Plate tectonics and lithosphere architecture: temporal and spatial consequences

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Volcanic rocks (alkaline basalts, kimberlites, carbonatites) and high pressure inclusions (plagioclase, spinel, garnet, diamond facies mantle) provide valuable information about the nature and origin of the shallow mantle. Integration of experimental, geochemical and geophysical data permits reconstruction of the 'stratigraphy' of the lithosphere beneath individual volcanic provinces. Lithostratigraphic variations can be (a) investigated across boundaries between major crustal age provinces, (b) studied in relation to heat flow variations, and, (c) correlated with the presence or absence of high velocity anomalies. In some unique circumstances the continental lithospheric mantle may have been sampled by xenolith-bearing magmas over several 100 m.y., thus allowing for an evaluation of any temporal changes in lithostratigraphy. Traditionally the formation of lithospheric mantle has been related (a) to the extraction of high temperature, magnesian melts from plumes in the Archaean (i.e. cratonic lithosphere; 2500 Ma; *c.* 200 km; spinel-diamond facies mantle); (b) to the extraction of basaltic magmas from the asthenosphere/ plumes in post-Archaean times (i.e. circum-cratonic lithosphere; 2500 Ma; spinel-garnet facies), ; (c) to the extraction of mid-ocean ridge basaltic magmas in the last 200 m.y. (i.e. oceanic lithosphere ($<200>$ Ma; <150 km; plagioclase-garnet facies mantle). However the lithosphere architecture that results from such processes can be greatly disturbed by thermo-tectonic processes. While the Archaean crust of the Kaapvaal and Siberian cratons (>2500 Ma) is associated with deep (*c.* 200 km) high velocity anomalies and low heat flow, consistent with the presence of a thick, cold, diamondiferous keel, several other 'cratons' (i.e. Sino-Korean, Hebridean and Arabian) are associated with shallow, low velocity structures and moderate-high heat flow. Plate-driven processes are believed to have been responsible for many of the changes to the topography at the lithosphere-asthenosphere boundary in western Europe and eastern China and plume-driven processes have also played a role in the destruction of the Archaean lithosphere beneath the Hebrides (distal effects of the Iceland plume) and Arabia (proximal effects of the Afar plume).

Eastern China : temporal variation in thickness and mantle facies

Palaeozoic - Lithostratigraphic studies, based on xenoliths in Palaeozoic kimberlites, indicate that the Archaean lithosphere was 150–220 km. thick with a shield geotherm of ($<40 mW/m^2$ ($<$ 1HFU) (Zhou *et al.*, 1994). The cratonic lithosphere had a metasome level around 80–100 km and was more lherzolitic in the west and more harzburgitic in the east where the keel protruded into the diamond stability field, thus accounting for the occurrence of diamondiferous kimberlites in E. China (e.g. Lu *et al.*, 1991).

Tertiary - Tertiary alkaline volcanic rocks appear to have a contribution from enriched (garnet-facies) sources that, on the basis of their isotopic character, were probably located in the lower lithosphere (e.g. Song *et al.*, 1990). Taken together with a paucity of Tertiary diamondiferous alkaline rocks it is evident that the Tertiary lithosphere was thinner ($\ll$ 150 km) than the Archaean lithosphere and that Tertiary magmatism may have been caused by interception of upwelling isotherms with a low melting portion of the old keel - the Archaean metasome level.

Quaternary- Peridotite xenoliths in basalts are predominantly spinel facies, lie on an 'oceanic geotherm' and have high temperature dislocations, properties that point to hot, thin Quaternary lithosphere (*ca.* 80 km thick). The presence of veined peridotite xenoliths points to magma genesis in deeper garnet facies mantle within the lower lithospheric mantle. These may be relict conduits of melt extraction episodes in pre-Quaternary lithosphere.

Present-day - Seismic tomography (Chen *et al.*, 1991) indicates that the 'present-day' lithosphere is *ca.* 70–80 km thick, with a shallow (80–180 km) low velocity structure and high heat flow (1.2–2.53 HFU) similar to that observed in ocean basins, particularly near ridge systems (50–105 mW/m^2). Since seismic tomography indicates that the lithosphere is 80 km thick (i.e. spinel facies mantle), one can speculate that reactivation of garnet to diamond facies mantle contributed to alkaline to potassic volcanism.

Mechanisms - Mantle plumes and subduction along the Pacific margin are not believed to have caused the dramatic change in the thermal, petrological and chemical character of the Archaean lithosphere beneath eastern China. However the stress field associated with the collision of India and Eurasia may have destroyed the physical integrity of the craton, with the provision of major shear zones/strike slip faults (e.g. Tan-Lu fault zone) that reactivated the keel (Menzies *et al.*, 1993). Thin lithosphere (< 80 km), a shallow low velocity structure, high heat flow and spinel facies (*c.* 75 km) mantle xenoliths plotting on the oceanic ('hot') geotherm are also found beneath the Hebridean craton of NW Scotland and the Yemen craton of Arabia. However their reactivation may have involved mantle plumes (i.e. Iceland and Afar).

Western Europe : spatial variation in thickness and mantle facies

Present-day. Mantle facies variation inferred from seismic (Blundell *et al.*, 1992) and experimental data reveals (a) a thick, heterogeneous, diamond-garnet facies keel (low heat flow, high velocity anomaly) beneath the Baltic Shield; (b) thin, relatively homogeneous, garnet-spinel facies mantle (high heat flow, shallow low velocity structure) beneath Variscan Europe (e.g. Eifel-Pannonian Basin); (c) overthickened diamond-spinel facies mantle (deep high velocity anomaly, variable heat flow) beneath the Alps, and, (d) extremely thin spinel-plagioclase facies mantle (shallow low velocity structure, high heat flow) beneath the Mediterranean Sea (Menzies and Bodinier, 1993, and references therein). Although crustal age provinces tend to young from north (Baltic Shield) to south (Alpine Orogen), thick lithosphere (150 km) is found beneath both old, stable, cratons and young, unstable mountain belts. In addition thin, heterogeneous lithosphere is found beneath the Archaean crust of NW Scotland, and thick, heterogeneous lithosphere is associated with the Alpine mountain belts of southern Europe. Integration of geophysical and geochemical data indicate that lithosphere architecture relates as much to plate tectonics as to the initial stabilisation age of the crust. Cenozoic volcanic rocks display a marked change in source region from north to south that is consistent with a change in lithosphere architecture and tectonic regime. On the Variscan foreland, Cenozoic volcanic rocks appear to be passively derived from the asthenosphere, or thin, young (Phanerozoic) lithospheric mantle (Wilson and Downes, 1991). In contrast along the active southern margin (Alpine Orogen) volcanic rocks are derived from thicker, subduction-modified lithospheric mantle and/or foundered oceanic lithospheric slabs incorporated into the active margin.

Mechanisms. In western Europe the role of mantle plumes is believed to have been minimal, but subduction associated with continent-continent collision has played a fundamental role in shaping lithosphere architecture beneath Variscan and Alpine Europe. The diverse lithosphere architecture of the Alpine orogeny provides a possible analogue for understanding the origin of peridotite-eclogite massifs (caledonides) and diamondiferous peridotite-pyroxenite massifs (Betics).

Conclusions

Lithosphere architecture can be greatly complicated by plate tectonic processes which can include (a) destruction of 'old' diamond-garnet facies mantle (e.g. E. China); (b) reactivation of 'old' metasomes within the MBL, causing episodes of alkaline to potassic volcanism (e.g. E. China, W. Europe, W. States, E. Australia, S. Africa); (c) accretion of 'young' oceanic mantle (plagioclase to spinel peridotites) beneath 'old' crust (e.g. E. China, W. Europe, W. States); (d) detachment of lower lithosphere (diamondiferous eclogites and peridotites) (W. Europe, W. States), and, (e) incorporation of recycled components (eclogites/ pyroxenites) into 'young' lithosphere along active margins (e.g. W. Europe).

References

Blundell, D.J., Freeman, R. and Muller, S. (1992) A Continent Revealed - The European Geotraverse. Cambridge University Press, 274pp.

Chen, G. Y., Song, Z-H., An, C-Q., Cheng, L-H., Zhuang, Z., Fu, Z-W., Lu, Z-L & Hu, J-F. (1991) *Acta Geophys. Sinica*, **34**, 172–81.

Lu, F., Huan, Z., Zheng, J. and Ren, Y. (1991) *Geol. Sci. Technol. Inf.*, **10**, 1–20. China University of Geosciences, Beijing (in Chinese).

Menzies, M.A. and Bodinier, J.L. (1993) *Phys. Earth Planet. Int.*, **17**, 1–22.

Menzies, M.A., Zhang, M. and Weiming, F. (1993) *Geol. Soc. London Special Publication*, **76**, 71–81.

Song, Y., Frey, F.A. and Zhi, X.C. (1990) *Chem. Geol.*, **85**, 35–52.

Wilson, M. and Downes, H. (1991) *J. Petrol.*, **32**, 811–50.

Zhou, J., Griffin, W.L., Jaques, A.L., Ryan, C.G., and Win, T.T. (1994) *Proceedings of the Fifth Kimberlite Conference* (in press).