Hydrothermal vent complexes associated with sill intrusions in sedimentary basins

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Abstract: Subvolcanic intrusions in sedimentary basins cause strong thermal perturbations and frequently cause extensive hydrothermal activity. Hydrothermal vent complexes emanating from the tips of transgressive sills are observed in seismic profiles from the Northeast Atlantic margin, and geometrically similar complexes occur in the Stormberg Group within the Late Carboniferous–Middle Jurassic Karoo Basin in South Africa. Distinct features include inward-dipping sedimentary strata surrounding a central vent complex, comprising multiple sandstone dykes, pipes, and hydrothermal breccias. Theoretical arguments reveal that the extent of fluid-pressure build-up depends largely on a single dimensionless number (***Ve***) that reflects the relative rates of heat and fluid transport. For ***Ve*** >> 1, 'explosive' release of fluids from the area near the upper sill surface triggers hydrothermal venting shortly after sill emplacement. In the Karoo Basin, the formation of shallow (< 1 km) sandstone-hosted vents was initially associated with extensive brecciation, followed by emplacement of sandstone dykes and pipes in the central parts of the vent complexes. High fluid fluxes towards the surface were sustained by boiling of aqueous fluids near the sill. Both the sill bodies and the hydrothermal vent complexes represent major perturbations of the permeability structure of the sedimentary basin, and are likely to have long time-scale effects on its hydrogeological evolution.

Large igneous provinces, such as the Northeast Atlantic igneous province and the Karoo igneous province in South Africa, are characterized by the presence of an extensive network of sills and dykes embedded in sedimentary strata. The thermal and hydrological effects of these intrusions on surrounding sedimentary rock strata are of considerable interest not only to the research community, but also to companies carrying out petroleum exploration in volcanic basins.

Previous field studies of sills emplaced in porous sedimentary rocks and loosely consolidated sediments describe fluidization of initially consolidated sediments near sill contacts and expulsion of large volumes of pore-waters towards the surface, thus creating a hydrothermal system (Grapes *et al.* 1973; Einsele 1982; Krynauw *et al.* 1988). Major hydrothermal effects triggered by sills have also been inferred from seismic profiles from the sedimentary basins along the Northeast Atlantic margins (Svensen *et al.* 2003). Figure 1 shows our interpretation of a seismic profile in the north-central Vøring Basin on the mid-Norwegian margin. Vertical structures starting at sill tips reach the palaeosurface, where they terminate in eye-like structures interpreted to represent ancient hydrothermal eruption centres similar to mud volcanoes (Planke *et al.* 2003; Svensen *et al.* 2003, 2004).

In this paper we describe and characterize hydrothermal vent complexes from the Karoo Basin in central South Africa. These structures are geometrically very similar to the subsurface vent complexes identified on seismic reflection data in sedimentary basins along the NE Atlantic margins. It is demonstrated how high fluid pressures, fluidization processes, and channelized flow play a major role in restructuring the sediments around sills, affecting both the short- and long time-scale hydrological evolution of the system. We finally present a model quantifying the conditions required for the build-up of fluid pressures sufficient to trigger hydrothermal vent complex formation above sills, in the case where the pore fluid is pure water.

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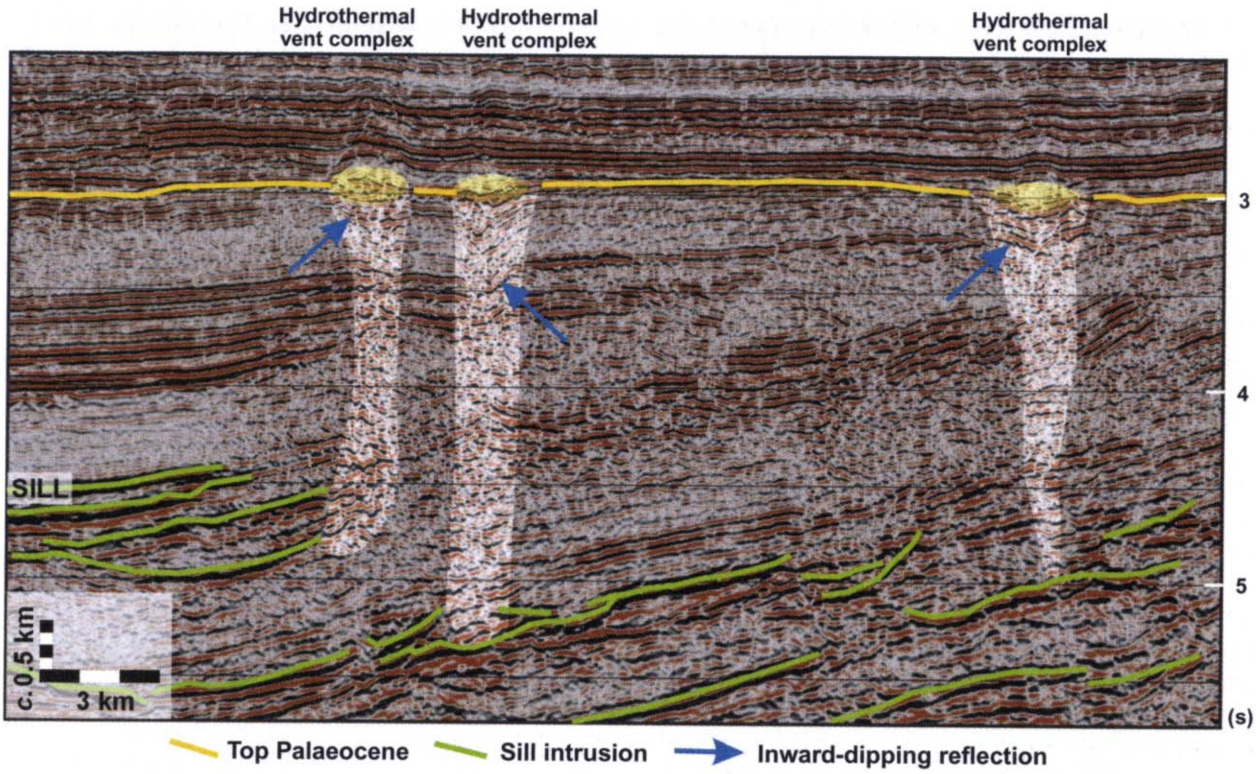

Fig. 1. Seismic expression of three hydrothermal vent complexes cutting Palaeocene and Cretaceous clastic sedimentary strata in the north-central Vøring Basin. High-amplitude reflections are interpreted as mafic sills based on their morphology, seismic shadowing effects, aeromagnetic and well data. Note that the sedimentary strata dip into the vent (blue arrows). The vent complexes are associated with a positive perturbation of the topographic relief at the palaeosurface (yellow ellipses). These vent eye-like structures are interpreted as 'mud-volcanoes' and may reach several kilometres in diameter.

Hydrothermal vent complexes in the Karoo Basin

The Karoo Basin in South Africa is a sedimentary basin covering more than half of South Africa. The basin comprises up to 6 km of sedimentary strata, capped by at least 1.4 km of basaltic lava, and is bounded by the Cape Fold Belt along its southern margin (Smith 1990; Johnson *et al.* 1997). The sediments accumulated from the Late Carboniferous to the Mid-Jurassic, in an environment ranging from marine (the Dwyka and Ecca groups) to fluvial (the Beaufort and parts of the Stormberg Group) and aeolian (upper part of the Stormberg Group) (Catuneanu *et al.* 1998). At the time of lava eruption, an up to 400-m thick sequence of fine-grained sand had been deposited by aeolian, fluvial and lacustrine processes (Smith 1990). The sedimentary rocks comprising the SE parts of the basin were gently folded during phases of the Cape Orogeny (278–215 Ma; Catuneanu *et al.* 1998), whereas the rest of the basin is essentially undeformed.

Both southern Africa and Antarctica experienced extensive volcanic activity in early Jurassic times (183 ± 1 Ma; Duncan *et al.* 1999). Sills and dykes are present throughout the sedimentary succession, and locally make up 70% of the basin volume (Rowsell and de Swardt 1976). Horizontal sill intrusions preferentially occur in the deep basin sequences (the Ecca Group), whereas transgressive sheets and rings are common in intermediate sequences (the Beaufort Group) (Chevallier & Woodford 1999; Woodford *et al.* 2001). The magmatic material in the upper formations of the Stormberg Group is dominantly present as dykes.

Hundreds of vent complexes have been identified in the Stormberg Group (Du Toit 1904; Keyser 1997; Dingle *et al.* 1983), but have previously received limited attention. The complexes range from being almost purely volcanic to being almost entirely filled by sedimentary material (Du Toit 1904, 1912; Gevers 1928; Seme 1997; Dingle *et al.* 1983; Woodford *et al.* 2001). The hydrothermal vent complexes have also been termed diatremes, volcanic necks, and breccias, and, since the pioneer work of Du Toit, have been interpreted as results of phreatic or phreatomagmatic activity (e.g. Gevers 1928; Coetzee 1966; Taylor 1970; Seme 1997; Woodford *et al.* 2001).

However, the presence of juvenile magmatic material in the sediment-dominated hydrothermal vent complexes is minor (Seme 1997). The focus in this paper is on the sediment-dominated hydrothermal vent complexes in the Molteno–Rossouw area in the central parts of the Karoo Basin (Fig. 2A).

The hydrothermal vent complexes in the Molteno–Rossouw area are observed as erosional remnants in the subhorizontal Clarens and Elliot formations (upper Stormberg Group). They comprise an inner and an outer zone with structurally modified strata (Fig. 2B). The outer zone is characterized by flexured and inward-dipping (up to 45°) sedimentary sequences. The inner zone represents circular topographic highs with diameters up to 300–400 metres (Fig. 2B). Characteristic features of the inner zones include sediment breccias with clay and sandstone fragments in a sandstone matrix, and cross-cutting sandstone dykes and pipes (Fig. 2C, 2D & 2E). Brecciated sediments are volumetrically important in most of the sediment-dominated hydrothermal vent complexes. Sharp cross-cutting relations, with deformed border zones, are common between sandstone pipes and the brecciated sediments. The field observations indicate that brecciation took place before the intrusion of sediment pipes and dykes. Together, these structures represent unambiguous evidence that these vent complexes represent conduits for overpressured fluids, fragmented and fluidized sediments that at least partly originated at deeper stratigraphic levels (at least from the level of the Molteno Formation).

Modelling the fluid pressure evolution around shallow sill intrusions

Studies of geothermal systems suddenly heated from below distinguish an early stage of isothermal pressurization from a later period of heating and hydrothermal circulation (Delaney 1982). Previous numerical models for the early (prior to the onset of convection) heat and fluid flow around cooling magmatic intrusives assume stable one-dimensional removal of fluid away from the sill contact (cf. Delaney 1982; Litvinovskiy *et al.* 1990; Podladchikov & Wickham 1994). However, if the fluid pressure exceeds the lithostatic load pressure, the fluid flow away from the heat source will be associated with matrix deformation and fluid channelling.

The conditions necessary to generate fluid overpressures sufficient to cause fluid channeling (i.e. hydrothermal venting) *shortly after* sill emplacement can be constrained by simple scaling relationships for diffusive transport. At the early stages, the width of the overpressured (fluid pressure exceeding hydrostatic) zone (H_{OP}) is given by the characteristic length scale for hydraulic diffusion:

$$H_{\mathrm{OP}} \approx 2\sqrt{k_{\mathrm{fluid}}t} \quad (1)$$

where $k_{\mathrm{fluid}} = \dfrac{k}{\beta\phi\mu_{\mathrm{fluid}}}$ is hydraulic diffusivity, $\beta \approx 10^{-8}\ \mathrm{Pa}^{-1}$ is the effective fluid and pore compressibility, ϕ is porosity, k is permeability, μ_{fluid} is fluid viscosity, and t is the time since (instantaneous) sill emplacement. A similar scaling relation expresses the boiling zone thickness:

$$H_{\mathrm{boil}} \approx 2\sqrt{k_{\mathrm{T}}t} \quad (2)$$

where $k_{\mathrm{T}} \approx 10^{-6}\ \mathrm{m}^2\mathrm{s}^{-1}$ is the heat diffusivity. Therefore, the boiling front velocity can be expressed as:

$$V_{\mathrm{boil}} \approx \sqrt{\frac{k_{\mathrm{T}}}{t}} \quad (3)$$

Note that at the early stages of sill cooling the fluid is heated by the rock, and not vice versa. At these early stages, advective heat transport is insignificant (due to the small volume of pore-fluids stored initially in the rocks), and permeability does not have a first-order effect on the boiling zone thickness, not even when its effect on fluid pressure is taken into account (cf. Delaney 1982; Podladchikov & Wickham 1994). At the later hydrothermal circulation stages, advection becomes important due to the large volume of fluids circulating through the same rock, and fluids start to dominate the heat transport and to 'heat the rocks'. In such advection-dominated convecting systems, some fluid pathways are near adiabatic, which gives rise to extensive two-phase regions (the latent heat of vaporization of water is very large and prevents adiabatic vaporization by decompression (cf. Ingebritsen & Sanford 1998, p. 200)). On the contrary, at the early stages, the boiling two-phase zone is restricted to a narrow front mainly controlled by conductive heat transfer in the solid.

The hot vapour may move faster through the boiling front but, after coming in contact with cold rocks, it quickly condenses back into water without significant influence on the boiling front velocity. Delaney (1982) concluded that '. . . the properties of the steam region do not play a significant role in determining the maximum pressure'. Since we are interested in the

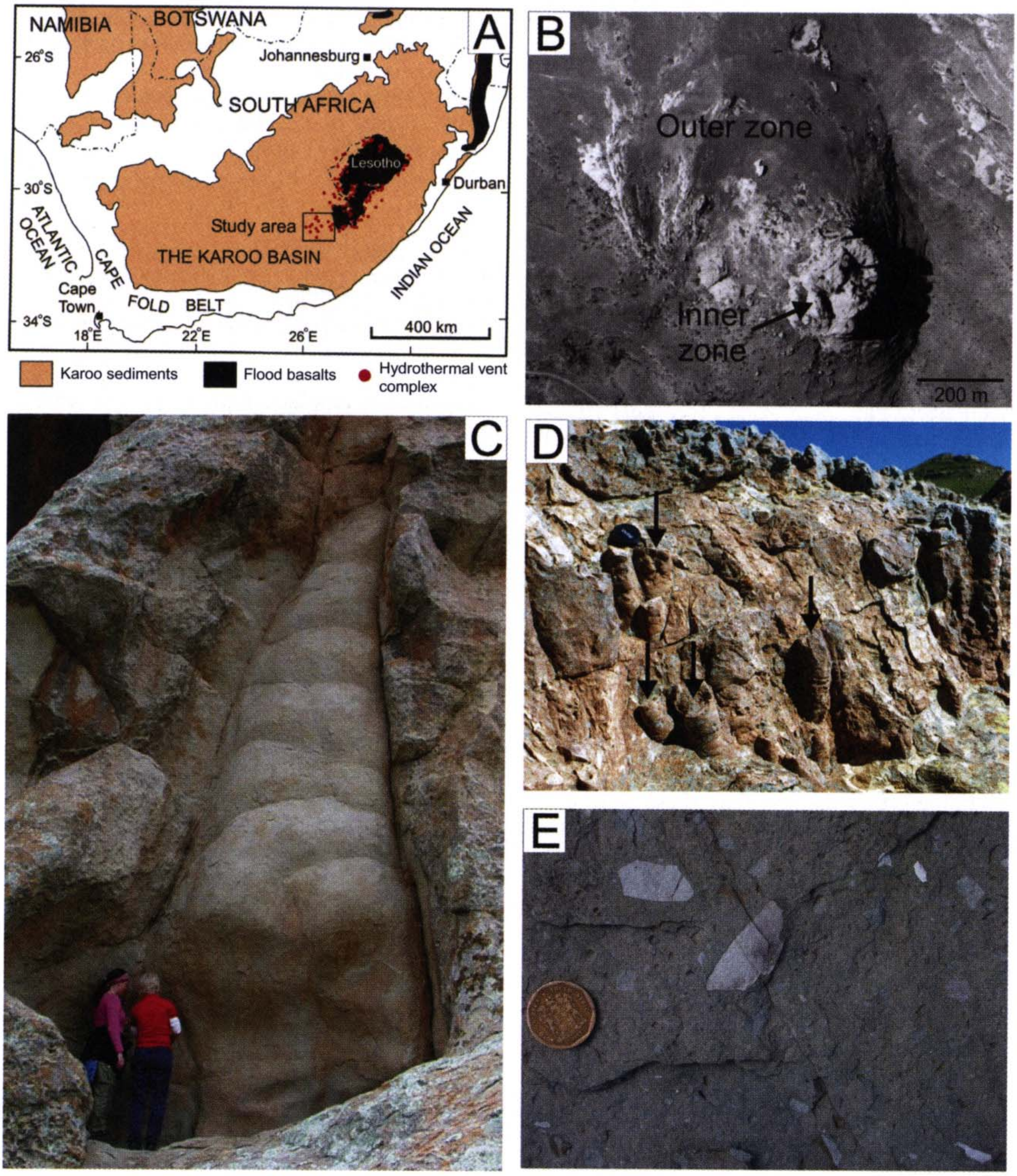

Fig. 2. (**A**) The Karoo Basin, with the Lesotho flood basalts and the locations of abundant shallow hydrothermal vent complexes. (**B**) Aerial photo of hydrothermal vent complex from the Molteno–Rossow area. The vent complex comprises an inner zone seen as a vegetation-free erosional remnant, and an outer zone with inward dipping sedimentary strata. The surrounding sedimentary layering is subhorizontal. (**C**) Sandstone dyke in hydrothermal vent complexes. The dyke contains abundant carbonate cement and erodes more easily than the surrounding vent sandstone. (**D**) Numerous small (up to 30 cm in diameter) sandstone pipes (position shown by arrows) are present within the inner zone of vent complex. (**E**) Brecciated sediment from a hydrothermal vent complex. Clasts are mostly of sedimentary origin (sandstone, claystone and siltstone), although a minor component of juvenile magmatic material is present. The sediment clasts are believed to have formed during fluidization of a mixture of fragmented sediments from the Elliot and Clarens formations, and fine-grained sand from the Clarens Formation.

maximum fluid pressure achieved during the early pressurization stage and for the cases of our interest H_{boil} is much smaller than H_{OP}, we can employ simple cold-water properties for the porous flow outside the narrow boiling zone. The Darcian fluid flux (Q_{D}) out of the boiling zone is approximately:

$$Q_{\mathrm{D}} \approx \frac{k}{\mu_{\mathrm{fluid}}} \frac{P_{\mathrm{fluid}} - P_{\mathrm{hyd}}}{H_{\mathrm{OP}}} \qquad (4)$$

where ($P_{\mathrm{fluid}} - P_{\mathrm{hyd}}$) is the difference between fluid pressure and hydrostatic pressure (the overpressure). Initially, the overpressure is small, thus $Q_{\mathrm{D}} << V_{\mathrm{boil}}$, leading to massive production of steam. Thus the fluid pressure will rise to a slowly decaying value characterized by a quasi-static flux balance:

$$\rho Q_{\mathrm{D}} = \phi \Delta\rho_{\mathrm{boil}} V_{\mathrm{boil}} \qquad (5)$$

where ρ and $\Delta\rho_{\mathrm{boil}} (\approx \rho)$ are the density of the cold water and the density difference between cold water and supercritical steam. Solving for non-hydrostatic fluid pressure build-up we obtain:

$$P_{\mathrm{fluid}}^{\mathrm{max}} \approx P_{\mathrm{hyd}} \left(1 + 2 \frac{\Delta\rho_{\mathrm{boil}}}{\rho\beta P_{\mathrm{hyd}}} \sqrt{\frac{k_{\mathrm{T}}}{k_{\mathrm{fluid}}}} \right) \qquad (6)$$

In order to quantify the proximity of this pressure build-up to venting we define the dimensionless parameter ***Ve*** as follows:

$$Ve = \frac{P_{\mathrm{fluid}}^{\mathrm{max}} - P_{\mathrm{hyd}}}{P_{\mathrm{hyd}}} \approx 2 \frac{\Delta\rho_{\mathrm{boil}}}{\rho\beta P_{\mathrm{hyd}}} \sqrt{\frac{k_{\mathrm{T}}}{k_{\mathrm{fluid}}}} \qquad (7)$$

Assuming $\Delta\rho_{\mathrm{boil}} \approx \rho/2$ and substituting parameters yields:

$$Ve = \frac{1}{\beta P_{\mathrm{hyd}}} \sqrt{\frac{k_{\mathrm{T}}}{k_{\mathrm{fluid}}}} \approx \frac{1}{10^7 Z} \sqrt{\frac{\mu_{\mathrm{fluid}} k_{\mathrm{T}}}{k\beta}} \approx \frac{10^{-7}}{Z\sqrt{k}} \qquad (8)$$

where Z is the intrusion depth in km. ***Ve*** $<< 1$ corresponds to the situation where a sill is emplaced in an environment that is sufficiently permeable to prevent significant fluid pressure build-up because pressure diffusion is fast compared to the rate of pressure production. In contrast, for shallow emplacement depths, ***Ve*** $>> 1$ leads to a fluid-pressure increase and a 'blowout' situation when the fluid pressure exceeds the lithostatic pressure. At this stage, overpressured fluids will create their own permeability by deforming the overlying rocks and generating fluid release structures, i.e. hydrothermal vent complexes. Figure 3 shows under what depth and permeability conditions boiling-driven venting may occur, based on eqn (8). Note that, for pure water, boiling-driven venting will not occur at depths exceeding approximately 1.1 km, because the lithostatic pressure at such depths exceeds the critical pressure of water. This is consistent with the confinement of Karoo Basin hydrothermal vent complexes to the shallow-level strata below the Lesotho basalts (Fig. 2A). The results of the simple 1D model presented above are in full agreement with a recently developed fully coupled 2D numerical model, including the complete thermodynamics of H_2O (Podladchikov *et al.* in prep.).

Given the range of permeabilities, as well as the spatial permeability variations in natural systems, it is clear that the permeability is *the* controlling parameter. For a given field scenario, the total uncertainty in the estimated ***Ve***-value due to all other parameters will be orders of magnitude less than the uncertainty due to poorly constrained permeability. It is important to realize that the relevant permeability in this case is the bulk permeability for the sedimentary rocks on a scale comparable to H_{OP}. This is likely to be controlled by the permeability of the least-permeable sedimentary strata in the sedimentary sequence near the sills.

In the three-dimensional world, the pressure build-up is largest near the highest point of the sill surface (i.e. near the tip of the sill for the gently climbing sills in the shallow parts of the Karoo Basin). For high ***Ve***-numbers, boiling will boost the fluid pressure shortly after sill emplacement. In reality, boiling and significant rises in fluid pressure may already take place during emplacement.

The analysis above is not constrained to the situation where the porous fluid is pure H_2O. In the pure H_2O case, the ***Ve***-number will be reduced at depths corresponding to the critical point of water, due to the growing density of steam $\Delta\rho_{\mathrm{boil}} < \rho$. However, in a sedimentary basin setting one can easily imagine deeper hydrothermal venting processes driven by boiling of saline solutions, pressure build-up mechanisms related to gas generation from organic-rich sediments, devolatilization reactions (e.g. Litvinovskiy *et al.* 1990), retrograde boiling of crystallizing magma (Podladchikov & Wickham 1994), or increasing ***Ve***-numbers with depth resulting from a permeability reduction. This may explain the presence of the deep roots of the hydrothermal vent complexes from the Mid-Norwegian volcanic margin (Fig. 1).

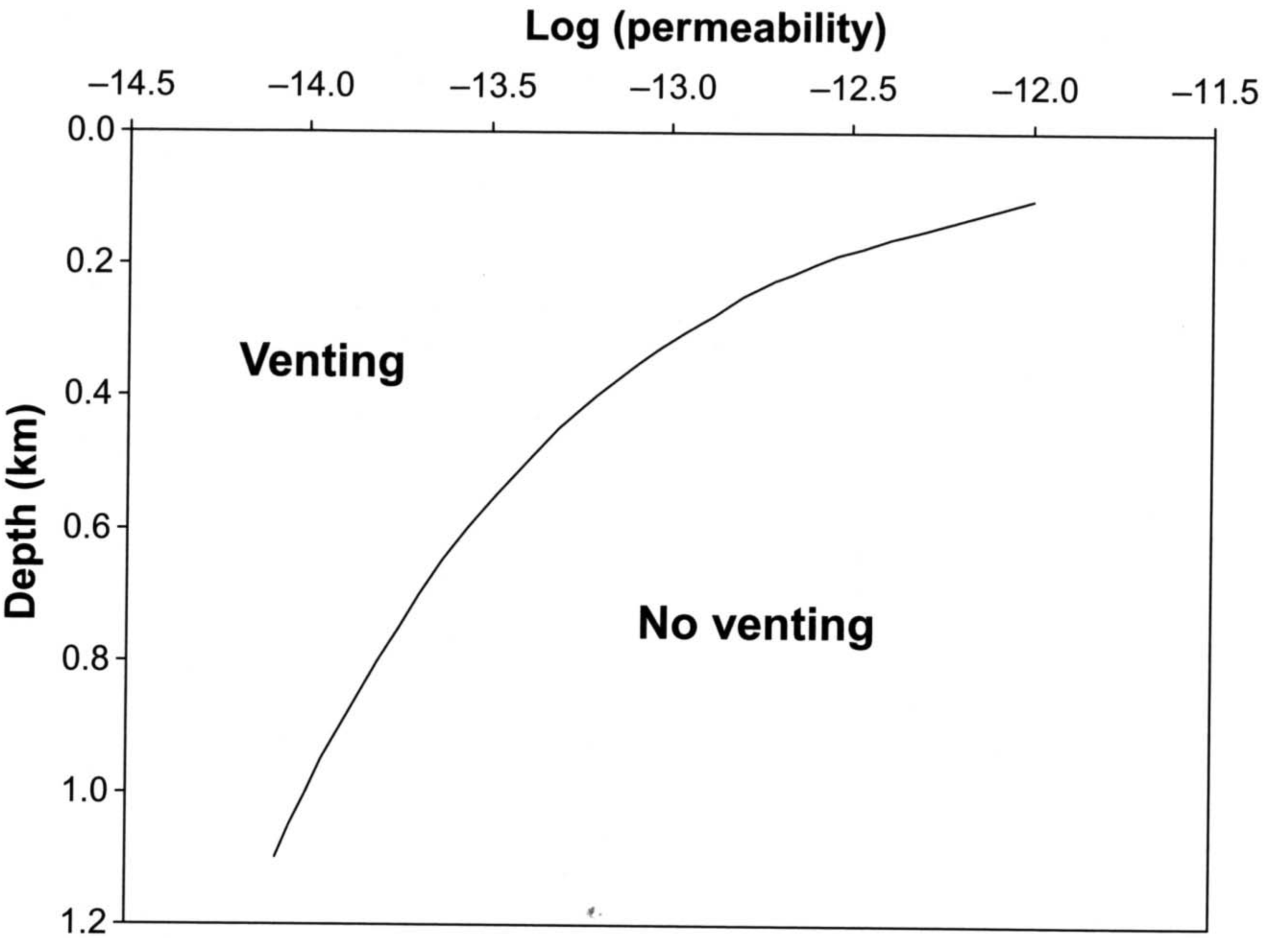

Fig. 3. Depth of intrusion versus log permeability of country rock for a ***Ve***-value of 1, based on eqn (8). Venting may occur in the region where depths are shallow and/or permeabilities are low. In the region to the right, fluid pressure will leak off too rapidly for venting to occur. At depths exceeding *c.* 1.1 km, boiling does not occur in pure water because the lithostatic pressure exceeds the critical pressure. Hence, no venting is expected.

Discussion

Field observations from the Karoo Basin demonstrate that the semi-circular hydrothermal vent complexes readily identified from aerial photos (Fig. 2B) represent restructured conical bodies typically having a surface diameter of hundreds of metres. By analogy with seismic profiles from the Mid-Norwegian volcanic margin (Fig. 1), we argue that these hydrothermal vent complexes are spatially connected to the termination of sill intrusions deeper in the basin.

We propose a model where overpressure generated from boiling of pore fluids near the sill–sediment interface is the driving mechanism for venting. The most obvious source of fluid overpressure in the shallow-level Karoo sediments is boiling of aqueous pore fluids. This will result in a short-lived and gas-driven system able to brecciate consolidated sediments in the source region and fluidize sand closer to the surface. In contrast to previous models applicable to hydrothermally driven piercement structures in sedimentary basins (e.g. Du Toit 1904, 1912; Grapes *et al.* 1973; Navikov & Slobodskoy 1979; Lorenz 1985), our model does not depend on the presence of a dyke network or emplacement-related fracturing in the source region, or on extensive mixing between magma and sediments. Juvenile volcanic material is present only sporadically in the sandstone-dominated complexes, suggesting phreatic activity without disintegration of sill dolerite or major restructuring of the sill–sediment interface.

Formation of hydrothermal vent complexes related to overpressured fluids derived from close to the sill–sediment contact is supported by ongoing aureole studies around sills in the Beaufort Group. Abundant sediment dykes cutting dolerite sills are evidence for high fluid pressures in contact-metamorphic aureoles, where fluidization and brecciation of sandstone beds below sills cause back-veining following cooling and thermal contraction (Walker & Poldervaart 1949; van Biljon & Smitter 1956; Planke *et al.* 2000).

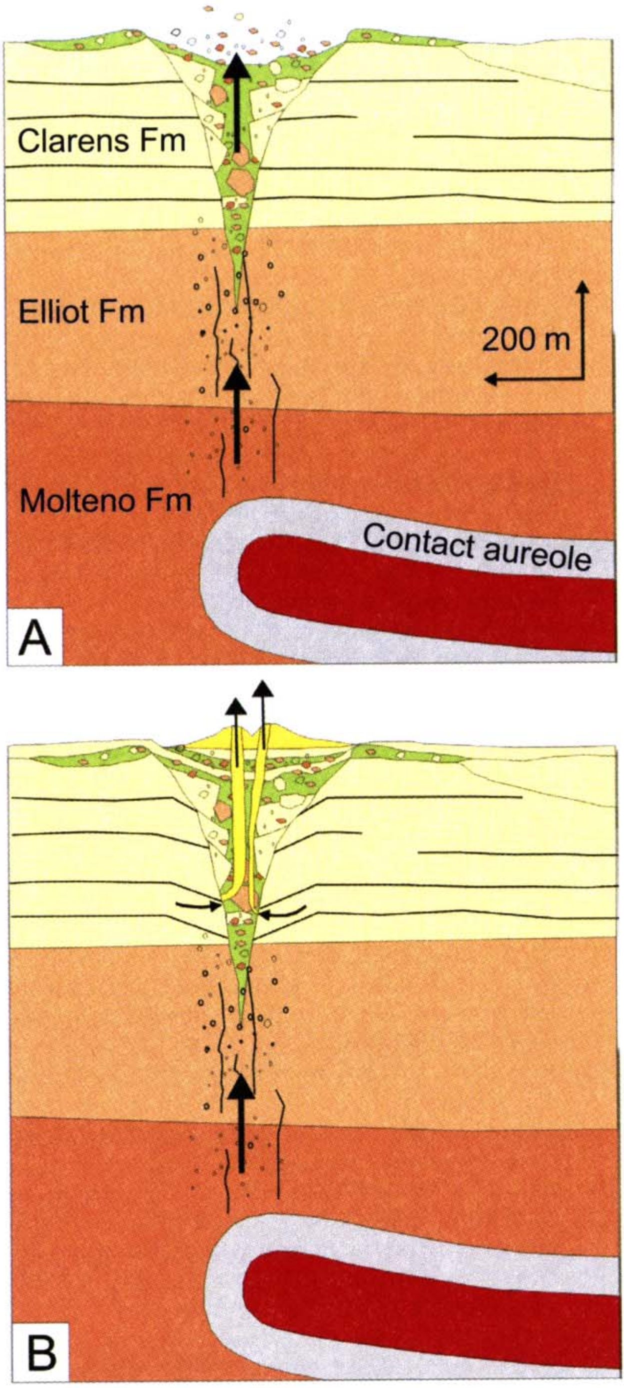

Fig. 4. Schematic evolution of hydrothermal vent complexes, based on data from the Karoo Basin, seismic data from the Norwegian Sea, and numerical modelling. The labelling of key units and the approximate scale applies to the Karoo Basin. (**A**) Boiling of pore fluids causes fluid pressure build-up and formation of a cone-shaped hydrothermal vent complex. The initial fluid expulsion is associated with fragmentation and generation of hydrothermal breccias. The erupted material may have formed crater rim deposits, but these have not been identified in the field, due to the level of erosion. (**B**) Subsequently, large (several metres across) pipes of fluidized sand cross-cut the brecciated rocks. Smaller hydrothermal pipes (centimetre-size) form during later reworking of the cone structure, following a reduction in fluid pressure gradients.

Our modelling results indicate that fluid discharge vents triggered by sill intrusions may have formed very shortly after sill emplacement, probably while most of the sill was still molten. An important consequence of the rapid evolution of the system is that the formation of hydrothermal vent complexes mainly depends on the dimensionless number ***Ve***. The sensitivity both to the detailed geometry of the system and possible uncertainties in the control parameters is negligible for the short time-scale evolution of the system.

Analogue experiments of fluid flow through sand beds have produced vent structures very similar to those observed in the Karoo Basin, including inward-dipping strata towards subvertical pipes of fluidized sand (Woolsley 1975). More recently, experiments on gas flow through beds of ultrafine cohesive powders showed how gas flow through porous beds leads to a sequence of different migration mechanisms, depending on gas flux (Li *et al.* 1999). For low gas fluxes, the gas flows through the stagnant porous medium, as in normal Darcian flow. However, with increasing gas flux, channel-ways form through the particle beds and, for very high fluxes, the overpressured gas lifts the roof and ultimately causes disaggregation and partial fluidization of the overlying porous wedge.

In the Karoo Basin, the fluid pressure must have been very high during initial vent formation and subsequently dropped as the system 'ran out of steam'. Thus an initial stage where the overpressured fluids literally lifted the roof and caused the observed disruption, disaggregation and brecciation of the initially well-stratified sediments may have been followed by a period where reduced fluid pressure pushed the system into a state where release of fluid and fluidized sand occurred through smaller discrete pipes or channels. The venting process produced local topographic depressions that could have acted as sites for aeolian and lacustrine sediment deposition (cf. Holzförster *et al.* 2002). A model of the vent complex formation consistent with field observations, modelling and the above-mentioned analogue experiments, is outlined in Figure 4.

Drilling of vent structures both in the western and eastern Karoo has shown that these structures represent local aquifers and thus a 'permanent' local perturbation of the hydrological properties of the Karoo Basin (Woodford *et al.* 2001). The long time-scale utilization of hydrothermal vent complexes for basin fluids is furthermore emphasized by the close association between seep-carbonate deposits and underlying vent structures (Svensen *et al.* 2003).

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