Journal of the Geological Society, *London*, Vol. **163**, 2006, pp. 671–682. Printed in Great Britain.

Structure and evolution of hydrothermal vent complexes in the Karoo Basin, South Africa

HENRIK SVENSEN[1], BJØRN JAMTVEIT[1], SVERRE PLANKE[1,2] & LUC CHEVALLIER[3]

[1]*Physics of Geological Processes (PGP), Department of Physics, PO Box 1048, Blindern, University of Oslo, Norway (e-mail: hensven@fys.uio.no)*

[2]*Volcanic Basin Petroleum Research (VBPR), Oslo Research Park, 0349 Oslo, Norway*

[3]*Council for Geoscience, PO Box 572, Bellville 7535, Cape Town, South Africa*

Abstract: The Karoo large igneous province, formed at *c*. 183 Ma, is characterized by the presence of voluminous basaltic intrusive complexes within the Karoo Basin, extrusive lava sequences and hydrothermal vent complexes. These last are pipe-like structures, up to several hundred metres in diameter, piercing the horizontally stratified sediments of the basin. Detailed mapping of two sediment-dominated hydrothermal vent complexes shows that they are composed of sediment breccias and sandstone. The breccias cut and intrude tilted host rocks, and are composed of mudstone and sandstone fragments with rare dolerite boulders. Sandstone clasts in the breccias are locally cemented by zeolite, which represents the only hydrothermal mineral in the vent complexes. Our data document that the hydrothermal vent complexes were formed by one or a few phreatic events, leading to the collapse of the surrounding sedimentary strata. We propose a model in which hydrothermal vent complexes originate in contact metamorphic aureoles around sill intrusions. Heating and expansion of host rock pore fluids resulted in rapid pore pressure build-up and phreatic eruptions. The hydrothermal vent complexes represent conduits for gases and fluids produced in contact metamorphic aureoles, slightly predating the onset of the main phase of flood volcanism.

Large igneous provinces, such as the North Atlantic and the Karoo–Lesotho provinces, are characterized by the presence of an extensive network of sills and dykes emplaced in sedimentary strata (e.g. Du Toit 1920; Walker & Poldervaart 1949; Chevallier & Woodford 1999; Berndt *et al*. 2000; Brekke 2000; Bell & Butcher 2002; Smallwood & Maresh 2002; Trude *et al*. 2003; Planke *et al*. 2005). An important consequence of intrusive activity in sedimentary basins is that the magma causes rapid heating of the intruded sediments and their pore fluids, causing expansion and boiling of the pore fluid (Jamtveit *et al*. 2004), and metamorphic dehydration reactions. These processes may lead to phreatic volcanic activity by the formation of cylindrical conduits that pierce sedimentary strata all the way to the surface. The hydrothermal vent complexes thus represent pathways for gases produced in contact aureoles to the atmosphere, with the potential to induce global climate changes (Svensen *et al*. 2004). Consequently, constraints on processes leading to the formation of hydrothermal vent complexes in sedimentary basins, their abundance and structure may lead to a better understanding of the causes of the abrupt climate changes that are associated with many large igneous provinces (e.g. Wignall 2001; Courtillot & Renne 2003).

Hydrothermal and phreatomagmatic vent complexes are recognized from several sedimentary basins associated with large igneous provinces, including the Vøring and Møre basins off mid-Norway (Skogseid *et al*. 1992; Svensen *et al*. 2003; Planke *et al*. 2005), the Faeroe–Shetland Basin (e.g. Bell & Butcher 2002), the Karoo Basin in southern Africa (e.g. Du Toit 1904, 1912; Gevers 1928; Stockley 1947; Dingle *et al*. 1983; Jamtveit *et al*. 2004), in the Karoo-equivalent basins of Antarctica (Grapes *et al*. 1973; Hanson & Elliot 1996; White & McClintock 2001), and the Tunguska Basin in Siberia, Russia (e.g. Zolotukhin & Al'mukhamedov 1988). Two- and three-dimensional seismic data have provided constraints on the spatial relationship between sill intrusions and hydrothermal vent complexes (Planke *et al*. 2005). Generally, the hydrothermal vent complexes represent conduit zones up to 8 km long rooted in contact aureoles around sill intrusions, where the upper part of the vent complexes comprise eyes, craters or mounds, up to 10 km in diameter (Fig. 1; Planke *et al*. 2005). Field observations from the Karoo Basin show that similar hydrothermal vent complexes commonly comprise breccias of sedimentary rocks with a varying degree of magmatic material (e.g. Dingle *et al*. 1983; Woodford *et al*. 2001; Jamtveit *et al*. 2004).

The aim of this paper is to document the structure, composition and evolution of sediment-dominated hydrothermal vent complexes in the Karoo Basin, South Africa (Fig. 2a). Here, we have chosen to focus on two representative complexes that were selected after reconnaissance fieldwork on more than 10 complexes in the Dordrecht–Rossow area in the Eastern Cape Province (Fig. 2b). Specifically, we want to address the following questions that can be tested by detailed fieldwork and petrographic analysis. (1) Do sediment-dominated hydrothermal vent complexes represent phreatic explosion events? (2) What is the involvement of igneous material in phreatic sediment-dominated vent complexes? (3) What is the degree of hydrothermal alteration in and around short-lived phreatic systems? Quantitative aspects of the formation of hydrothermal vent complexes and processes in volcanic basins are addressed elsewhere (Jamtveit *et al*. 2004; Malthe-Sørenssen *et al*. 2004).

Terminology

Volcanic basins are sedimentary basins with a significant amount of primary volcanic rocks (e.g. sills and dykes).

Pierced basins are sedimentary basins with many piercement

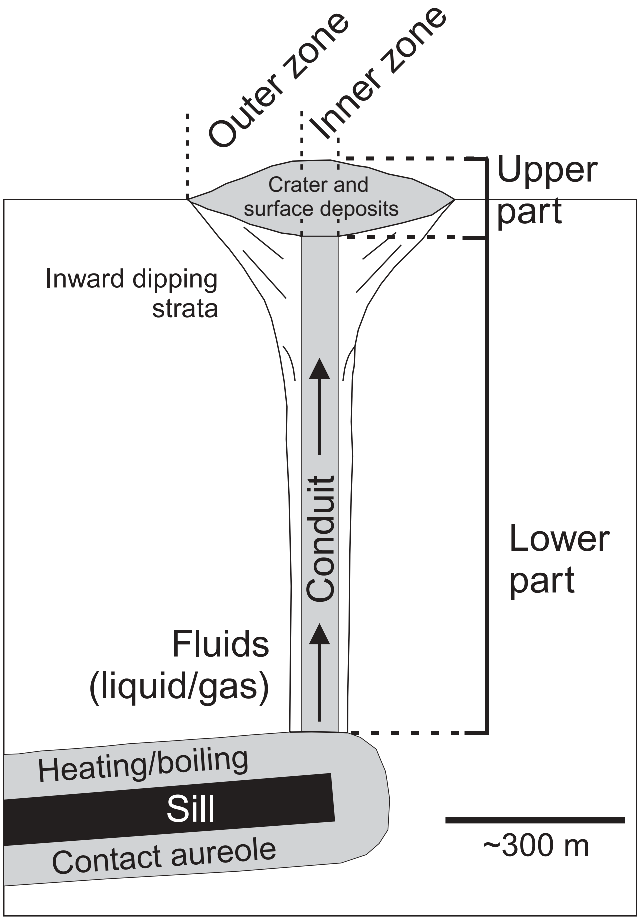

Fig. 1. Idealized cross-section through a hydrothermal vent complex based on field observations from the Karoo Basin and seismic interpretation from the Norwegian Sea (Jamtveit *et al*. 2004; Planke *et al*. 2005). We divide hydrothermal vent complexes into a lower and an upper part, and an inner and an outer zone.

structures such as mud volcanoes, dewatering pipes and hydrothermal vent complexes.

Sills are tabular igneous intrusions that are dominantly layer parallel. They are commonly subhorizontal. Sills may locally have transgressive segments, i.e. segments that cross-cut the stratigraphy.

Hydrothermal vent complexes are pipe-like structures formed by fracturing, transport and eruption of hydrothermal fluids. The complexes described here are dominated by sedimentary rocks with a negligible content of igneous material.

Sediment volcanism is surface eruption of mud, sand or sediment breccias through a vent complex.

The Karoo Basin

The Karoo Basin (Fig. 2a) covers more than half of South Africa. The basin is bounded by the Cape Fold Belt along its southern margins and comprises up to 6 km of clastic sedimentary strata capped by at least 1.4 km of basaltic lava (Fig. 2c; Smith 1990; Johnson *et al*. 1997). The sediments were deposited from the Late Carboniferous to the Mid-Jurassic, in an environment ranging from partly marine (the Dwyka and Ecca groups), to fluvial (the Beaufort Group and parts of the Stormberg Group), and aeolian (upper part of the Stormberg Group) (Catuneanu *et al*. 1998). At the time of flood basalt eruption, up to 400 m of fine-grained sand had been deposited by aeolian, fluvial and lacustrine processes (Smith 1990; Veevers *et al*. 1994). The sedimentary rocks forming the southwestern parts of the basin were gently folded during 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 the early Jurassic Period. Dolerites and lavas in the Karoo Basin were emplaced and erupted within a relatively short time span (183 $\pm$1 Ma; Duncan *et al*. 1997). Sills and dykes are present throughout the sedimentary succession, and locally form up to 70% of the basin volume (e.g. Rowsell & De Swardt 1976). Hydrothermal vent complexes and volcanic phreatic complexes are numerous in the Karoo Basin, and primarily exposed within the Stormberg Group sediments. The complexes comprise a range of different rock types, ranging from lava and pyroclastic rocks to sediment breccia and sandstone (e.g. Du Toit 1904, 1912; Gevers 1928; Taylor 1970; Dingle *et al*. 1983). The formation of the complexes is related to the sill emplacement episode and the formation of the Karoo igneous province (e.g. Dingle *et al*. 1983; Woodford *et al*. 2001; Jamtveit *et al*. 2004). The hydrothermal vent complexes represent a very prominent feature of the Karoo Basin, and more than 320 have been identified in the Stormberg Group.

Methods

Detailed mapping of two hydrothermal vent complexes, Witkop II and III (Fig. 2b), was carried out during three field seasons, including an extensive sampling programme (*c*. 100 samples). The fieldwork focused on mapping the total extent of the vent complexes, identifying and mapping sedimentary facies units and their boundaries, logging of sections in the vent complexes, and identifying structural features such as faults and pipes. Aerial photographs from the Chief Directorate of Surveys and Mapping in Cape Town (South Africa) were used for geological mapping because of the lack of detailed topographic sheets for the area. Length and height measurements were made by a Garmin Etrex global positioning system (GPS), and used to calibrate maps and logs.

Petrography of a large number of thin sections (>50) has been studied by optical and electronic microscopes at the Department of Earth Sciences, University of Oslo, with a JEOL JSM 840 SEM and a CAMECA SX 100 electron microprobe. A microprobe analysis of zeolite was carried out with an accelerating voltage of 15 kV, a beam current of 5 nA and a 5 μm raster size, using synthetic and natural standards.

The Department of Water Affairs in South Africa drilled a percussion borehole trough the inner zone of the Witkop III hydrothermal vent complex in April 2003. The borehole started at 1908 m above sea level, and terminated at 300 m below the surface. Chips were collected every metre during drilling, and were washed and logged.

Facies units

Geological mapping of the two hydrothermal vent complexes revealed the presence of distinct sediment facies units (Fig. 3). These include (1) sandstone in the inner zone of the vent complex, (2) zeolite-cemented sandstone, and (3) sediment breccia. Descriptions of the surrounding Elliot and Clarens formations have been given by Catuneanu *et al*. (1998).

Homogeneous sandstone in the inner zone of the vent complex (Unit I)

Figure 3b shows typical sandstone from Unit I, with a dominance of quartz and feldspar grains. The vent complex sandstone

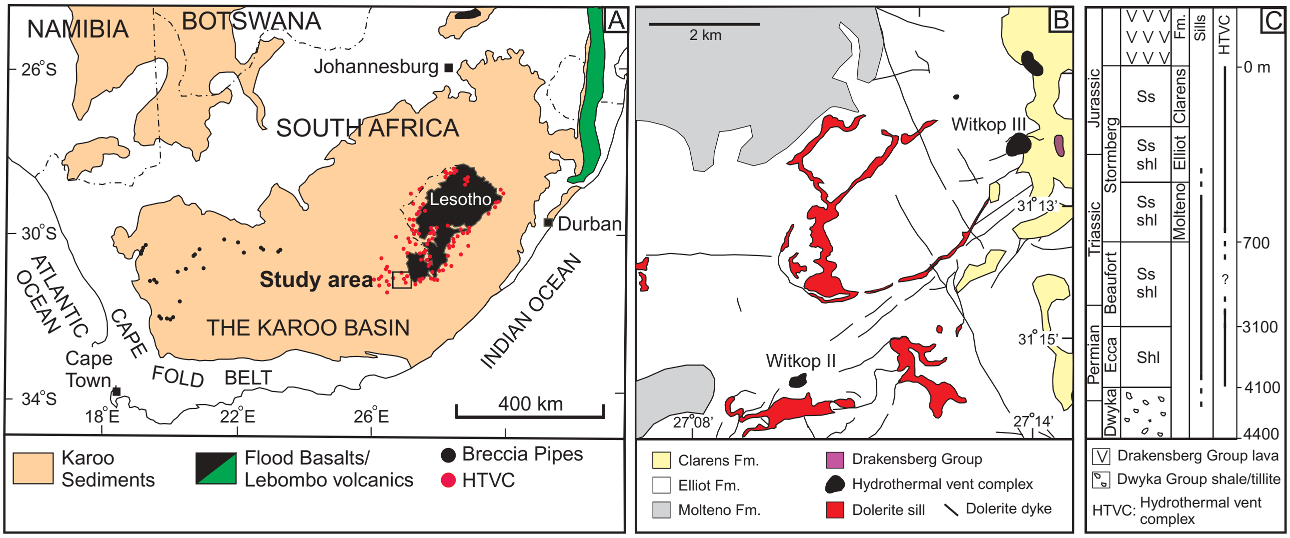

Fig. 2. (**a**) Distribution of hydrothermal vent complexes (HTVC) and breccia pipes in the Karoo Basin, South Africa. The hydrothermal vent complexes are mainly confined to outcrops in the Stormberg Group sediments, whereas the breccia pipes are confined to the Ecca and Beaufort groups (Woodford *et al*. 2001). Fieldwork has been carried out on more than 10 hydrothermal vent complexes in the study area (the Molteno–Dordrecht–Rossow area). The map is modified and compiled from Gevers (1928), Dingle *et al*. (1983), Keyser (1997) and Woodford *et al*. (2001). It should be noted that the symbols for the breccia pipes represent pipe clusters and not individual pipes. (**b**) Simplified geological map of the study area showing the spatial relationship between hydrothermal vent complexes and sill intrusions in the Dordrecht–Rossow area. The map is based on unpublished data from the Council of Geoscience (L. Chevallier, pers. comm.). (**c**) Simplified stratigraphic overview of the Karoo deposits in South Africa. The dominant sediment types are sandstone (Ss) and shale (Shl). The stratigraphic positions of sill intrusions and hydrothermal vent complexes (HTVC) are shown for reference. The stratigraphy is based on a compilation by Catuneanu *et al*. (1998), and the position of sill intrusions is from Chevallier & Woodford (1999). The thicknesses of the individual groups are not to scale. The given thicknesses of the formations below the Stormberg Group are from borehole WE1/66 (Leith & Trümpelmann 1967), whereas a thickness of *c*. 700 m for the Stormberg Group in the same area is adopted from Dingle *et al*. (1983). The thickness of the Karoo Basin sediments varies considerably within the basin (e.g. Rowsell & De Swardt 1976), but for this study the WE1/66 stratigraphy is considered representative, as the borehole is located just north of our study area (30°53′50″S, 26°50′26″E). A total of 19 sill intrusions are present in the borehole (a total of 956 m).

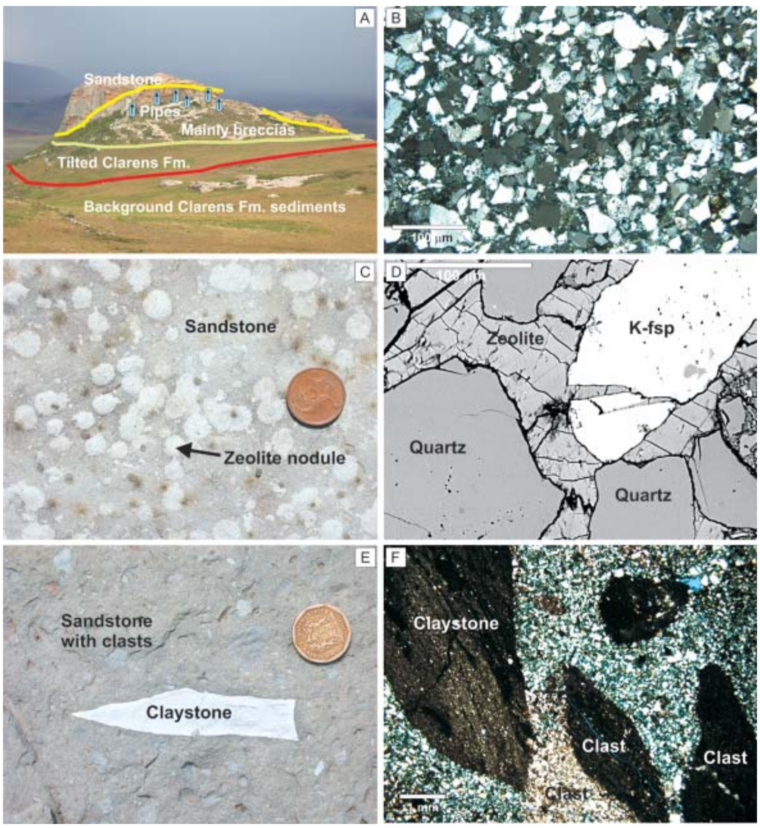

Fig. 3. Rocks and textures from hydrothermal vent complexes. (**a**) Photograph showing the main lithologies at the Witkop III hydrothermal vent complex. (**b**) Photomicrograph of sandstone (Unit I) from the inner zone of Witkop III showing quartz and feldspar grains without any altered igneous material. (**c**) Sandstone with nodules of zeolite cement from the outer zone at Witkop III. This rock type is present in about 30 m of stratigraphy, and is called Unit II. (**d**) SEM backscatter image of a sample from Unit II showing authigenic zeolite cement in sandstone. The zeolite fills a fracture in K-feldspar, documenting an early stage of precipitation. Also noteworthy is the absence of authigenic K-feldspar and quartz cement. (**e**) Close-up of a sediment breccia from Witkop II with an angular claystone fragment in a matrix of fine-grained sediment breccia. (**f**) Photomicrograph of a sediment breccia from a pipe at Witkop III. The dark fragments represent claystone, and are aligned parallel to the wall of the pipe. The matrix is fine-grained sandstone.

resembles the Clarens Formation sandstone in texture, colour and grain size, although it may locally be more clast-rich. The cream-coloured sandstone is locally interbedded with breccia (Unit III), and contains varying degrees of sedimentary rock fragments. The topographic high in the inner zone of Witkop III is dominated by sandstone, and has a characteristic reddish weathering crust showing secondary silica cement and feldspar dissolution. The weathering has resulted in problems identifying the primary mineral assemblages in the sandstone. Clasts of other sedimentary rocks (shale, siltstone) occur occasionally.

Zeolite-cemented sandstone (Unit II)

The basal parts of the Clarens Formation in the northern parts of Witkop III contain distinct white nodules of zeolite (Fig. 3c). The nodules are commonly circular and about 1 cm in diameter, and represent sandstone cemented by authigenic laumontite. Sandstone with this nodular type of zeolite cement (Fig. 3d) has not been observed elsewhere in the study area, although the Clarens sandstone immediately underlying the lavas contains a zone of a few metres thickness with zeolite nodules. The zeolite sandstone unit contains thin (<20 cm) horizons of siltstone without zeolite cement. The thickness of the zeolite-cemented unit is about 30 m, and features such as sandstone dykes and up to 30 cm high calcite-cemented cylindrical pipe structures are abundant. The pipes are interpreted as dewatering structures.

Sediment breccia (Unit III)

The sediment breccia comprises clasts of sedimentary rocks (sandstone, siltstone and claystone) within a matrix of fine-grained sandstone (Fig. 3e and f). The sediment breccia is matrix supported with a greenish colour, in contrast to the cream-coloured Clarens sandstone and vent complex sandstone. The modal content of clasts varies considerably, from high ($>50\%$) to sporadic ($<5\%$), and the clasts vary greatly in size, from millimetre to decimetre scale. The matrix consists of sandstone–siltstone and fine-grained breccia with clasts <2 mm. Likewise, the shapes of the clasts are often both angular and subrounded within the same exposure. Many of the sandstone clasts resemble the Clarens sandstone in colour and grain size, whereas others are identified as Elliot and Molteno sandstone based on colour, mineralogy and grain size. Molteno sandstone is easily identified by its coarse grain size (coarse sand) and abundant visible quartz cement (see Turner 1972), whereas the Clarens sandstone is identified by its small grain size (fine sand) and cream colour. Elliot sandstone outside the vent complexes has commonly a characteristic red to purple colour, but red clasts are rare in the breccias. It should be pointed out that it is difficult to trace most of the sandstone and siltstone clasts to their source formations. However, the Elliot Formation is regarded as the major source of siltstone fragments as siltstone is more abundant in the Elliot than in the Molteno and Clarens formations.

Clasts and boulders of rounded sandstone are abundant in Witkop II and III. They are well cemented, with secondary pore-filling calcite. Aggradation is a possible explanation for the rounded and smooth surfaces of the boulders, and could possibly have occurred during transport in the vent complex. Furthermore, micritic calcite clasts (up to 5 cm in diameter) with a small component of detrital minerals occur locally in the sediment breccia. The micritic calcite clasts may represent remobilized pedogenic carbonate, which is common locally in the Clarens and Elliot formations (see Eriksson 1981).

No igneous boulders or fragments were found in the breccia at Witkop III. At Witkop II, however, a basaltic boulder (25 cm in diameter) is present in sediment breccia near the top of the vent complex (Fig. 4). The boulder comprises tabular crystals of plagioclase in a fine-grained matrix, suggesting relatively rapid cooling. It has previously been suggested that the sediments from the inner zone of Witkop III contain altered glass shards but no juvenile igneous material (Seme 1997). We have not been able to demonstrate the presence of volcanic material or altered igneous material in the vent sandstone or in the sediment breccia, although identification could be difficult due to alteration to clay minerals. The clay-dominated fragments in the studied sediment breccia, which potentially could represent altered mafic material, are of clastic origin (see Fig. 3f). The zeolite in sandstone could have formed *in situ* from reaction between water and mafic material. However, we have not been able to positively verify the presence of altered volcanic material texturally associated with the zeolite (by using optical and electronic microscopes). Furthermore, the zeolite in Unit II is pore filling (*c.* 10–20 vol.%) in 30 m of Clarens stratigraphy, suggesting a major precipitation event.

The Witkop III hydrothermal vent complex

The sediment-dominated Witkop III hydrothermal vent complex is situated NW of Dordrecht in the Eastern Cape Province (Fig. 2b). In this area, the Clarens Formation is about 140 m thick, including two main horizons with dune structures. Volcaniclastic sediments are present in the upper parts, overlain by fine-grained laminated sandstone close to the base of the Drakensberg Group flood basalts.

External structure

The base of the Witkop III complex crops out at the transition between the Elliot and Clarens formations. The complex overlies a sill intrusion cropping out in the Molteno Formation (Fig. 2b). The complex is divided into an inner and outer zone. The diameter of the complex is about 700 m with the inner zone having a diameter of 400 m. The outer zone comprises structurally modified Clarens strata with dips ranging from background values (*c.* 5°) to about 60° into the complex (Figs 5 and 6). The inner zone is a topographic high, rising about 200 m above the grass-covered plains in front. The boundary between the inner and the outer zone is exposed in a gully with slumped sediments (Fig. 6a).

Facies assemblages

Sediment breccia (Unit III) overlies tilted Clarens sandstone in the western parts of the inner zone, and is overlain by Unit I sandstone containing few to no clasts (Fig. 6b). Sedimentary structures in both units are sparse, but channel-like strata of conglomerate are present in sandstone towards the top of log B in Figure 6b. Both the breccia and the sandstone dip inward towards the centre of the complex, with dips between 5 and 58°. At the border zone between the inner and outer zone, tilted layers of alternating sandstone and conglomerate are aligned in contact with sandstone from the outer zone. Slumping structures in sandstone indicates soft sediment deformation. The dips of the strata in log B are consistent throughout the sequence. This can be related to the tilting of the Clarens sandstone in the outer zone. The basal Unit III sediment breccia from log B has a massive appearance and a general absence of sedimentary structures. In the upper half of log B, Clarens sandstone and reworked breccia dominate. The heterogeneity of the complex is, however, demonstrated in log C from the eastern side of the complex. Here, the base of the inner zone comprises a mixture of sediment breccia and sandstone, the middle part is dominated by coarse sediment breccia (fragments up to 40 cm), and the upper 15 m is sandstone dominated (Unit I). However, as a result of weathering of the sediments and poor exposures, the details in the stratigraphy of the sediments between logs B and C remain uncertain. Unit II zeolite-cemented sandstone is present north of the outer zone.

Logging of chips from the borehole at Witkop III (Fig. 6b) shows that only the upper 2 m comprise sediment breccia. The rest of the borehole penetrates Clarens and Elliot strata. The Elliot–Clarens transition is located about 50 m deeper within the borehole than outside the complex, demonstrating the structural modifications of the sediments surrounding the inner zone. Furthermore, the dolerite dyke or sill cropping out in the inner and outer zone of the complex (Fig. 6a) was intersected at 117–123 m in the borehole.

Sediment pipes and dykes

Circular and elliptical vertical to subvertical sediment pipes are numerous within the inner zone of Witkop III (Fig. 6a). A total of 21 large pipes (>0.5 m) and about 40 small pipes (<0.5 m) have been identified. Small pipes are particularly abundant in two areas within the complex, where they form topographically positive structures up to about 30 cm in diameter. The pipes are all composed of sandstone of Unit I type. The large pipes are positive structures with sharp contacts with surrounding rocks, often displaying deformation grooves, grain-size reduction, and flow banding around the margins (Fig. 7). Many of the large pipes have diameters of 8–10 m, some up to 30 m. All the large pipes cut the sediment breccia within the inner zone of the vent complex, and are filled with both sandstone and sediment breccia. Detailed mapping of one of the large sandstone pipes shows an outer partially undulating deformation zone up to 50 cm in thickness (Fig. 7a and b) with both horizontal and vertical deformation grooves. One sandstone pipe has a sandstone dyke extending about 4 m outward from its wall.

Sediment dykes are abundant within the inner zone (Fig. 6a); most of them are <30 cm wide and <10 m long, pinching out at both ends. They are easily distinguished from pipes. A few sediment dykes reach 0.5 m in width. The dykes are composed of sandstone or sediment breccias, and many are distributed around the topographic high of the inner zone. Sandstone dykes are also abundant in the outer zone, usually being a few metres long and up to 10 cm wide. They are especially common in the area with zeolite-cemented sandstone. The hinge-point of the outer zone of the complex (Fig. 5a) is furthermore defined by the presence of a 0.5 m wide sandstone dyke that cuts at least 30 m of stratigraphy.

Petrography and hydrothermal minerals

The authigenic minerals in sandstone and breccia from the Witkop III hydrothermal vent complexes are K-feldspar, albite, quartz and zeolite. Most samples have clays (mainly illite) as the dominant matrix minerals, but calcite cement occurs locally. The K-feldspar is often zoned as a result of substitution of ammonium for potassium (buddingtonite). Zeolite forms late-stage cement in (1) Clarens sandstone from the outer zone (Fig. 3d), (2) sandstone from the upper 100 m in the borehole, and (3) sandstone clasts from sediment breccias (both in pipes and elsewhere). It should be noted that zeolite is locally present in the Clarens Formation surrounding the Witkop III complex, but the macro-textures are different (less pronounced nodular development) from those in Unit II. In the upper part of the Clarens Formation, zeolite is associated with local alteration of fine-grained volcanic material (Fig. 8a). Zeolite has also been identified in sandstone without igneous material, where zeolite apparently formed during dissolution and replacement of feldspar (Fig. 8b).

The Witkop II hydrothermal vent complex

The Witkop II hydrothermal vent complex is located 5–6 km SW of Witkop III (Fig. 2b). The structure consists of two connected circular structures piercing the Elliot Formation (Fig. 9a). The border between the two circular parts is seen in the field as a depression in the terrain comprising sediment breccias. The complex is cut by a dolerite dyke that transforms into a sill by following the internal structures in the complex, in a similar way to the dolerite dyke at Witkop III.

Two sediment facies units are identified in Witkop II; vent sandstone (Unit I) and sediment breccia (Unit III). The bulk of the complex is composed of inward dipping Clarens sandstone with dune structures and parallel-bedded horizons overlain by interlayered sequences of sediment breccia and Clarens sandstone. An important feature of Witkop II is that sediment breccia cuts both the Elliot Formation and the tilted Clarens sandstone. These relationships are well exposed in the area between the two circular structures. In addition, an undulating network of sandstone dykes up to about 1 m thick cuts the breccia. A log from the southwestern part of the complex shows that a tilted block of Clarens sandstone is overlain by interlayered sequences of sediment breccia and sandstone (Fig. 9b). Only one large sandstone pipe was found at Witkop II, located along the border of the complex. The pipe cuts the surrounding sediment breccia with an internal deformation zone along the contact.

Geological synthesis

The Witkop II and Witkop III hydrothermal vent complexes share many characteristic features: (1) both contain inward dipping sequences of Clarens sandstone cut by sediment breccia; (2) both contain sediment dykes and pipes; (3) no, or little, igneous material is found. Witkop III is considered the more interesting of the two because of the presence of a wider range of structures such as pipes and dykes that give information about the evolution of the complex. However, the best examples of intrusive sediment breccias come from Witkop II. Zeolite-cemented rocks have so far only been found at Witkop III and igneous clasts only at Witkop II.

Figure 10 shows an interpretative cross-section through Witkop III. The boundaries between the inner and outer zones are well defined from field geology and aerial photographs, but the structure of the deeper parts of the inferred conduit zone are poorly constrained because of lack of outcrops. Rock fragments in breccias and pipes originate from the Elliot and Molteno formations, which require a diatreme-like structure at depth. The absence of breccia in the borehole, except in the upper metres, suggests that the conduit zone is narrow. Tilting of the surrounding Clarens sediments occurred after the deposition of Unit III breccia. The vent sandstone (Unit I) represents Clarens Formation sandstone covering the sediment breccias, possible with a component of sand vented from the sediment pipes.

Discussion

Volcanic basins and hydrothermal vent complexes

Recent studies have shown that hydrothermal vent complexes are abundant in the Vøring and Møre basins of offshore Norway (Svensen *et al*. 2004; Planke *et al*. 2005). The >700 hydrothermal vent complexes mapped in these basins are spatially associated with deeper sill intrusions. The sills intruded the shale-dominated basins during the break-up of the North Atlan-

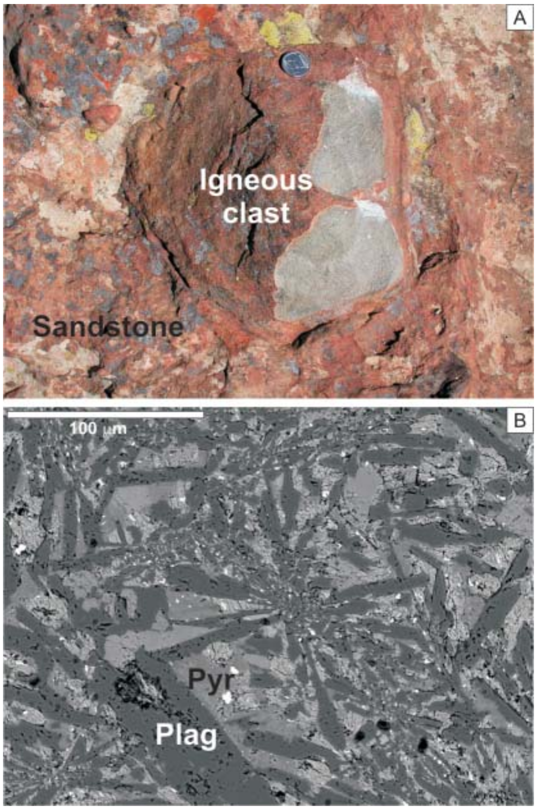

Fig. 4. (**a**) Crystalline basaltic boulder from an outcrop at the Witkop II hydrothermal vent complex. (**b**) SEM backscatter image of the basaltic boulder. The dominant minerals are plagioclase (Plag) and pyroxene (Pyr). The tabular quench-like plagioclase crystals in the relatively fine-grained matrix suggest rapid cooling of the parent melt.

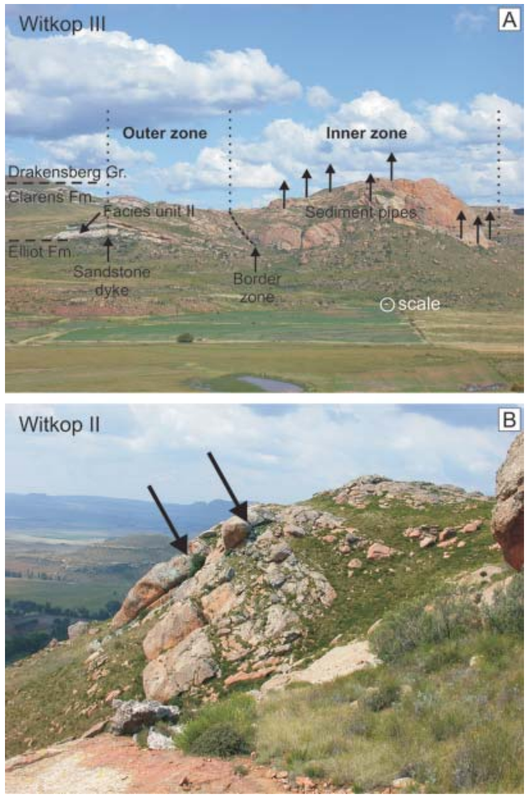

Fig. 5. (**a**) The Witkop III hydrothermal vent complex comprises an outer zone with structurally modified Clarens strata, and an inner zone with abundant sediment breccia. The whole Clarens Formation is exposed in the area, and the Drakensberg Group basalts are seen in the background. Car for scale. (**b**) Inward dipping strata of Clarens sandstone at the Witkop II hydrothermal vent complex. The grass-covered areas on the right represent sediment breccia and those to the left the Elliot Formation.

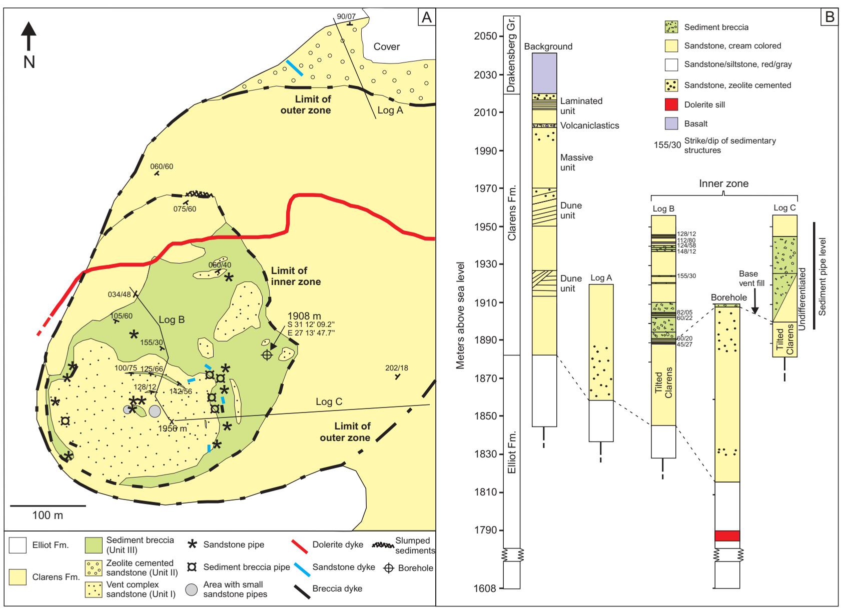

Fig. 6. (**a**) Geological map of the Witkop III hydrothermal vent complex. Three composite logs based on surface exposures are presented in (**b**). A prominent feature of this locality is the presence of well-preserved sediment pipes reaching tens of metres in diameter. (**b**) Stratigraphy of the Witkop III area, showing sedimentary strata from the Elliot and Clarens formations unaffected by the vent complex formation (left), surface logs of breccias and sandstone (logs A–C), and a log of the borehole. The ‘background log’ is constructed based on exposures between the Elliot Formation (exposed underneath Unit II) and the Drakensberg Group lavas east of the complex.

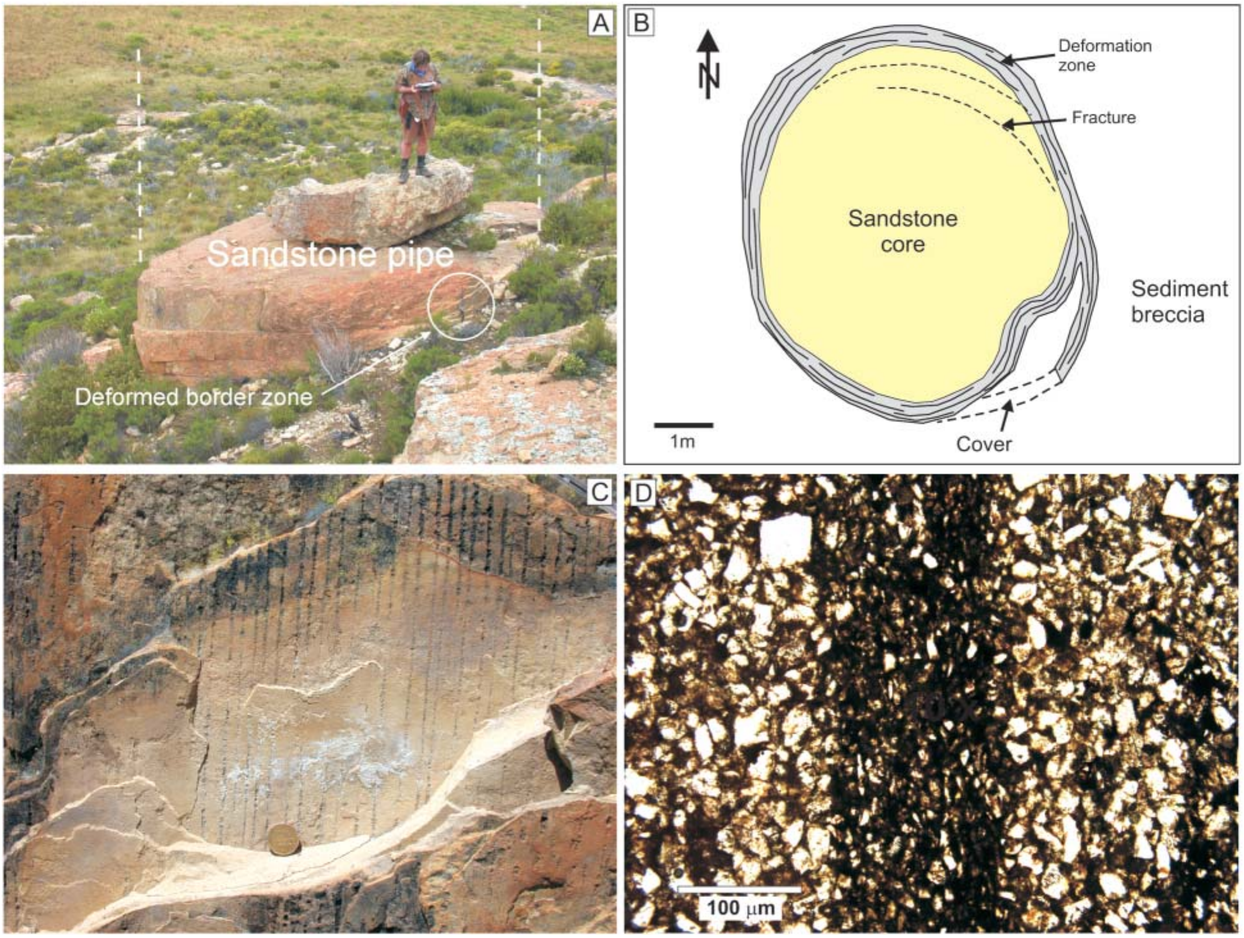

Fig. 7. Sediment pipes. (**a**) Sandstone pipe (6 m × 6.5 m) cutting sediment breccia in the inner zone of Witkop III. The pipe has a 40 cm thick internal deformation zone along the margin. Both vertical and horizontal deformation grooves are present within this zone. (**b**) Detailed map of the sandstone pipe shown in (**a**). The partly undulating border zone is typical for the pipes at Witkop III. (**c**) Close-up of a deformation zone in a sandstone pipe at Witkop III. The near-vertical deformation grooves and the slate-like appearance of the sandstone should be noted. (**d**) Thin-section photomicrograph of a deformation band showing variation in grain size between the matrix and the deformation zone.

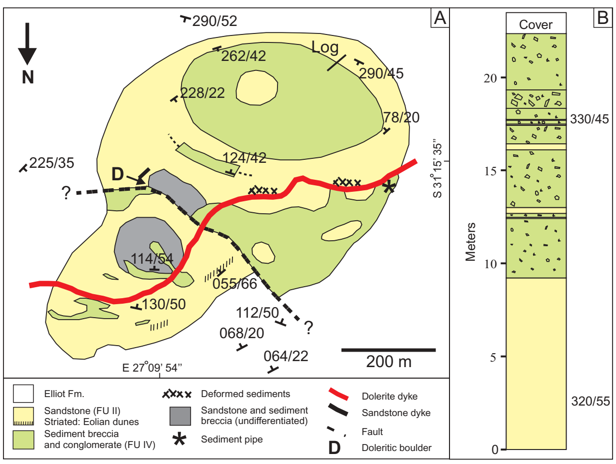

Fig. 9. (**a**) Geological map of the Witkop II hydrothermal vent complex showing two circular structures defined by inward dipping Clarens sandstone and sediment breccia. (**b**) Log from the southeastern part of the Witkop II hydrothermal vent complex; 15 m of sediment breccias overlie a tilted block of Clarens sandstone. The strike and dip of the layers are consistent throughout the section, suggesting tilting of the whole sequence after breccia deposition.

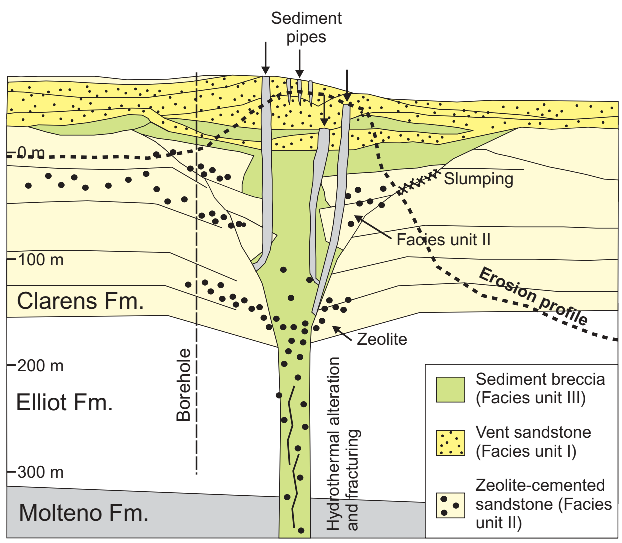

Fig. 10. Composite schematic cross-section through the Witkop III hydrothermal vent complex. The section is based on outcrop data and borehole information. (See text for explanation.)

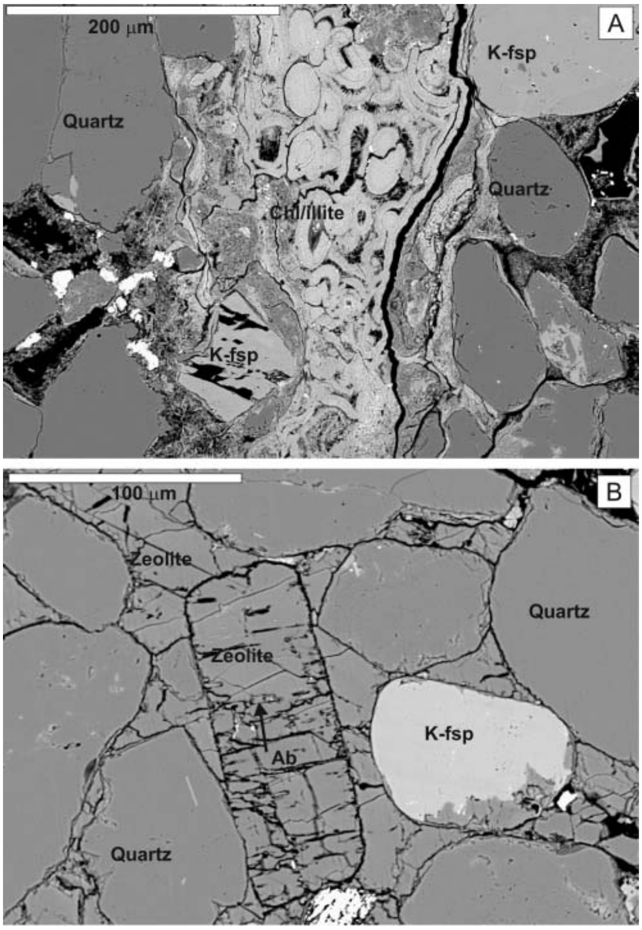

Fig. 8. SEM backscatter images from Clarens Formation sandstone surrounding the Witkop III complex. (**a**) Possible volcanic material (glass) now altered to chlorite and illite. The texture differs from anything seen in the sediment breccia from the hydrothermal vent complexes. (**b**) Zeolite-cemented Clarens sandstone (from the upper part of the uppermost dune unit in Fig. 6b). The absence of other authigenic minerals (indicating early zeolite precipitation), and that the zeolite forms pseudomorphs after feldspar (albite), should be noted.

tic, at *c*. 55 Ma. The total number of hydrothermal vent complexes may be as high as 2000–3000. From the size of the volcanic basin (85 000 km^2) this results in an average of 20–40 complexes per square kilometre. The stratigraphic level where >95% of the hydrothermal vent complexes terminate continues beneath the extrusive basalts, and no hydrothermal vent complexes have been identified within, or above, the extrusive sequence (Planke *et al*. 2005). An important conclusion from these studies is that the hydrothermal vent complexes are spatially associated with sill intrusions at depth.

When adopting these results to the Karoo Basin, hydrothermal vent complexes were probably present where sills crop out today. As a result of erosion, only a small part of the original size of the Stormberg Group is present, and thus the original number of hydrothermal vent complexes was probably higher. Considering the exposed area of the Stormberg Group (*c*. 42 000 km^2) with *c*. 325 mapped hydrothermal vent complexes (e.g. Du Toit 1954), the resulting vent complex density is one per 130 km^2. If scaled to the area with present-day sill intrusions (*c*. 390 000 km^2), the total number of vent complexes in the Karoo Basin would have been about 3000. Not included are hundreds of sediment-dominated cylindrical pipes present in the Ecca Group (‘breccia pipes’; Woodford *et al*. 2001). They possibly represent the deep roots of hydrothermal vent complexes.

Pressure build-up mechanisms

The hydrothermal vent complexes have previously been termed diatremes and volcanic necks, and have, since the pioneer work of Du Toit (1904, 1912), been interpreted as the result of phreatic or phreatomagmatic activity (e.g. Gevers 1928; Botha & Theron 1966; Coetzee 1966; Taylor 1970; Dingle *et al*. 1983; Seme 1997; Woodford *et al*. 2001). The Witkop II and III hydrothermal vent complexes are spatially associated with sill intrusions (Fig. 2b), but a direct relationship between conduit zones and contact aureoles cannot be demonstrated because of lack of exposures and boreholes. A general genetic relationship between sills and vent complexes is, however, supported by interpretations of seismic data from the Vøring and Møre basins of offshore mid-Norway, where it is shown that hydrothermal vent complexes are rooted in aureole segments of sill intrusions (Jamtveit *et al*. 2004; Planke *et al*. 2005). The general lack of igneous material in the hydrothermal vent complexes strongly suggests that they are rooted in a zone without major magma disintegration. We have recently proposed a model of vent complex formation by heating and boiling of pore fluids in contact aureoles around shallow sills (Jamtveit *et al*. 2004). In this model, boiling of pore fluids may occur at depths as great as *c*. 1 km, and overpressure and possibly venting occur if the local permeability is low. Thick sills are common in the Stormberg Group sediments, at least in the Molteno Formation, which can be assumed to have caused shallow (<1 km) boiling and expansion of pore fluids in contact aureoles. A high-permeability host rock requires a very rapid pressure build-up compared with permeability to initiate hydrofracturing. Following hydrofracturing, the gas phase may expand and lead to a velocity increase during vertical flow through the conduit zone. Thus, the vent formation mechanism bears resemblance to shallow breccia-forming processes in hydrothermal and volcanic systems (e.g. Grapes *et al*. 1973; Navikov & Slobodskoy 1979; Lorenz 1985).

In systems dominated by fragmentation of magma (e.g. kimberlite pipes and diatremes), the resulting conduit zone will comprise mixtures of sediments and igneous material, and associated surface deposits dominated by pyroclastic material (e.g. Navikov & Slobodskoy 1979; Lorenz 1985; Clement & Reid 1989; Webb *et al*. 2004). Kimberlite pipes are generally formed from fragmentation of deep dyke complexes (e.g. Lorenz 1985; Clement & Reid 1989), and this mechanism may also explain the formation of the phreatomagmatic complexes in the Karoo Basin (e.g. Surtees 1999; McClintock *et al*. 2002). The data from Witkop II and Witkop III support the theory that hydrothermal vent complexes represent cylindrical conduit zones formed by overpressured gas and fluids originating in contact aureoles within sedimentary rocks.

Eruption and deformation

At both Witkop II and Witkop III, sediment breccia cut or intrude the Elliot and tilted Clarens formations. Fragments up to 50 cm in diameter within breccia imply high transport velocities during phreatic activity, supported by the presence of craters at the palaeo-surface at some hydrothermal vent complexes. The basalt-dominated Welgesien vent complex, located near the Brosterlea volcanic complex west of Dordrecht, has a crater filled with lacustrine deposits directly overlying volcaniclastic rocks (Marsh & Skilling 1998).

A model involving one (Witkop III) or two (Witkop II) main eruptive phases is favoured based on, for example, the ring structures seen on the aerial photographs of Witkop II and the logs from Witkop III. Mixtures of brecciated and fragmented sediments from well-consolidated and cemented strata were transported to the surface during eruptions, and mixed with loosely consolidated sandstone or sand from higher in the stratigraphy. Rounded blocks and chaotic structure of parts of the inner zone of Witkop III can be explained by partial reworking or aggradation in the conduit zone.

Dipping of sedimentary strata towards vent complexes is known from mud volcanoes and about 40% of the hydrothermal vent complexes of offshore Mid-Norway (Planke *et al*. 2005), and has been reproduced in analogue experiments (Woolsey *et al*. 1975). Furthermore, phreatomagmatic eruptions are commonly associated with collapse and inward tilting of strata (e.g. Lorenz 1985). At both Witkop II and III, tilted sequences of breccias overlie massive tilted blocks of Clarens sandstone. Tilting of both breccia and Clarens sequences shows that collapse occurred after deposition of the vented material. The tilting of the outer zone of the Witkop III complex can be explained by mass transport from either the base of the Clarens or the underlying formations. The zeolite-cemented outer zone at Witkop III could have acted as a rigid layer through which unconsolidated sand could be fluidized. This explains the sandstone dyke in the hinge-point of the outer zone of Witkop III.

Formation of sediment pipes and dykes

Sediment pipes and dykes may form from a variety of pressure build-up mechanisms, ranging from boiling (Jamtveit *et al*. 2004), overpressured clastic beds with brines or petroleum (e.g. Lowe 1975; Hannum 1980; Mount 1993; Shoulders & Cartwright 2004), flow of ground water (Guhman & Pederson 1992), and impact cratering (Kenkmann 2003). Sediment dykes and pipes at Witkop III emphasize the dynamic nature of the hydrothermal vent complex. The large sediment pipes at Witkop III postdate the breccia formation, as documented by cutting relations. Both brecciation and fluidization (transport of granular material in a fluid) were probably involved during this stage of pipe formation. How high was the transport velocity in the sediment pipes? Minimum fluidization velocities in pipes are commonly of the order of several hundred metres per second during phreatic explosive events (e.g. Navikov & Slobodskoy 1979; Zimanowski *et al*. 1991; Kurszlaukis *et al*. 1998; Boorman *et al*. 2003). However, minimum transport velocities required to form sand pipes may be as low as 1 cm s^{-1} (see Lowe 1975). Rapid formation of the large pipes, and hence a relatively high velocity, is supported by wall deformation structures (lineation, fracturing, grain-size reduction; see Fig. 7), indicating high internal pressure. As a consequence, the pipes acted as conduits for sediments and fluids that were rapidly transported to the surface. This model implies that the sediment pipes represent conduit zones of sediment volcanoes.

Hydrothermal activity

Local occurrence of zeolites within the inner and outer zones of the Witkop III hydrothermal vent complex represents an anomaly compared with the normal Stormberg Group mineralogy, and suggests a hydrothermal influence. Zeolites have previously been found only in Clarens sandstone a few metres below the Drakensberg Group basalt (Potgieter *et al*. 1982). Considering the geological setting of Witkop III, the zeolite documents a precipitation event related to the formation of the hydrothermal vent complex. The zeolite in Witkop III is laumontite (Table 1 and verified by XRD), which can form in a range of environments, during both diagenesis and hydrothermal alteration. However, precipitation requires alkaline (with high Ca/Na activity ratio) and silica-rich fluids (e.g. Chipera & Apps 2001; Iijima 2001). In the Witkop III system, the source of alkalis for precipitating zeolite could either be albitization of plagioclase or alteration of volcanic material (see Boles & Coombs 1977; Iijima 2001). The general absence of volcaniclastic horizons or igneous clasts in the Witkop III complex makes the possibility that the zeolites in Unit II were formed by *in situ* alteration unlikely. The absence of typical hydrothermal mineralization (i.e. silica varieties, sulphides, epidote, amphibole) suggests that the hydrothermal event was short lived, and that the near-surface parts experienced relatively low temperatures.

Timing

The present-day exposures of the Witkop III vent complex terminates about 65 m below the base of the Drakensberg Group. This shows that the phreatic activity predated the lava flows in this area. Additional evidence supports phreatic activity prior to flood basalt eruptions: (1) the vent complexes rarely cut the extrusive basalts, although some phreatomagmatic complexes postdate the earliest flood basalts (Stockley 1947; I. Skilling, pers. comm.); (2) as at Witkop III, blocks of extrusive basalt are not found within other sediment-dominated vent complexes (Du Toit 1912; Gevers 1928; Seme 1997); (3) pyroclastic horizons are located within the upper parts of the Clarens Formation sandstone (e.g. Botha & Theron 1966; Lock *et al*. 1974; Dingle *et al*. 1983; McClintock *et al*. 2002). A supportive conclusion is that phreatomagmatic eruptions also predated the main phase of the time-equivalent Jurassic Ferrar extrusive volcanism in Antarctica (Hanson & Elliot 1996; White & McClintock 2001). We conclude that the phreatic volcanism in the Karoo Basin was synchronous with sill emplacement, slightly predating the main phase of extrusive activity.

Formation model

Based upon observations and interpretations from Witkop II and Witkop III, we propose a qualitative model for the formation and evolution of sediment-dominated hydrothermal vent complexes (Fig. 11). The processes leading to the formation of hydrothermal vent complexes are initiated during sill emplacement (Fig. 11a). Boiling of pore fluids and metamorphic reactions in contact aureoles may increase the fluid pressure and initiate hydrofracturing. Hydrofracturing in aureoles causes vertical fluid migration and results in extended brecciation of sedimentary rocks. A conduit zone to the surface is ultimately produced (Fig. 11b), and some of the eruptive driving force may be the result of fluid expansion during decompression in the conduit zone. The conduit zone is cylindrical, becoming cone-shaped closer to the surface because of increasing velocities and erosion of wall rock. The igneous component in the conduit zone is negligible, indicating insignificant hydraulic brecciation of the sill. Circulation of hydrothermal solutions causes zeolite precipitation at various depths in the system, in both the inner and outer zones of

Table 1. *Microprobe analysis of laumontite from Witkop III*

Sample:	K01HS-44	K02HS-28	K03HS-20
Type:	Clarens sandstone	Sediment pipe	Sediment breccia
Latitude (S):	31°11′57.7″	31°12′11.5″	31°12′08.5″
Longitude (E):	27°13′52.9″	27°13′44.9″	27°13′42.1″
Na_2O	0.28	0.08	0.15
Al_2O_3	20.23	19.86	19.98
SiO_2	51.98	52.98	53.12
K_2O	0.82	1.54	1.60
CaO	11.09	10.41	10.36
Total	84.40	84.87	85.21
Structural formula, based on 48 oxygen			
Na	0.17	0.05	0.09
Al	7.52	7.35	7.37
Si	16.40	16.64	16.63
K	0.16	0.31	0.32
Ca	3.75	3.50	3.47
Total	28.01	27.86	27.89
Ca + Na + K	4.08	3.86	3.89
Al + Si	23.92	24.00	24.00

the complex. Formation of the conduit zone leads to wall-rock collapse and tilting of surrounding sedimentary strata (Fig. 11c). The collapse initiates fluidization of sediments through pipes and dykes. Material removed from the wall rock or the conduit may be fluidized through pipes and erupted at the surface through small sediment volcanoes (Fig. 11d). Erupted material from the sediment pipes mixes with surface sediments. The surface topography can be a depression or a crater that fills at rates depending upon the local sedimentation regime.

Conclusions

The structure and sediment petrography of two hydrothermal vent complexes in the Karoo Basin give insight into the dynamics of phreatic activity in volcanic basins. The complexes represent sediment-dominated piercement structures in the basin. The following conclusions may be reached.

(1) The formation of the hydrothermal vent complexes was synchronous with sill emplacement, slightly predating the major phase of Karoo flood volcanism.

(2) Phreatic explosive activity formed sediment breccias within the conduit zone, with rock fragments from different stratigraphic levels.

(3) Ejected material (sediment breccia and sand) fills the vent.

(4) Hydrothermal fluids affect sediments in shallow and intermediate parts of the complex and precipitate zeolite.

(5) Fluidization of sand and breccia occurs in pipes during further cooling of the underlying sill complex, and documents a late phase of pressure build-up. The pipes terminated at the surface, resulting in sediment volcanism.

This study was supported by grant 146832/431 from the Norwegian Research Council. Continuous support by VBPR, TGS-NOPEC, and the industrial participants in the 'Petroleum Implications of Sill Intrusions' project is gratefully acknowledged. We thank G. Marsh for discussions and valuable support during our trips to South Africa, the Department of Water Affairs and the Council for Geoscience (South Africa) for borehole drilling and logistics, S. and N. Polteau, S. A. L. Sali, C. Haave and D. Liss, for the company and assistance during fieldwork, and D. Cole for sharing his knowledge on the Karoo Basin. We would also like to thank I. Skilling for a constructive review, and M. Erambert for electron microprobe analytical support.

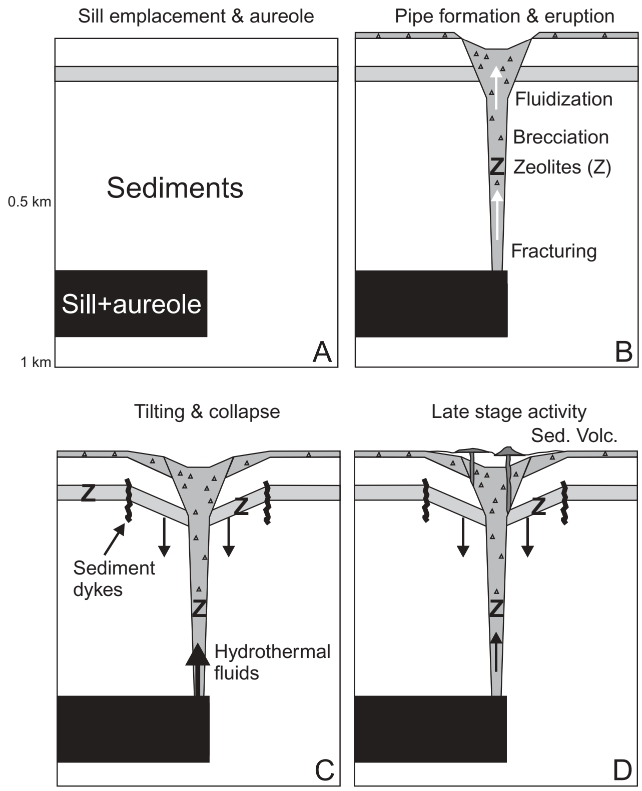

Fig. 11. A schematic model for the formation and evolution of sediment-dominated hydrothermal vent complexes. The model represents a synthesis of field observations and data from the Karoo Basin. (See text for explanation.) (**a**) Emplacement of melt and aureole formation. (**b**) Hydrofracturing in the source region and conduit formation. (**c**) Wall-rock collapse and tilting. (**d**) The late-stage activity.

References

Bell, B. & Butcher, H. 2002. On the emplacement of sill complexes: evidence from the Faroe–Shetland Basin. *In:* Jolley, D.W. & Bell, B.R. (eds) *The North Atlantic Igneous Province: Stratigraphy, Tectonic, Volcanic and Magmatic Processes*. Geological Society, London, Special Publications, **197**, 307–329.

Berndt, C., Skogly, O.P., Planke, S. & Eldholm, O. 2000. High-velocity breakup-related sills in the Vøring Basin, off Norway. *Journal of Geophysical Research*, **105**, 28443–28454.

Boles, J.R. & Coombs, D.S. 1977. Zeolite facies alteration of sandstones in the Southland Syncline, New Zealand. *American Journal of Science*, **277**, 982–1012.

Boorman, S.J., McGuire, J.B., Boudreau, A.E. & Kruger, F.J. 2003. Fluid overpressure in layered intrusions: formation of a breccia pipe in the Eastern Bushveld Complex, Republic of South Africa. *Mineralium Deposita*, **38**, 356–369.

Botha, B.V.J. & Theron, J.C. 1966. New evidence for the early commencement of Stormberg volcanism. *Tydskrif vir Natuurwetenskappe*, **7**, 469–473.

Brekke, H. 2000. The tectonic evolution of the Norwegian Sea Continental Margin with emphasis on the Vøring and Møre Basins. *In:* Nøttvedt, A., Brekke, H. & Birkeland, Ø. (eds) *Dynamics of the Norwegian Margin*. Geological Society, London, Special Publications, **167**, 327–378.

Catuneanu, O., Hancox, P.J. & Rubidge, B.S. 1998. Reciprocal flexural behaviour and contrasting stratigraphies: a new basin development model for the Karoo retroarc foreland system, South Africa. *Basin Research*, **10**, 417–439.

Chevallier, L. & Woodford, A.C. 1999. Morpho-tectonics and mechanism of emplacement of the dolerite rings and sills of the western Karoo, South Africa. *South African Journal of Geology*, **102**, 43–54.

Chipera, S.J. & Apps, J.A. 2001. Geochemical stability of natural zeolites. *Reviews in Mineralogy and Geochemistry*, **45**, 117–161.

Clement, C.R. & Reid, A.M. 1989. The origin of kimberlite pipes: an interpretation based on a synthesis of geological features displayed by southern African occurrences. *In:* Ross, J. et al. (eds) *Kimberlites and Related Rocks*. Geological Society of Australia, Special Publications, **14**, 632–646.

Coetzee, C.B. 1966. An ancient volcanic vent on Boschplaat 369 in the Bloemfontein district, Orange Free State. *Transactions of the Geological Society of South Africa*, **69**, 127–137.

Courtillot, V.E. & Renne, P.R. 2003. On the ages of flood basalt events. *Comptes Rendus de l'Académie des Sciences, Geoscience*, **335**, 113–140.

Dingle, R.V., Siesser, W.G. & Newton, A.R. 1983. *Mesozoic and Tertiary Geology of Southern Africa*. Balkema, Rotterdam.

Du Toit, A.L. 1904. *Geological Survey of Elliot and Xalanga, Tembuland*. Annual Report of the Geological Commission Cape of Good Hope for 1903, **8**, 169–205.

Du Toit, A.L. 1912. *Geological Survey of Part of the Stormbergen*. Annual Report of the Geological Commission Cape of Good Hope for 1911, **16**, 112–136.

Du Toit, A.L. 1920. The Karoo dolerites of South Africa: a study in hypabyssal injection. *Transactions of the Geological Society of South Africa*, **23**, 1–42.

Du Toit, A.L. 1954. *The Geology of South Africa*. Oliver & Boyd, Edinburgh.

Duncan, R.A., Hooper, P.R., Rehacek, J., Marsh, J.S. & Duncan, R.A. 1997. The timing and duration of the Karoo igneous event, Southern Gondwana. *Journal of Geophysical Research*, **102**, 18127–18138.

Eriksson, P.G. 1981. A palaeoenvironmental analysis of the Clarens Formation in the Natal Drakensberg. *Transactions of the Geological Society of South Africa*, **84**, 7–17.

Gevers, T.W. 1928. The volcanic vents of the Western Stormberg. *Transactions of the Geological Society of South Africa*, **31**, 43–62.

Grapes, R.H., Reid, D.L. & McPherson, J.G. 1973. Shallow dolerite intrusions and phreatic eruption in the Allan Hills region, Antarctica. *New Zealand Journal of Geology and Geophysics*, **17**, 563–577.

Guhman, A.I. & Pederson, D.T. 1992. Boiling sand springs, Dismal River, Nebraska: agents for formation of vertical cylindrical structures and geomorphic change. *Geology*, **20**, 8–10.

Hannum, C. 1980. Sandstone and conglomerate–breccia pipes and dikes of the Kodachrome Basin area, Kane County, Utah. *Geology Studies, Brigham Young University*, **27**, 31–50.

Hanson, R.E. & Elliot, D.H. 1996. Rift-related Jurassic basaltic phreatomagmatic volcanism in the central Transantarctic Mountains: precursory stage to flood-basalt effusion. *Bulletin of Volcanology*, **58**, 327–347.

Iijima, A. 2001. Zeolites in petroleum and natural gas reservoirs. *Reviews in Mineralogy and Geochemistry*, **45**, 347–402.

Jamtveit, B., Svensen, H., Podladchikov, Y.Y. & Planke, S. 2004. Hydrothermal vent complexes associated with sill intrusions in sedimentary basins. *In:* Breitkreuz, C. & Petford, N. (eds) *Physical Geology of High-Level Magmatic Systems*. Geological Society of London, Special Publications, **234**, 233–241.

Johnson, M.R., Van Vuuren, C.J. & Visser, J.N.J. et al. 1997. The foreland Karoo Basin, South Africa. *In:* Selley, R.C. (ed.) *African Basins. Sedimentary Basins of the World*. Elsevier, Amsterdam, **3**, 269–317.

Kenkmann, T. 2003. Dike formation, cataclastic flow, and rock fluidization during impact cratering: an example from the Upheaval Dome structure, Utah. *Earth and Planetary Science Letters*, **214**, 43–58.

Keyser, N. 1997. *Geological Map of the Republic of South Africa and the Kingdoms of Lesotho and Swaziland, 1:1 000 000*. Council for Geoscience, South Africa.

Kurszlaukis, S., Buttner, R., Zimanowski, B. & Lorenz, V. 1998. On the first experimental phreatomagmatic explosion of a kimberlite melt. *Journal of Volcanology and Geothermal Research*, **80**, 323–326.

Leith, M.J. & Trümpelmann, F. 1967. *Well completion report for Southern Oil Exploration Corporation (Pty) Limited of WE1/66*. Soekor report.

Lock, B.E., Paverd, A.L. & Broderick, T.J. 1974. Stratigraphy of the Karoo volcanic rocks of the Barkly East district. *Transactions of the Geological Society of South Africa*, **77**, 117–129.

Lorenz, V. 1985. Maars and diatremes of phreatomagmatic origin: a review. *Transactions of the Geological Society of South Africa*, **88**, 459–470.

Lowe, D.R. 1975. Water escape structures in coarse-grained sediments. *Sedimentology*, **22**, 157–204.

Malthe-Sørenssen, A., Planke, S., Svensen, H. & Jamtveit, B. 2004. Formation of saucer-shaped sills. *In:* Breitkreuz, C. & Petford, N. (eds) *Physical Geology of High-Level Magmatic Systems*. Geological Society of London, Special Publications, **234**, 215–227.

Marsh, J.S. & Skilling, I.P. 1998. *Karoo Volcanic and Entrusive Rocks, Eastern Cape*. Field Excursion Guide A3, IAVCEI, International Volcanological Congress 'Magmatic Diversity: Volcanoes and their Roots', Cape Town, July 1998.

McClintock, M.K., Houghton, B.F., Skilling, I.P. & White, J.D.L. 2002. The volcaniclastic opening phase of Karoo flood basalt volcanism, Drakensberg Formation, South Africa. *EOS Transactions of the American Geophysical Union*, **83**, 47.

Mount, J.F. 1993. Formation of fluidization pipes during liquefaction: examples from the Uratanna Formation (Lower Cambrian), South Australia. *Sedimentology*, **40**, 1027–1037.

Navikov, L.A. & Slobodskoy, R.M. 1979. Mechanism of formation of diatremes. *International Geology Review*, **21**, 1131–1139.

Planke, S., Rassmussen, T., Rey, S.S. & Myklebust, R. 2005. Seismic characteristics and distribution of volcanic intrusions and hydrothermal vent complexes in the Vøring and Møre basins. *In:* Dore, A. & Vining, B. (eds) *Petroleum Geology: North-West Europe and Global Perspectives. Proceedings of the 6th Geology Conference*. Geological Society, London, 833–844.

Potgieter, C.D., Snyman, C.P. & Förtsch, E.B. 1982. Epigenetic laumontite in the Jurassic Clarens and Drakensberg formations of the Karoo sequence. *Transactions of the Geological Society of South Africa*, **85**, 203–210.

Rowsell, D.M. & De Swardt, A.M.J. 1976. Diagenesis in Cape and Karoo sediments, South Africa and its bearing on their hydrocarbon potential. *Transactions of the Geological Society of South Africa*, **79**, 81–145.

Seme, U.T. 1997. *Diatreme deposits near Rossouw, north Eastern Cape: sedimentology–volcanology and mode of origin*. BSc(Hons) project, Rhodes University, Grahamstown, South Africa.

Shoulders, S.J. & Cartwright, J. 2004. Constraining the depth and timing of large-scale conical sandstone intrusions. *Geology*, **32**, 661–664.

Skogseid, J., Pedersen, T., Eldholm, O. & Larsen, B.T. 1992. Tectonism and magmatism during NE Atlantic continental break-up: the Vøring Margin. *In:* Storey, B.C., Alabaster, T. & Pankhurst, R.J. (eds) *Magmatism and the Causes of Continental Break-up*. Geological Society, London, Special Publications, **68**, 305–320.

Smallwood, J.R. & Maresh, J. 2002. The properties, morphology and distribution of igneous sills: modelling, borehole data and 3D seismic from the Faroe–Shetland area. *In:* Jolley, D.W. & Bell, B.R. (eds) *The North Atlantic Igneous Province: Stratigraphy, Tectonic, Volcanic and Magmatic Processes*. Geological Society, London, Special Publications, **197**, 271–306.

Smith, R.M. 1990. A review of stratigraphy and sedimentary environments of the Karoo Basin of South Africa. *Journal of African Earth Sciences*, **16**, 143–169.

Stockley, G.M. 1947. *Report on the Geology of Basutoland*. Published by the authority of the Basutoland Government, Maseru.

Surtees, G.B. 1999. *The evolution of the Brosterlea Volcanic Complex, Eastern Cape, South Africa*. MSc thesis, Rhodes University, Grahamstown, South Africa.

Svensen, H., Planke, S., Jamtveit, B. & Pedersen, T. 2003. Seep carbonate formation controlled by hydrothermal vent complexes: a case study from the Vøring Basin, the Norwegian Sea. *Geo-Marine Letters*, **23**, 351–358.

Svensen, H., Planke, S., Malthe-Sørenssen, A., Jamtveit, B., Myklebust, R., Eidem, T. & Rey, S.S. 2004. Release of methane from a volcanic basin as a mechanism for initial Eocene global warming. *Nature*, **429**, 542–545.

Taylor, N.C. 1970. *The volcanic vents of the Stormberg series*. BSc(Hons) project, Rhodes University, Grahamstown, South Africa.

Trude, J., Cartwright, J., Davies, R.J. & Smallwood, J. 2003. New technique for dating igneous sills. *Geology*, **31**, 813–816.

Turner, B.R. 1972. Silica diagenesis in the Molteno sandstone. *Transactions of the Geological Society of South Africa*, **75**, 55–66.

Veevers, J.J., Cole, D.I. & Cowan, E.J. 1994. *Southern Africa: Karoo Basin and Cape Fold Belt*. Geological Society of America, Memoirs, **184**, 223–279.

Walker, F. & Poldervaart, A. 1949. Karoo dolerites of the Union of South Africa. *Geological Society of America Bulletin*, **60**, 591–706.

Webb, K.J., Scott Smith, B.H., Paul, J.L. & Hetman, C.M. 2004. Geology of the Victor Kimberlite, Attawapiskat, Northern Ontario, Canada: cross-cutting and nested craters. *Lithos*, **76**, 29–50.

White, J.D.L. & McClintock, M.K. 2001. Immense vent complex marks flood-basalt eruption in a wet, failed rift: Coombs Hills, Antarctica. *Geology*, **29**, 935–938.

Wignall, P.B. 2001. Large igneous provinces and mass extinctions. *Earth-Science Reviews*, **53**, 1–33.

Woodford, A.C., Botha, J.F. & Chevallier, L. et al. 2001. *Hydrogeology of the main Karoo Basin: Current Knowledge and Research Needs*. Water Research Commission Pretoria, Report, **860**.

Woolsey, T.S., McCallum, M.E. & Schumm, S.A. 1975. Modeling of diatreme emplacement by fluidization. *Physics and Chemistry of the Earth*, **9**, 29–42.

Zimanowski, B., Fröhlich, G. & Lorenz, V. 1991. Quantitative experiments on phreatomagmatic explosions. *Journal of Volcanology and Geothermal Research*, **48**, 341–358.

Zolotukhin, V.V. & Al'mukhamedov, A.I. 1988. Traps of the Siberian Platform. *In:* Macdougall, J.D. (ed.) *Continental Flood Basalts*. Kluwer, Dordrecht, 273–310.

Received 8 March 2005; revised typescript accepted 18 November 2005.
Scientific editing by Sally Gibson