins, extending approximately from 70-150 km, which is widely attributed to the occurrence of a small degree of partial melting. A less well-defined low velocity zone for S waves can be recognised beneath stable continental regions. Some but not all sub-continental profiles show evidence for a sharp increase of velocity near 200 km which is difficult to explain in terms of known phase changes or plausible changes in chemistry and mineralogy. It is possible that the "200 km discontinuity" is caused by a high degree of velocity-anisotropy in a layer near this depth, which may mark a zone where the sub-continental tectosphere is mechanically decoupled from underlying mantle.

Seismic profiles display large velocity discontinuities at depths near 400 and 670 km. The capacity of pyrolite and related compositions to explain the seismic velocity distributions is examined below. The transition of olivine and pyroxene to β -Mg₂SiO₄ plus garnet provides a quantitative explanation of the velocity changes associated with the 400 km discontinuity within the limits of error of the seismic velocity determinations. Likewise, seismic velocities in the region between 400-670 km are consistent with this region being of pyrolite composition and crystallizing as an assemblage of $\beta,\gamma(Mg,Fe)_2SiO_4$ spinel + garnet. The depth of the 670 km seismic discontinuity corresponds closely to the pressure at which spinel disproportionates to $MgSiO_3$ perovskite plus (Mg,Fe)O magnesiowistite. Considerable controversy exists as to whether this transformation, together with a related transformation of garnet to perovskite, is capable of providing an adequate explanation of the 670 km discontinuity and the properties of the lower mantle, or whether in addition, a major change in chemical composition occurs at this depth, e.g. an increase in SiO_2 and a decrease in Recent experimental data have shown that the spinel to perovskite plus FeO. magnesiowüstite transformation is sharper than previously realized and is probably capable of explaining the sharpness of the 670 km discontinuity. Moreover the elastic properties and density of the lower mantle are readily explained within their observational uncertainties by a pyrolite composition crystallizing as an assemblage of perovskites plus magnesiowüstite.

It is concluded that a substantial change in chemical composition at the 670 km discontinuity is neither required nor implied by available geophysical data. Whilst a substantial change in chemical composition cannot be excluded, it would represent a somewhat arbitrary assumption. An essentially isochemical interpretation of the 670 km discontinuity is favoured by other sources of evidence, which, whilst not compelling, are nevertheless strongly suggestive. These include (1) the close geochemical relationship of upper mantle pyrolite to a chondrite-derived composition suggests that the pyrolite composition is essentially primitive and is unlikely to have been formed by differentiation of even more primitive parental material in the lower mantle, (2) recent seismic evidence suggests that subducted slabs may penetrate deeply below the 670 km discontinuity to an extent which implies continuing and extensive interchange of material between upper and lower mantle, (3) it would be highly coincidental for the depth of a gross change in mantle chemical composition to be identical with the depth of which (Mg,Fe)_SiO4 spinel happens to transform to perovskite plus magnesiowidstite.

GEOCHEMICAL AND DYNAMICAL EVOLUTION

The geochemical evolution and dynamical behaviour of the mantle are strongly influenced by the petrological differentiation of pyrolite at mid-oceanic spreading centres to form new oceanic lithosphere. This consists of a basaltic crust underlain by harzburgite and further underlain by pyrolite which has experienced depletion only of highly incompatible elements. When this differentiated lithosphere is ultimately consumed at trenches, the gravitational body forces driving subduction are concentrated mainly in the upper cool, dense and brittle layers of basalt and harzburgite. The density contrast between the lower layer of depleted pyrolite and surrounding mantle is small and so this layer experiences a correspondingly small body force. Because of its relatively ductile nature, depleted pyrolite is continually eroded from the base of the sinking plate and resorbed into the convective system which circulates within the upper mantle. Mixing of depleted pyrolite into the upper mantle generates source regions for mid-oceanic (MORB) basalts which are produced during subsequent partial melting episodes. Chemical and isotopic characteristics of MORB's can be explained on the basis of this model.

The slab which sinks to the 670 km seismic discontinuity is comprised mainly of former basalt and harzburgite. These differentiated layers undergo a significantly different series of phase transformations to those experienced by mantle pyrolite. Former basaltic crust remains 0.1 - 0.2 g/cm³ denser than surrounding pyrolite above and below the discontinuity. However former harzburgite becomes appreciably buoyant relative to pyrolite below 670 km. As a result of this inhomogeneous density distribution, a bending couple is applied to the tip of the slab at 670 km, causing it to buckle. This process is magnified by the high viscosity in the slab arising from its lower temperature than surrounding mantle. In consequence, the descending slab piles up and forms a large melange or "megalith" of mixed, former harzburgite and oceanic crust. The megalith has a mean density similar to surrounding mantle below 670 km and accumulates as an ovoid body in the lower mantle, beneath the intersection of the slab with the 670 km discontinuity. Its cross-sectional dimensions may exceed 500 km.

BASALT PETROGENESIS

The integrity of the megalith is maintained initially by its high viscosity relative to surrounding mantle. However, after the cessation of subduction, on timescales exceeding 10° y., conduction of heat from the surrounding mantle raises the temperatures of the outer shell of the megalith. Partial melting of entrained oceanic crust ensues. The resultant liquids extract incompatible elements from the former erust and react with former harzburgite, causing the latter to become fertile in the sense of its future capacity to produce basaltic magmas. With further heating, the viscosity of the outer shell of the megalith is reduced and large blocks of former oceanic crust (now depleted in incompatible elements by partial melting) sink into the lower mantle. Newly fertile, thermally equilibrated, former harzburgite is now buoyant relative to the lower mantle, and flows upwards, spreading out to form a layer at depths of 500-670 km, which is gravitationally stable. After an extended residence time in this layer (0.5 - 2.0 b.y.), diapirs of fertilized former harzburgite ascend into the upper mantle. Large diapirs rise comparatively rapidly and experience small

degrees of partial melting to produce alkalic, and in some cases, 'enriched' tholeiitic magmas. These diapirs possess sufficient energy to penetrate the lithosphere and are responsible for intraplate hot-spots beneath oceans and continents, with their associated volcanism. Small diapirs of fertilized former harzburgite ascend much more slowly from the 500-670 km source region, and do not experience partial melting. Where they ascend beneath continents, the smaller diapirs become incorporated into the sub-continental lithsophere which grows by accretion from this source. Ascending small diapirs beneath oceans become trapped in the sub-oceanic lithosphere. When subjected to later episodes of partial melting these geochemically enriched local source regions contribute to the chemical and isotopic diversity of oceanic basaltic magmas.

The above model implies that a significant relationship exists between the petrogenesis of intraplate basaltic magmas (mainly alkalic) and that of calcalkaline magmas erupted above subduction zones. In both cases, the incompatible element characteristics and isotopic systematics of the respective source regions are believed to have been inherited from a liquid extracted at depth from subducted former oceanic crust and transferred to depleted former peridotite. The essential differences are that in the case of calcalkaline magmas, the process occurred at shallow depths (80-150 km) shortly after subduction, whereas, in the case of intraplate basalts, the process occurred at depths of 650-1000 km, and the enriched sources were stored in the mantle for 0.5 - 2.0 b.y. prior to eruption of magmas at the surface.