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Magma migration and the thermal evolution of volcanic passive margins

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The thermal evolution of the continental lithosphere (both crust and mantle) is a function of both the conduction and the advection of heat. Conduction is an extremely slow process and perturbed geothermal gradients may take tens of millions of years to re-equilibrate. Advection of heat by rising magma is, in contrast, an extremely efficient heat transfer mechanism.

In order to construct realistic models of the thermal history of magmatically active sedimentary basins and volcanic passive continental margins we need to understand the relationship between rates (and relative magnitudes) of convective and advective heat transfer. To do this we need to be able to constrain the system of pathways along which basaltic magmas migrate from their asthenospheric mantle source (depths ca 80-100 km), through the Earth's lithosphere, to the surface. Until recently such data have been difficult to obtain because the mantle and lower-crustal parts of magmatic systems are not generally well exposed at the Earth's surface. Industry 2-D and 3-D seismic reflection surveys of volcanic continental margins (e.g. Wheeler et al., submitted), however, now provide us with the tools to image entire crustal magmatic plumbing systems, from Moho-level magma storage systems (mafic underplates), through complexes of sills and dykes, to lavas and vent fields extruded at the paleo surface.

Mafic underplates (5-10 km thick) appear to underlie heavily extended continental crust along many volcanic passive margins. These sill-like bodies act as magma storage reservoirs at the base of the crust, feeding magma upwards via a complex system of dykes to a plexus of sills at mid- to upper-crustal depths. On the Norwegian margin (Wheeler et al., submitted) a laterally-extensive secondary magma storage reservoir, also sill-like, appears to have developed in the middle crust at the interface between the crystalline basement and the overlying Palaeozoic-Mesozoic sedimentary sequence. From this secondary reservoir, magma has risen to higher levels through a system of interconnected sills and dykes to form a nested sill complex with a cuspate "boat-like" geometry.

The thermal effects of surface lava flows, the build up of an "underplate" of basaltic magma at the Moho, the development of a mid-crustal sill complex and of the injection of high level dykes and sills into upper crustal sedimentary sequences can be modelled using basic heat conduction equations to visualise the thermal evolution of the crust following a major large igneous event. The concept of "thermal loading" is developed which demonstrates that laterally extensive, shallow-level, sill intrusions are the most effective agents for generating thermal perturbations within sedimentary basins. The emplacement of high-level dykes and sills has a much greater transient thermal effect, in terms of perturbation of crustal geothermal gradients, than, for example, a large-scale, thermally anomalous, mantle plume head spreading out at the base of the lithosphere or an underplate of basaltic magma at Moho depths. The "thermal load" introduced by mid-crustal sill complexes, emplaced between the top of the crystalline basement and the overlying supracrustal sequence, may, however, be significant.

The thermal evolution of a sedimentary basin will be complex if there is a protracted history of magma migration, resulting in a series of "thermal fronts" or an extended period of elevated temperatures depending upon the frequency of sill emplacement. At volcanic passive margins much of the magma is likely to migrate through the crustal plumbing system in as little as 1-2 million years; 10-15 km thick, basaltic, Moho underplates may, however, take up to 5 Myr to form.

Volcanic continental margins (e.g. the Tertiary North Atlantic margins) are commonly characterised by the development of central volcanic complexes (recognised on the basis of their distinctive gravity and magnetic anomalies) shortly after the main phase of flood basalt eruption. Such complexes reflect the development of upper crustal magma chambers (< 3-5 km below the paleosurface and up to 10-15 km in diameter), bounded by ring-faults, in which basaltic magmas are stored and differentiate, feeding late-stage surface volcanism. They are particularly effective “heat-engines” which drive hydrothermal fluid circulation systems within their contact zones.

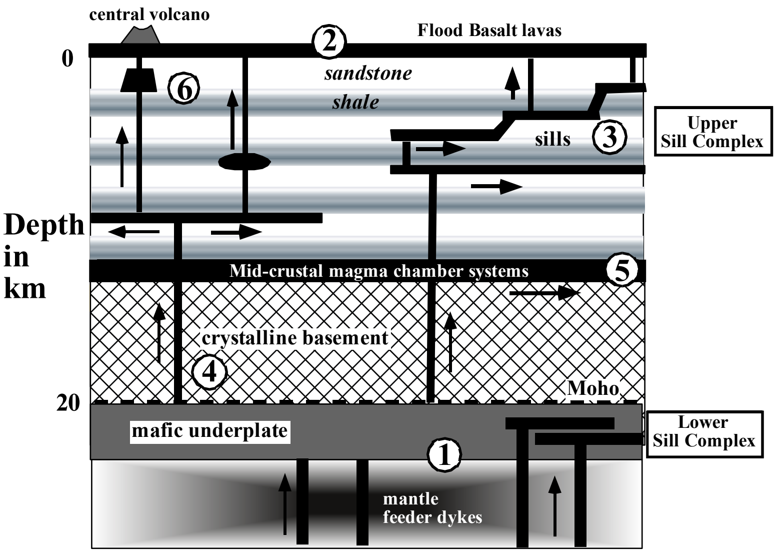
Figure 1 illustrates schematically the magmatic plumbing system of a volcanic continental margin, giving examples from the geological record where different parts of the section may be studied in outcrop.

REFERENCES

WHEELER, W., WILSON, M. KARPUZ, R. & HELLAND, R. (SUBMITTED TO NATURE)

The magmatic plumbing system of a volcanic continental margin: an image from 3D seismic.

Figure 1 (not to scale)



① **FOSSIL MOHO zones e.g. Ivrea Zone, Alps**

② **FLOOD BASALT PROVINCES**
e.g. E. Greenland(Tertiary)
Parana, Brazil (135 Ma); Karoo, S. Africa (180 Ma)

③ **SILL COMPLEXES**
e.g. Atlantic Margins (Tertiary)

④ **REGIONAL DYKE SWARMS**
e.g. Proterozoic, S. Sweden; S. Greenland

⑤ **Mid-crustal magma storage -**
indirect evidence from geochemical studies; 3-D seismic

⑥ **LAYERED IGNEOUS COMPLEXES**
e.g. Atlantic Margins (Tertiary intrusions)