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Petroleum implications of sill intrusions: Emplacement of magma in sedimentary basins

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Sheet-like intrusive complexes are commonly present in sedimentary basins on volcanic rifted margins. These sill complexes have important impact on petroleum maturation, migration and trapping. Exploration in volcanic basins thus requires methods to identify and map volcanic intrusive deposits, and knowledge of how volcanic processes and deposits influence the petroleum prospectivity.

We are currently completing an integrated seismic, field and theoretical study on the petroleum implications of sill intrusions. One aspect of this study has been to get new understanding of the magma emplacement processes based on integrated numerical modeling and geophysical/geological mapping.

Sill Complex Geometries
Extensive sill complexes have been identified and mapped in the NE Atlantic and Karoo basins based on seismic, borehole, remote sensing and field data. Early Tertiary intrusive complexes are present in the Vøring and Møre basins offshore mid-Norway. Similar sill complexes are exposed onshore in Cretaceous to Permian age sedimentary sequences on the conjugate central-east Greenland margin. A voluminous Jurassic age intrusive complex is well exposed in the Permian to Jurassic Karoo basin as the erosionally strong dolerites form an impressive mountainous landscape in large parts of South Africa.

From this mapping we observe that:

- The sheet intrusions are found at paleodepths of 0-6 km. The depth of the shallowest intrusion generally increases away from the breakup axis. Sills dominate in stratigraphic levels with shales and sandstone/shale interbeds.
- Deep intrusions are generally long and smooth, whereas shallow intrusions are rough, transgressive and commonly saucer-shaped.
- Saucer-shaped intrusions are present in unstructured basin segments. The diameter of the saucers increases with depth, from ca. 5 km at shallow levels up to 30 km in the deepest

parts of the basins. The saucers have a flat floor, steep transgressive flanks and commonly an outer sub-horizontal lobe. The saucers appear to be inter-connected. Feeder dikes sometimes merge with the transgressive flanks of the saucers.
- Structured basin segments are characterized by a variety of sill complex geometries. The intrusions generally mimic the basin structure. Planar, transgressive sheets are common near the flanks of the basin, whereas segmented, stepping intrusions are present in faulted parts of the basins.

Emplacement Theory and Modeling

In nature, magma is emplaced in internally pressurized planar cracks. The emplacement process is controlled by the local stress field and complex interactions of buoyancy forces, host rock resistance to fracture, elastic deformation of country rock, magma hydrostatic pressure and fluctuating magma pressure, magma viscosity and weight of overburden. We have developed a discrete element model to study the emplacement process. The discrete model reproduces isotropic linear elasticity on the large scale. Fracturing is modeled by the irreversible removal of discrete elements. In the first approximation, the sill emplacement process is modeled as a quasi-static hydrofracturing process, ignoring the viscous pressure drop along the sill.

Conclusions

Results from the modeling and geological/geophysical mapping show that sill emplacement is a dynamic process where both 1) stress field anisotropy generated by the emplacement process and 2) local structural heterogeneities have important influence on the final geometry of the sill complex.

Saucer-shaped sill complexes, commonly present in unstructured basins provinces, are formed spontaneously by the numerical model in a simple, stratified basin. An asymmetric stress field is developed around the tip of the sill during the emplacement, causing the melt to transgress and forming the inclined sheets. The transition from layer-parallel to transgressive intrusion depends on the depth (weight of overburden) and length of the sill: deep intrusions require long sills to generate sufficient stress anisotropy to force the melt to start to climb.

The modeling and field data show that faults and weak intra-sedimentary horizons are preferentially used during the emplacement process. Inflation and deflation cycles are particularly common in the vicinity of major structural heterogeneities. Finally, the model predicts that small-scale faulting is expected in the sedimentary strata above shallow-level intrusions, similar to magmatectonic faults observed in the field.