Volcanic Processes and Deposits on Rifted Margins and in Sedimentary Basins

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Abstract

Volcanic processes and deposits may have a strong impact on the structure and geodynamic development of continental margins and associated sedimentary basins. The identification of volcanic deposits and the evaluation of their impact on the margin history are thus two important aspects of the petroleum exploration on continental rifted margins. The melt potential of the mantle is controlled by its composition, volatile content and temperature. Voluminous volcanism is often associated with a mantle temperature anomaly, possibly caused by a mantle plume. However, there is also a strong link between tectonics and volcanism, for example lithospheric rifting may cause decompressional melting. Magma formed by partial melting of the mantle may migrate towards the surface through a plumbing system. The melt may subsequently be emplaced as intrusive bodies near the crust-mantle boundary and within the crust, or it may be extruded at the surface.

We have studied volcanic deposits and processes in the field (Karoo basin, South Africa; central-east Greenland) and on seismic data (NE Atlantic, W Greenland basins; S Atlantic; NW Australia) (Figure 1). These studies have focused on the identification, mapping and understanding of volcanic deposits and processes at shallow crustal levels where high-quality seismic data, potential field data, borehole data, or well-exposed field analogues provide us with detailed maps, 3D images, and geological data that can be applied to develop and constrain geodynamic models of scientific and exploration importance. The project results have been integrated with development of theoretical and numerical methods to understand the impact of the volcanic processes in sedimentary basins.

Objectives

The aim of this paper is to provide an overview of how volcanic deposits and processes influence the geodynamic development and the petroleum systems on rifted continental margins. The impact of the volcanism is related to (1) the nearly instant magma ascent and emplacement processes, and (2) the long-term influence by permanently changing the margin geology. On the short-time scale, intrusive volcanism causes deformation, heating, fluid expulsion, and metamorphic reactions. The short-term consequences of extrusive volcanism are normally less extensive, but may lead to loading, deformation, and regional environmental changes. The volcanic deposits and deformation structures may have major long-term impact on the basin geology, in particular by modifying the basin hydrogeology. In addition, volcanic deposits are commonly armoring the sedimentary basins, thereby influencing deformation processes related to compaction, doming, and landslides. Finally, volcanic deposits commonly obstruct seismic imaging of underlying basin sequences as they represent high-velocity bodies.

Imaging and Interpretation

The nature of volcanic deposits strongly depends on the eruption and emplacement environments. The presence or absence of water in both environments is of particular importance. In addition, the paleo-topography and the presence and structure of sedimentary basins may also have important impact on the construction of volcanic complexes. The seismic velocity of extrusive volcanic deposits can vary from 1.5 km/s (water-saturated tephra layers) to more than 6.0 km/s (interior of massive basalt flows). Mafic intrusive bodies have normally higher seismic velocities, typically in the range from 5.0 to 7.5 km/s, depending on their composition, thickness, and intrusive depth. The volcanic sequences may be homogenous (e.g, sheet intrusions), layered (e.g, subaerial basalt flows and foreset bedded volcaniclastic sequences), or chaotic (e.g, debris flows).

We have developed and used the concept of seismic volcanostratigraphy to study the nature, geological history, and emplacement environment of extrusive volcanic rocks from seismic reflection data. This work has been complimented with (1) seismic time horizon interpretation, (2) seismic anomaly interpretation (high-amplitude and high-velocity units, disrupted seismic data in hydrothermal vent complexes, and deep crustal line segment interpretation), (3) integrated seismic, gravity, and magnetic (SGM) interpretation, and (4) borehole studies.

Extrusive Volcanism

We have primarily been studying voluminous extrusive processes and deposits in the North Atlantic (Vøring and Møre basins offshore Norway, Greenland, Faroes, and Iceland) and on the W Australian margin (e.g., Figure 2). The construction of the extrusive volcanic sequences on rifted volcanic margins can schematically be divided into five main stages:
Stage 1: Initial explosive volcanism in an aquatic or wet sediment environment forming basalt-sediment complexes.
Stage 2: Effusive subaerial volcanism, including coastal hydrovolcanic and sedimentary processes.
Stage 3: Continuing effusive subaerial volcanism infilling the rapidly subsiding rift basins along the incipient breakup axis.
Stage 4: Explosive shallow-marine volcanism.
Stage 5: Voluminous, effusive deep marine volcanism.

There are commonly large along-strike variations in the nature and volume of the volcanic deposits, for instance between the dominantly non-volcanic Perth and the adjacent volcanic Cuvier margin segments offshore W Australia. Furthermore, subdued volcanism is inferred along sheared margin segments, e.g., along the Vøring Transform Margin.

The along-strike variations in the volume of the volcanic complexes may for instance affect the slope stability. Seismic volcanostratigraphy reveals that the Storegga and Trænadjupet slide areas offshore mid-Norway are located on margin segments that have no Paleogene subaerial volcanic deposits near the continent-ocean boundary. The subaerially emplaced volcanic marginal highs stabilize the sediments on adjacent margin segments because (1) the continental slope is less steep, (2) the volcanic rocks are strong and prevent deep-cutting landslides, and (3) regional escarpments stabilize the sediments.

Inverted Cretaceous basins are located in the Vøring and Møre basins. The Helland-Hansen Arch is the most extensive Tertiary contractional dome offshore mid-Norway. It is located on the south-central Vøring Margin, i.e., mainly on a margin segment without landslides but with voluminous volcanic deposits near the continent-ocean boundary. There might be a causal link between the size of this dome and the absence of landslides because the loading by Plio-Pleistocene glacial sediments is partly responsible for the dome formation.

Sheet Intrusions

Extensive magmatic intrusive complexes are commonly present in sedimentary basins landward and below the extrusive complexes. The intrusive volcanic rocks are often located in prospective sedimentary basins, and are an important factor for petroleum explorationists.

Classical saucer-shaped intrusions are found at shallow depths in undeformed basin settings both in the NE Atlantic, on the Australian NW Shelf, and in the Karoo basin (Figure 3). The sizes of the saucers increase with increasing emplacement depth. New numerical models show that the saucer shape is caused by the development of stress anisotropy near the tip of the sills during the emplacement process. However, the geometry of the sheet intrusions is strongly modified by the basin geometry where the intrusions tend to follow the trend of underlying structural highs.

Pierced Basins

Sedimentary basins with a considerable amount of piercement structures can be classified as pierced basins. Piercement structures include hydrothermal vent complexes (Figure 4) and mud volcanoes. The need to distinguish between sedimentary basins with and without significant amounts of piercement structures arise when considering the importance of these structures for the basin hydrology. We have studied sedimentary basins in South Africa (the Karoo basin; Figure 5), in Azerbaijan (the South Caspian basin), and in the Norwegian Sea (the Vøring and Møre basins) to characterize and constrain the effect of piercing processes.

The geometry and nature of the piercement structures is similar in both volcanic and non-volcanic basin settings. This suggests that similar physical processes form the structures. Emplacement of magmatic intrusions will lead to heating of pore fluids and metamorphic reactions, possibly causing an explosive rise of fluids and fluidized sediments to the surface. Numerical modeling suggest that creation of hydrothermal vent complexes may be related to overpressure generation as a consequence of boiling of pore fluids and hydrofracturing on a very short timescale after sill emplacement (10’s of years). Similarly, the piercing process in non-volcanic basins is controlled by overpressure resulting from factors such as rapid burial of clays, decomposition of organic material, and tectonic compression.

We have mapped more than 700 hydrothermal vent complexes on seismic data in the Vøring and Møre basins and five similar hydrothermal vent complexes have been studied in detail in the Karoo basin. The upper part of the vent complexes consist of circular, eye- or mound-shaped strata near the paleosurface (Figure 4). Disturbed sequences and inward dipping strata are commonly identified in the lower part of the vent complexes (Figure 5). The vent complexes are mostly located above the termination, or stepping segments, of deeper sills present at 1-5 km depth below the paleosurface. The upper part of the vent complexes are typically 1-5 km in diameter, however, crater-shaped vent complexes with diameters of more than 10 km are also identified.

Mounded and disrupted seismic reflections are often present above the hydrothermal vent complexes in the Norwegian Sea. We interpret these observations to be connected with fluid seeps and re-use of the hydrothermal vent complex fracture system. The wildcat exploration well 6607/12-1 drilled the central part of a hydrothermal vent complex in the Vøring Basin. We have completed a detailed geophysical, geochemical, petrological, and biostratigraphic study of the well. The borehole data show that the inner zone of the upper part of the vent complex is associated with high porosities and low thermal exposure, whereas the lower part of the vent complex is associated with very high thermal exposure and locally silica-filled fractures. The vent complex is capped by a sequence dominated by carbonates. These carbonates are dominantly calcite, with δ^{13}C values between –37 and –40 permil (PDB), suggesting that the vent complex is used for secondary petroleum migration and seeps.

Hydrothermal vent complexes are not identified in several of the studied volcanic basins. However, high-amplitude seismic anomalies are identified above the tip of sill intrusions in these basins in a similar position as the hydrothermal vent complexes in the NE Atlantic. We argue that the seismic, field, and well observations show that fluid migration in volcanic basins is influenced by the sill and vent complexes long time after their formation.

We propose the following model for hydrothermal vent complex formation in a volcanic basin: (1) intrusion of magma leads to heating, and locally boiling, of pore fluids in the intruded sediments, (2) increased fluid pressure may cause hydrofracturing likely starting at the tip of the intrusion, (3) fluid decompression may lead to an explosive hydrothermal eruption at the paleosurface, forming a hydrothermal vent complex. The explosive rise of fluids towards the surface cause brecciation and fluidization of the sediments and commonly the formation of a crater at the surface, (4) the fracture system created during the explosive phase is later re-used for circulation of hydrothermal fluids during cooling of the magma. This stage is associated with sediment volcanism through up to 30 meter wide pipes cutting the brecciated sediments and in-fill of craters at the surface, and (5) the hydrothermal fracture system and vent complex rocks can later be re-used as fluid migration pathways, forming seeps and seep carbonates at the surface.

References

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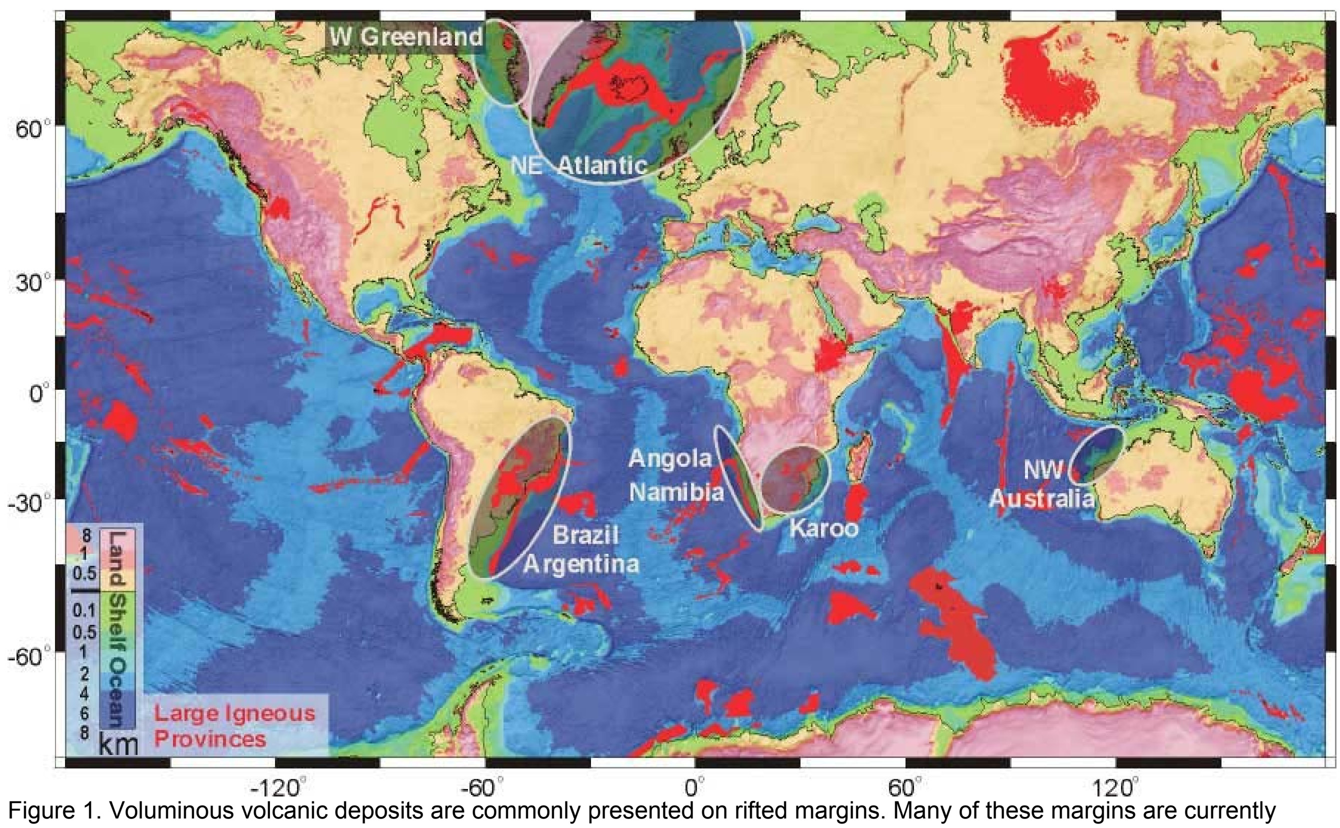

Figure 1. Voluminous volcanic deposits are commonly presented on rifted margins. Many of these margins are currently important petroleum exploration targets. Distribution of Large Igneous Provinces (LIPs) from Coffin and Eldholm (1994).

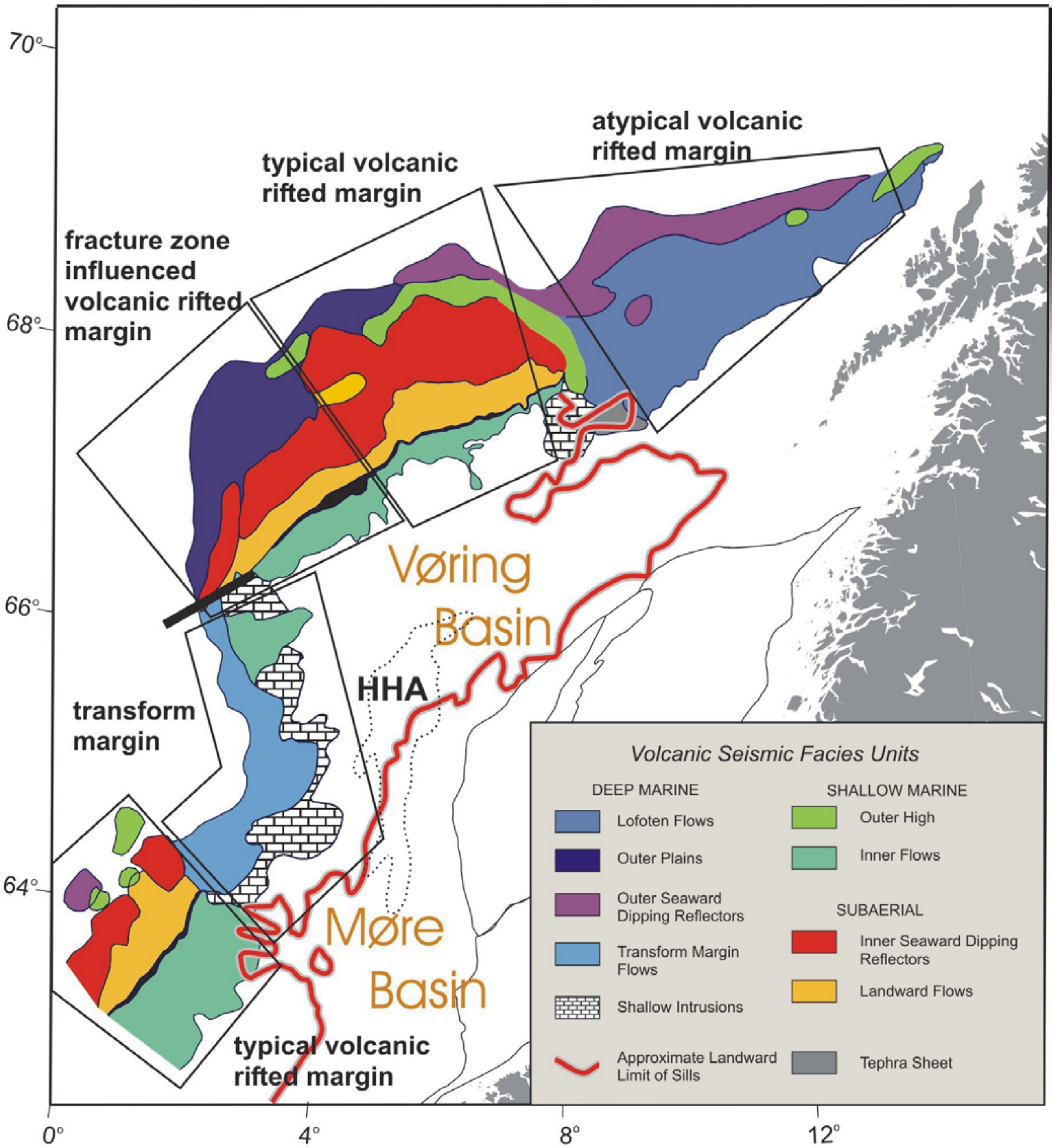

Figure 2. Distribution of volcanic seismic facies units on the mid-Norway margin. Seismic profile shows examples of the main seismic facies units. From Berndt et al. (2001) and Planke et al. (2000).

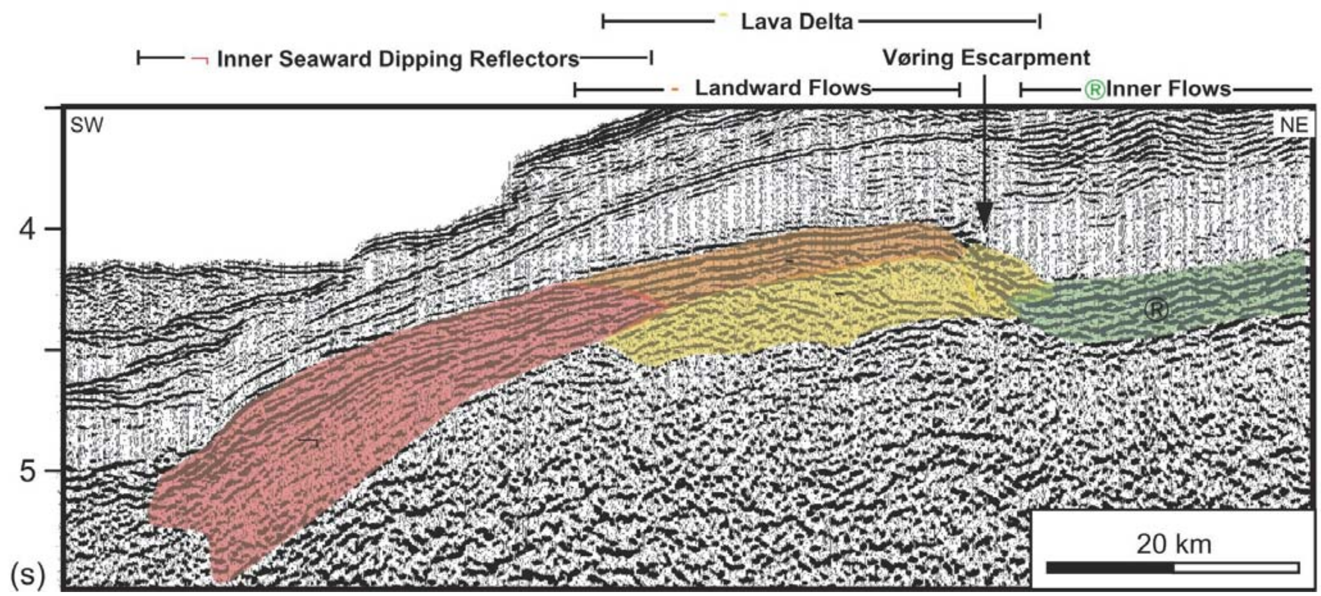

Figure 3. 3D visualization of a saucer-shaped sill in the Vøring Basin, offshore mid-Norway.
The main saucer is approximately 3 km by 4 km wide and has an elevation difference of ~500 m.

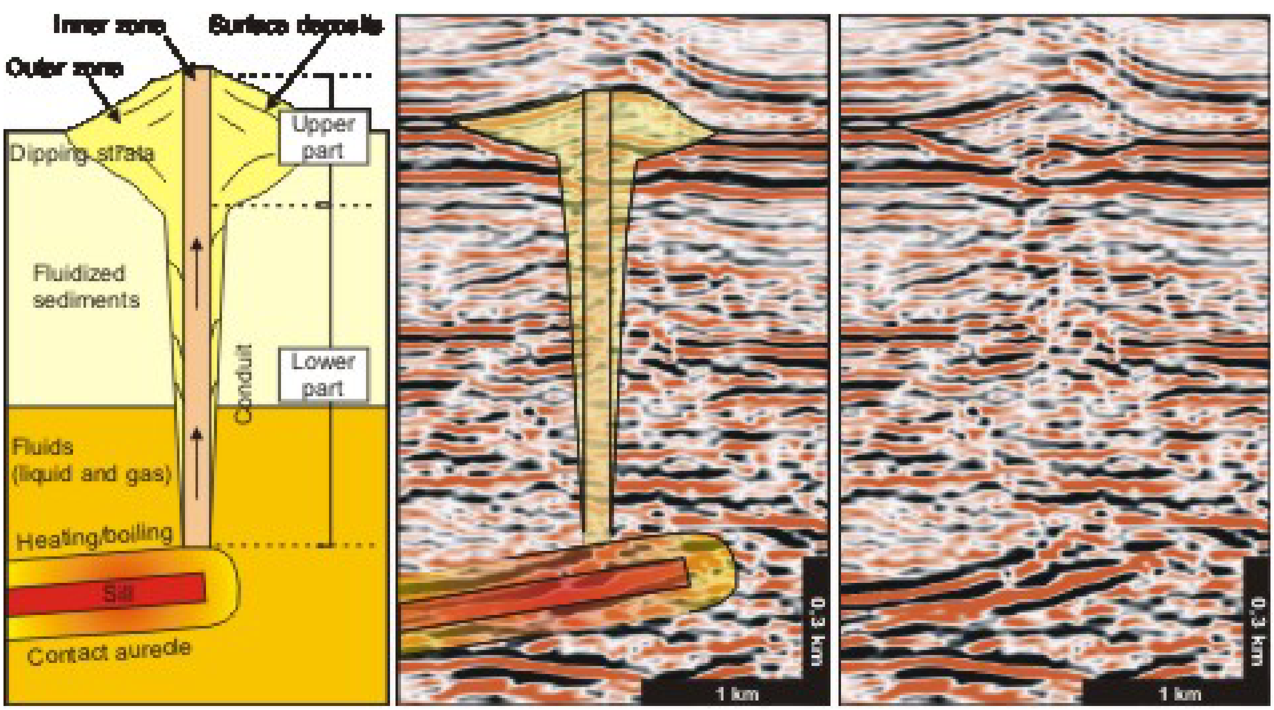

Figure 4. Nomenclature and seismic example of a hydrothermal vent complex.

Figure 5. The Witkop III hydrothermal vent complex in the Karoo basin.
The Inner Zone consists of massive sandstone, whereas the breccia dominates in the Outer Zone.
Note inward-dipping strata in the Outer Zone and white car for scale.