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The role of strain localization in the segregation and ascent of anatectic melts, Namaqualand, South Africa

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Abstract—Granulite-facies gneisses of the late-Proterozoic Okiep Copper District of the Namaqua Province in South Africa preserve evidence of a range of anatectic melt features that reflect the initial stages of segregation and ascent of crustally derived magmas during high-grade metamorphism. These melt bodies include both *in situ* and sharply transgressive, subvertical, pipe-like bodies, that show vertical dimensions of several hundreds of metres and horizontal dimensions of tens to hundreds of metres. Migmatite bodies are spatially closely linked with narrow, upright zones characterized by intense high-strain fabrics, locally referred to as 'steep structures'. They display a progressive textural development, from diktyonitic textures in *in situ* bodies, via schollen-and-raft textures to largely homogeneous intrusive granites that have migrated vertically for distances of several hundreds of metres or more. The intimate association of the migmatite bodies with the steep structures reflects strain-induced melt segregation, facilitated by increased permeabilities in these ductile deformation zones, and migration of melts into sites of strain incompatibility at the intersections between the regional subhorizontal gneissosity and the superimposed high-strain zones. Subsequent melt migration was focused along the network of subvertical structural anisotropies provided by the steep structures. Melt migration was controlled by a combination of buoyancy, shear-enhanced melt compaction during ongoing deformation, melt compaction due to the settling of wall-rock fragments from higher stratigraphic levels and subordinate brittle fracturing. The unusual geometry of the steep structures and the intensely heterogeneous nature of the strain, and the absence of similar strain features and voluminous melt bodies elsewhere in the granulite-facies terrane, suggest a positive feed-back mechanism between melt generation and strain localization in steep structures. The structural development of the migmatite bodies illustrates that the efficiency of melt segregation and migration in a mid-crustal segment is dependent not only on the fertility of its lithologies, but also on its deformational style. © 1998 Elsevier Science Ltd.

INTRODUCTION

One of the ongoing points of discussion about crustal anatexis during high-grade metamorphism concerns the mechanism(s) by which melts accumulate in their source regions and their migration to higher structural levels. The classical view of accumulation of melt to volumes exceeding the 'rheologically critical melt percentage', followed by buoyancy-induced diapiric ascent (e.g. Van der Molen and Paterson, 1979; Cruden, 1988; England, 1990; Weinberg, 1993), has been questioned in recent years (e.g. McLellan, 1988; Clemens and Mawer, 1992; Emerman and Marrett, 1990; Paterson and Fowler, 1993; Petford *et al.*, 1993; Sawyer, 1991, 1994; Petford, 1995). Most studies on magma transport have, in recent years, emphasized the role of deformation and strain localization for both melt generation and melt migration based on the close spatial and temporal relationship between deformation zones and granitic melts (e.g. Hollister and Crawford, 1986; Wickham, 1987; Allibone and Norris, 1992; McCaffrey, 1992; Brown, 1994 and references therein; Brown *et al.*, 1995; Rushmer, 1995). Numerous field and experimental studies have shown that the deformation of partially molten rocks provides pressure gradients and dilatant sites along which melts can migrate at considerably lower melt volumes than that of the experimentally determined critical melt fraction and current models favour tapping of anatectic crustal levels by brittle–ductile shear zones that provide conduits for subsequent melt ascent (e.g. Dell'Angelo and Tullis, 1988; Hutton, 1988; D'Lemos *et al.*, 1992; Hand and Dirks, 1992; Sawyer, 1994; Rutter and Neumann, 1995;

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Williams *et al.*, 1995). Although significant advances have been made in understanding the relationships between strain and small-scale melt segregation, the exact nature of the relationship between large-scale shear zones and melting is less well understood, and the pathways of the melts remain largely obscured.

In this paper, we report on a group of unusual anatectic melt features from parts of the granulite-facies portion of the Mesoproterozoic Namaqua Province of South Africa. These former melt bodies, locally referred to as 'megabreccias', range from *in situ* migmatites to sharply transgressive, intrusive pipe-like bodies up to several hundred metres in extent. We conclude that these bodies represent an unusual glimpse of the critical transition from *in situ* melting and local melt migration to the early stages of large-scale melt ascent. The role of deformation in assisting melt segregation and ascent is illustrated, and a positive feedback mechanism between melting and strain is proposed.

REGIONAL GEOLOGY

The Namaqualand Metamorphic Complex forms the western part of the Mesoproterozoic Namaqua–Natal mobile belt, which extends from southern Namibia and Namaqualand along the west coast of southern Africa to the Kwazulu–Natal Province along the eastern seaboard (Fig. 1a). Exposed within the western parts of the Complex is an extensive low-pressure amphibolite- to granulite-facies terrain (Fig. 1b) comprising supracrustals and a variety of pre-Namaqua granitic gneisses. Waters (1988, 1990) documented an anticlockwise P–T path for the granulite-facies rocks and established peak metamorphic conditions of 850–900°C and 0.5–0.6 GPa. Peak metamorphic conditions are thus well above those required for the melting of quartzofeldspathic gneisses (e.g. Rutter and Wyllie, 1988; Stevens *et al.*, 1995). Waters (1988) demonstrated that the formation of partial melts in the region was due primarily to fluid-absent biotite melting via the reaction bt + qtz + pl = opx + kfs + melt. These melts occur as small-scale (cm^3–dm^3) leucosome sheets and stringers that are generally concordant with the regional gneissosity (Waters and Whales, 1984; Waters, 1988). The anticlockwise P–T path followed by the rocks has been attributed to the underplating of hot, basaltic crust and the introduction of felsic magmas above the present level of erosion (Waters, 1988, 1990).

The Okiep Copper District is located in the northern part of the granulite-facies zone (Fig. 1b, c). It is characterized by a sequence of voluminous, subhorizontal sheets of gneisses and granites and minor intercalated metavolcanic and metasedimentary rocks. In detail, the lithostratigraphic column of the Okiep Copper District (SACS, 1980) comprises the following:

(1) a metavolcanosedimentary succession (the Okiep Group), which contains the Springbok Quartzite (a prominent stratigraphic marker) together with subordinate metapelites of the Wolfram Schist;

(2) an older suite of metamorphosed, gneissic granites of the Gladkop Suite;

(3) a suite of voluminous, pre- to syn-tectonic Namaqua-age (*c.* 1190–1250 My) granite gneisses (the Little Namaqualand Suite) which comprises the widespread Nababeep and Modderfontein Gneisses; and

(4) late-to post-tectonic granites (1060–1130 My) of the Spektakel Suite, which consists of the Concordia and Rietberg Granites (Clifford *et al.*, 1975, 1995; Robb *et al.*, in press).

The granite-gneiss sequence is invaded by a swarm of easterly trending basic-to-intermediate dyke-, sill- and plug-shaped bodies, the Koperberg Suite (1030–1060 My, Robb *et al.*, in press), which are the hosts of the copper mineralization in the Okiep Copper District. The crystalline basement is unconformably overlain in the west by mainly clastic and weakly deformed sediments of the Late Proterozoic to Early Phanerozoic Nama Group (Fig. 1c).

Based on geothermometry and geobarometry on orthopyroxene–sapphirine–cordierite–phlogopite–garnet–sillimanite parageneses in metapelites of the Okiep Group, Clifford *et al.* (1975, 1981) suggested peak P–T conditions for the Okiep Copper District during the main M_2 metamorphic event to be in the order of 0.6 GPa and 850–900°C. Raith and Prochaska (1995) determined similar peak metamorphic conditions of 750–850°C and 0.5–0.7 GPa.

Three main deformation events can be identified in the Okiep Copper District (Clifford *et al.*, 1975; McIver *et al.*, 1983; Joubert, 1986). An early deformation (D_1) is only manifested by intrafolial folds within the older units of the Okiep Group and the Gladkop Suite. The principal deformation phase, the D_2 or Namaqua event, which is associated with regional-scale thrusting and recumbent folding (Hartnady *et al.*, 1985; Joubert, 1986), has produced a regionally pervasive, subhorizontal gneissosity (S_2) in syntectonic granites of the Little Namaqualand Suite. The S_2 gneissosity is expressed as an augen texture in which a fine-grained quartz–feldspar matrix and biotite flakes anastomose around composite quartz–feldspar augen. During the subsequent D_3 event, the subhorizontal, sheet-like granite-gneisses and the D_2 fabric were deformed into km-scale, open, upright, ENE-trending, often doubly plunging folds (Fig. 1c). On a smaller scale, the NNW–SSE-directed shortening during D_3 produced narrow, linear, easterly-trending upright structures that are axial planar to the large-scale D_3 folds (see below) (Kisters *et al.*, 1996a,b). These 'steep structures' typically display strike lengths and vertical extents on the order of several hundreds of metres. As they are intimately associated with the melt bodies that form the central topic addressed in this paper, they are discussed in more detail below. Later local deformation

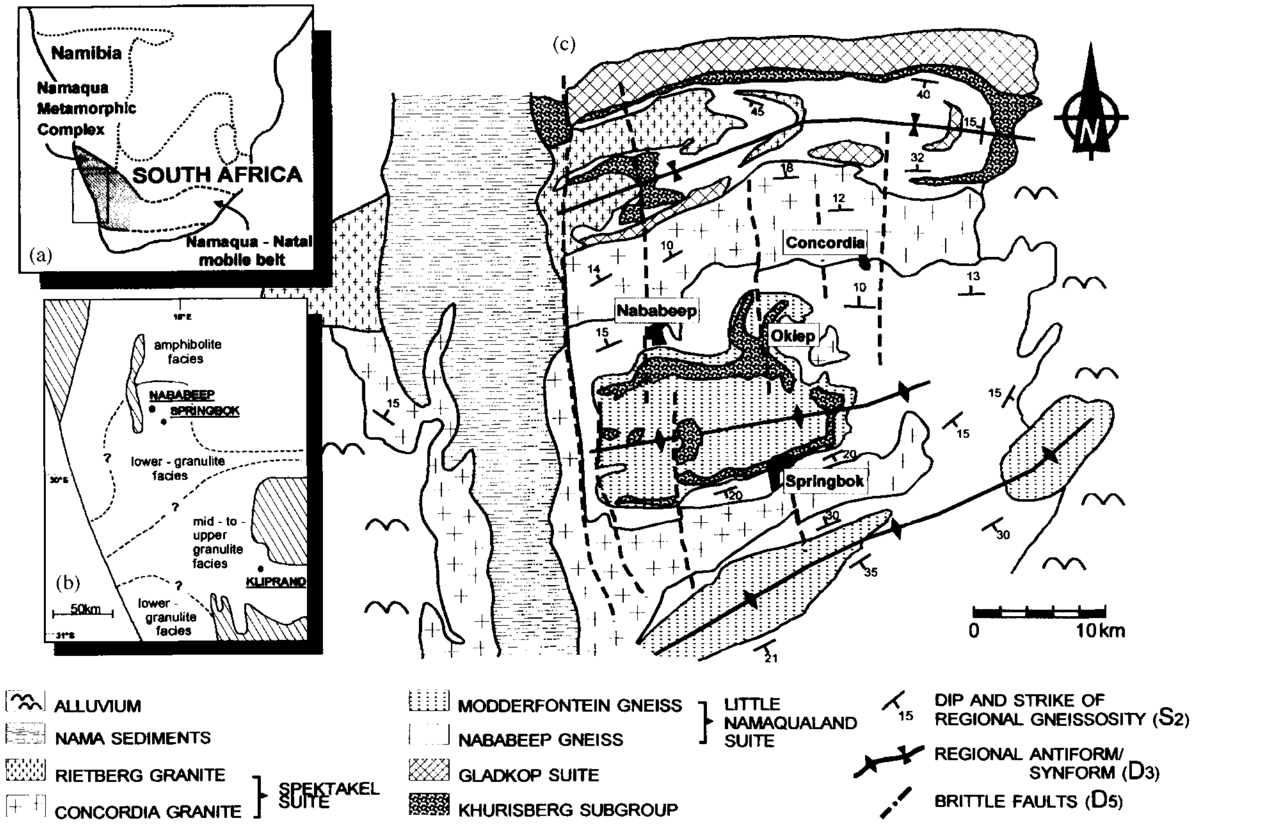

Fig. 1. (a) Sketch map of the location of the Namaqua Metamorphic Complex in southern Africa; (b) metamorphic map of western Namaqualand showing isograds and metamorphic zones in western Namaqualand (hatched areas represent younger cover sediments; modified after Waters, 1988); (c) simplified geological map of the Okiep Copper District (modified after Lombaard *et al.*, 1986).

of the high-grade metamorphic granite gneisses is evidenced by the development of conjugate sets of northwesterly and northeasterly trending dextral and sinistral mylonitic shear zones (D_4) and northerly trending, predominantly normal brittle faults (D_5), which displace and intensely brecciate both the granite gneisses and the overlying Nama sediments (Fig. 1c).

Waters (1989) placed the peak metamorphic conditions after the pervasive D_2 deformation, based on mineral textural relations. Gibson *et al.* (1996) have suggested a syn-D_3 timing for the metamorphic peak.

STEEP STRUCTURES

The occurrence of large-scale anatectic features in the Okiep Copper District is spatially intimately related with steep structures (Fig. 2). Steep structures represent ENE-trending, narrow deformation zones in which the regional subhorizontal S_2 gneissosity has been rotated to subvertical attitudes (Fig. 3). This steepening of the gneissosity is manifested as (a) symmetrical antiformal upwarps of the S_2 gneissosity that yields upward pointing, cusp-like geometries (Fig. 3) or (b) monoclinal warps of the regional gneissosity. Transitions between antiformal and monoclinal structures are common (Kisters *et al.*, 1996b). Steep structures are best developed in the gneissose lower and central parts of the sequence. Their spacing is typically between 200 and 700 m (Kisters, 1993). The width of the subvertical, locally mylonitic core zones varies from < 10 m to > 100 m and their strike length is, on average, 500–700 m, but can be as much as 7 km. The excellent 3-D exposure in the rugged terrain of the Okiep Copper District together with exploration drilling and mining has helped to establish their vertical extents of commonly 300–400 m, but they may exceed 1.5 km (Kisters, 1993; Lombaard *et al.*, 1986).

The formation of steep structures has been described by Kisters *et al.* (1996a) as a progression from initial upright folding, with axial planes parallel to the regional-scale D_3 folds, via the amplification and tightening of fold shapes, to the obliteration of folds by a mylonitic transposition fabric (S_2/S_3). The steep structures initiate as open antiformal upwarps of the regional S_2 gneissosity to produce open, upright, easterly trending folds. The upwarp of S_2 commonly occurs along subhorizontal detachment zones that are represented by shallowly dipping thrust zones or by the gently dipping S_2 gneissosity itself (Kisters, 1993; Kisters *et al.*, 1996a). The dramatic steepening of the shear zones is associated with a tightening and amplification of folds yielding

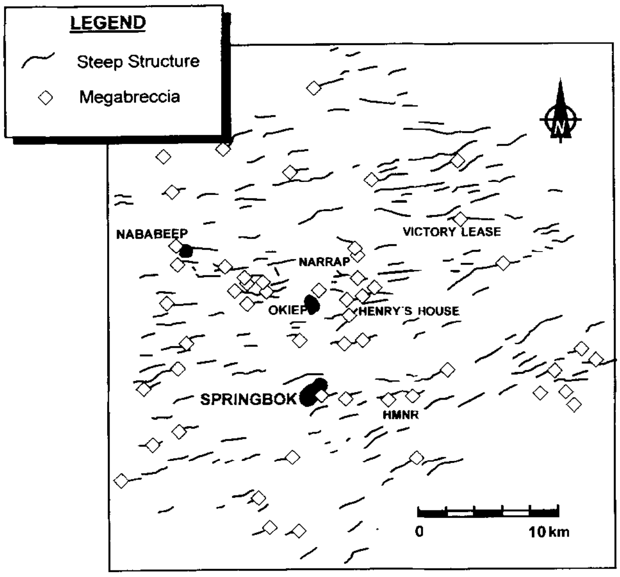

Fig. 2. Compilation of prominent steep structure and megabreccia occurrences in the Okiep Copper District, illustrating their close spatial relationship (compiled after maps of the O'okiep Copper Company). Localities are mentioned in the text. HMNR: Hester Malan Nature Reserve.

upright, tight-to-isoclinal folds with strongly attenuated limbs that are progressively sheared out. In addition, folds are transected by a subvertical, E–W to ENE–WSW-trending foliation (S_3) that is axial planar to the folds and which is defined by a preferred grain-shape orientation of quartz. Towards the cores of steep structures, folds are progressively transposed into the subvertical, high-strain S_2/S_3 fabric, and the coarse-grained augen textures typical of the granite gneisses outside steep structures give way to banded textures. Locally, the S_2/S_3 foliation contains a subvertically plunging mineral stretching lineation defined by stretched quartz–feldspar aggregates. Microscopically, textures are characterized by pervasive grain-size reduction testifying to the mylonitic nature of the fabric. Centimetre-to-decimetre scale sinistral and dextral oblique shear bands deform the mylonitic foliation both in plan view and in cross-section. Locally, they form closely spaced conjugate sets. The shear sense and orientation of shear bands are consistent with a subhorizontal, approximately NNW–SSE-directed shortening normal to the S_2/S_3 gneissosity and an associated component of extension both in the vertical and in an ENE–WSW direction parallel to the subvertical foliation. Boudinage occurs both in the country-rock gneisses and in the noritic rocks of the Koperberg Suite that have intruded steep structure zones (Kisters *et al.*, 1994). Boudins trend ENE–WSW with subvertically inclined necklines indicating a subhorizontal ENE–WSW-directed component of extension parallel to the S_2/S_3 fabric in the cores of steep structures. Based on these fabric relationships, Kisters *et al.* (1996a) concluded that steep structures formed under a subhorizontal, roughly NNE–SSW-directed bulk shortening strain. The strain incompatibility associated with a coaxial flattening perpendicular to the steep structures was mainly accommodated by (a) bounding shear discontinuies at the base of steep structures (i.e. along lower detachment zones) and parallel to steep structures, and (b) material extrusion in the cores of the steep structures (Kisters *et al.*, 1996a).

Fig. 3. Field example of an antiformal steep structure developed in Nababeep Gneiss illustrating the steepening of the regional subhorizontal S_2 gneissosity (annotated) to subvertical attitudes yielding the typical cusp-like geometry of steep structures (Narrap Northwest steep structure, viewed to the west).

SMALL-SCALE ANATECTIC FEATURES IN THE GNEISSES

Small-scale leucosomes, similar to those described by Waters and Whales (1984) and Waters (1988) from the Kliprand area to the immediate south of the Okiep Copper District (Fig. 1b), occur in the subhorizontal granite-gneiss sequence of the Copper District. The leucosomes consist of potassium feldspar, plagioclase and quartz, with minor amounts of biotite, orthopyroxene and garnet. They are commonly fine-grained, but pegmatitic textures are also present. The centimetre- to decimetre-wide leucosomes are mainly contained within the subhorizontal regional gneissosity, but also cross-cut the foliation at low angles. In places, partial melting has resulted in the development of stromatic gneisses or the formation of m-scale, irregular pods of leucosomes that transgress the regional gneissosity. Most leucosomes are undeformed, although a weak, subhorizontal fabric expressed by a grain-shape orientation of quartz, is locally present, indicating a late- to post-D_2 timing of their formation.

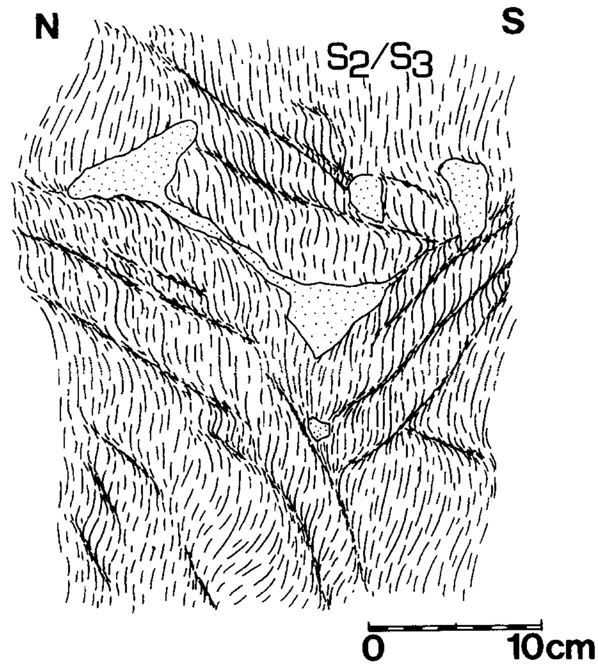

Fig. 4. Field sketch of the development of closely-spaced conjugate shear bands which deform the upright, high-strain S_2/S_3 fabric in the core of steep structures and the formation of small-scale leucosomes (stippled) (cross-section, Bloustasie Hill steep structure).

ANATECTIC FEATURES IN STEEP STRUCTURES

Small-scale leucosomes occur abundantly in the subvertical fabric zones of the steep structures. Here, they are mainly structurally controlled, occurring in shear bands, along the intersections of conjugate shear bands or in boudin necks that are developed in the high-strain S_2/S_3 fabric of steep structures (Fig. 4). The leucosomes form centimetre-scale, irregularly shaped pods and stringers that locally coalesce. Coarse-grained pegmatitic leucosomes that consist of large K-feldspar (up to 5 cm), plagioclase, quartz, orthopyroxene, and biotite crystals are also contained within the subvertical fabric. Macroscopically, leucosomes appear to be undeformed. However, the formation of subgrains along the margins of feldspar crystals and a faint preferred grain-shape orientation of quartz parallel to the S_3 foliation in steep structures indicates that the leucosomes have been deformed after their emplacement.

Evidence of the formation of more voluminous melt bodies in the Okiep District is preserved in steep structures in the form of megabreccias. The term 'megabreccia' was coined by geologists in the Okiep Copper District to describe roughly elliptical outcrops characterized by the juxtaposition of angular- to subangular blocks of highly disoriented country-rock gneisses (Fig. 5). The jumble-like assortment of country-rock fragments is typically 'cemented' by a leucocratic matrix of granitic composition that is referred to as the 'breccia granite' (Lombaard and Schreuder, 1978; Lombaard *et al.*, 1986).

Eighty prominent megabreccia occurrences are documented in the Okiep District (Lombaard and Schreuder, 1978). They are spatially closely associated with steep structures (Fig. 2). In plan, megabreccias are predominantly oval in shape with aspect ratios varying from 1.5:1 to 8:1. The long axes of megabreccias trend easterly, parallel to the subvertical fabric of the enveloping steep structures. The largest known megabreccia measures 1000×400 m in outcrop (Lombaard and Schreuder, 1978), but their typical size is commonly in the order of 100×50 m. The three-dimensional geometry of some megabreccias is well established by exploration drilling and mining of the copper-mineralized intrusions of the Koperberg Suite that have locally intruded megabreccia bodies (e.g. at the Okiep Mine; Lombaard *et al.*, 1986), and megabreccias can be shown to be of a mainly steeply inclined, pipe-like geometry with vertical extents of locally in excess of 1000 m.

Megabreccias are rarely developed over the entire strike length of the steep structures. In fact, numerous structures show no evidence of megabreccia-type features. Megabreccias occur preferentially in two structural sites along the steep structures, including (1) the initiation/termination of steep structures, i.e. where the sharp-crested antiformal upwarps of the steep structures grade into the regional, subhorizontal gneissosity (Fig. 6), or (2) along the transitions between monoclinal and antiformal steep structure geometries (Fig. 7) (Kisters *et al.*, 1992).

The granite that forms the matrix to the wall-rock fragments in the megabreccias is a medium-grained, grey to pink rock with quartz, perthitic K-feldspar, plagioclase, biotite, orthopyroxene and accessory garnet, zircon, and hornblende. Biotite surrounds or completely

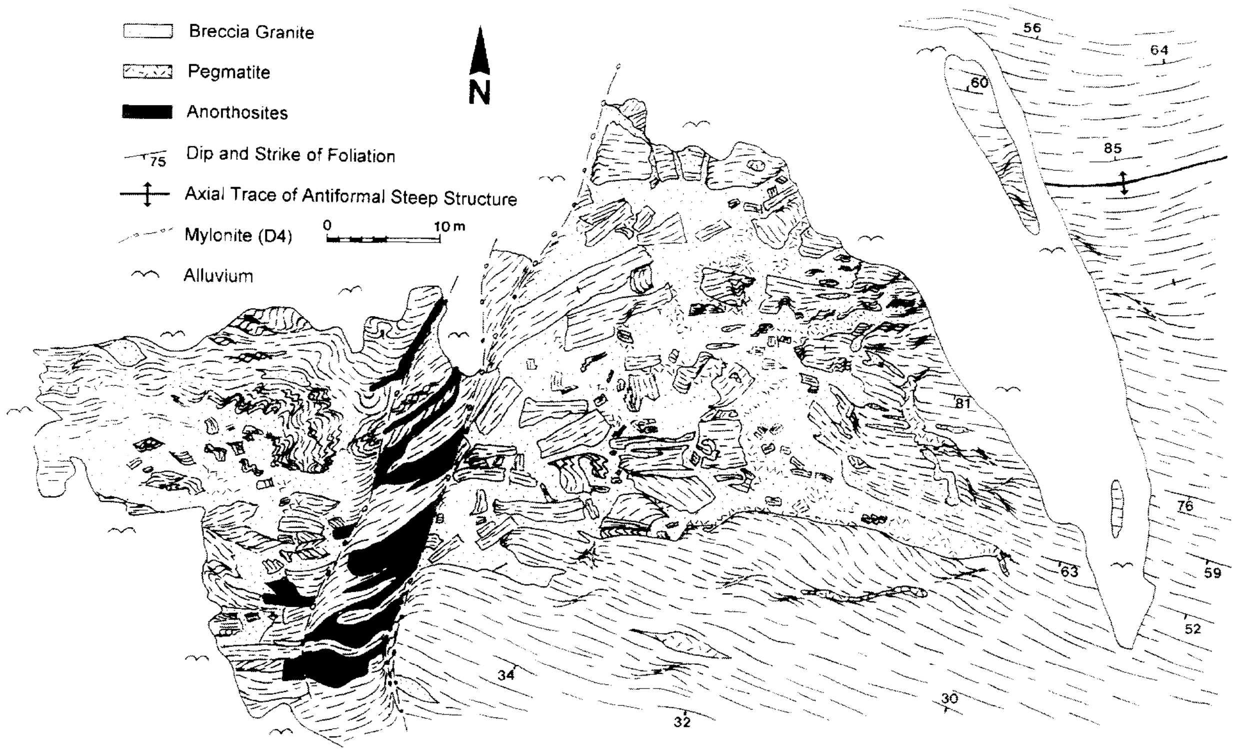

Fig. 5. Structural map of a megabreccia in the Hester Malan Nature Reserve. The megabreccia is located along the transition between an antiformal steep structure in the east and a monoclinal structure to the west. Note the progressive separation of wall-rock fragments along leucosome filled shear bands from the margins of the megabreccia and the rotation of fragments in the breccia granite.

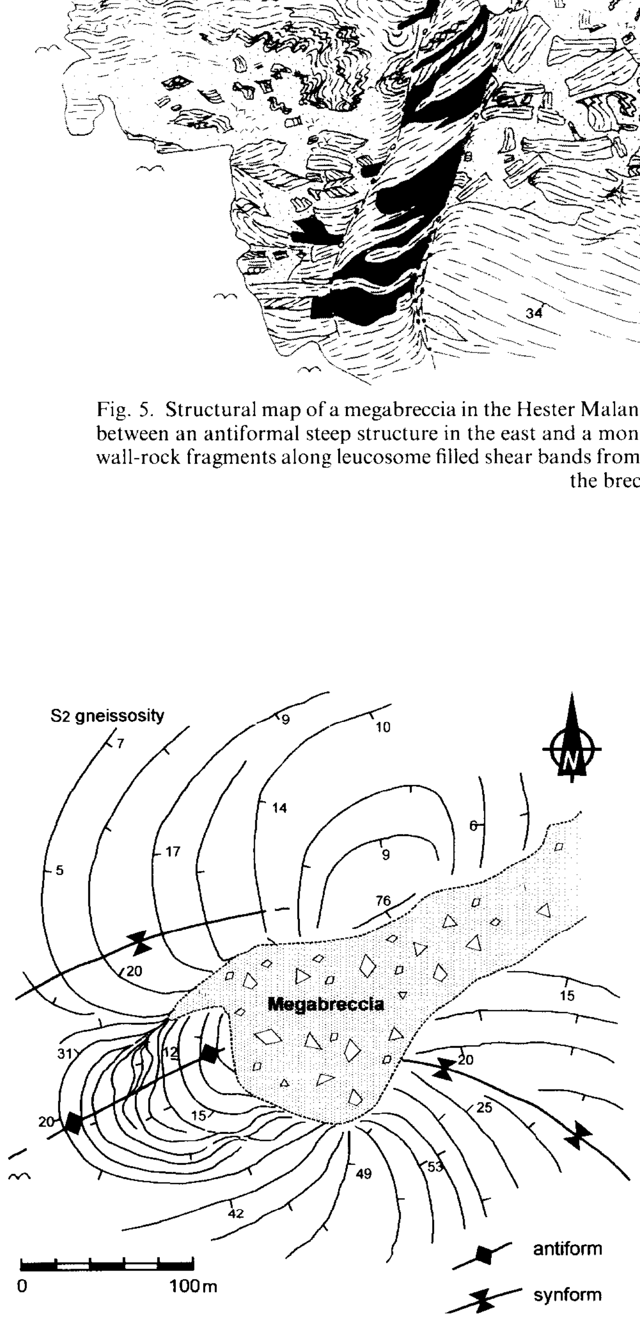

Fig. 6. Structural map of the Narrap Valley megabreccia. The complex structural pattern around the megabreccia is the result of the initial stages of steep structure formation, i.e. of the antiformal steepening of the regional, subhorizontal gneissosity. The megabreccia body is located in the core of the antiform and shows an ENE trend parallel to the antiformal upwarp.

replaces orthopyroxene, probably as a result of partial or complete back-reaction. Garnet is only present in coarse-grained feldspathic leucosomes in the immediate vicinity of fragments of the peraluminous Wolfram Schist, suggesting the biotite-breakdown reaction bt + si + qtz + pl = grt + kfs + melt. Chlorite commonly replaces the mafic minerals in surface samples.

The amount of the breccia granite in individual outcrops is highly variable and ranges from <5 up to >90 vol.% so that megabreccias can be composed of (1) closely packed fragments that are in mutual contact with the breccia granite occurring only as a volumetrically minor (<5–20 vol.%) interstitial phase between fragments; (2) isolated country-rock fragments that 'float' within the megabreccia matrix (20–50 vol.% matrix); or (3) homogeneous granitic bodies that contain very few or no wall-rock inclusions ($\gg 50$ vol.% matrix). Transitions between these types occur vertically and laterally over tens of metres even within individual outcrops (Fig. 5).

Pegmatites are closely associated with the breccia granite. They occur as irregular pods and stringers within the megabreccia, or continuous stringers parallel to the margins of megabreccias and/or around country-rock fragments (Fig. 5). Two types of pegmatite can be distinguished. Very coarse pegmatites consist of large (up to 10 cm in diameter) euhedral, perthitic microcline, interstitial greyish-blue quartz and large biotite books that partially or completely replace orthopyroxene. Similar pegmatites occur also in the subvertical gneisses

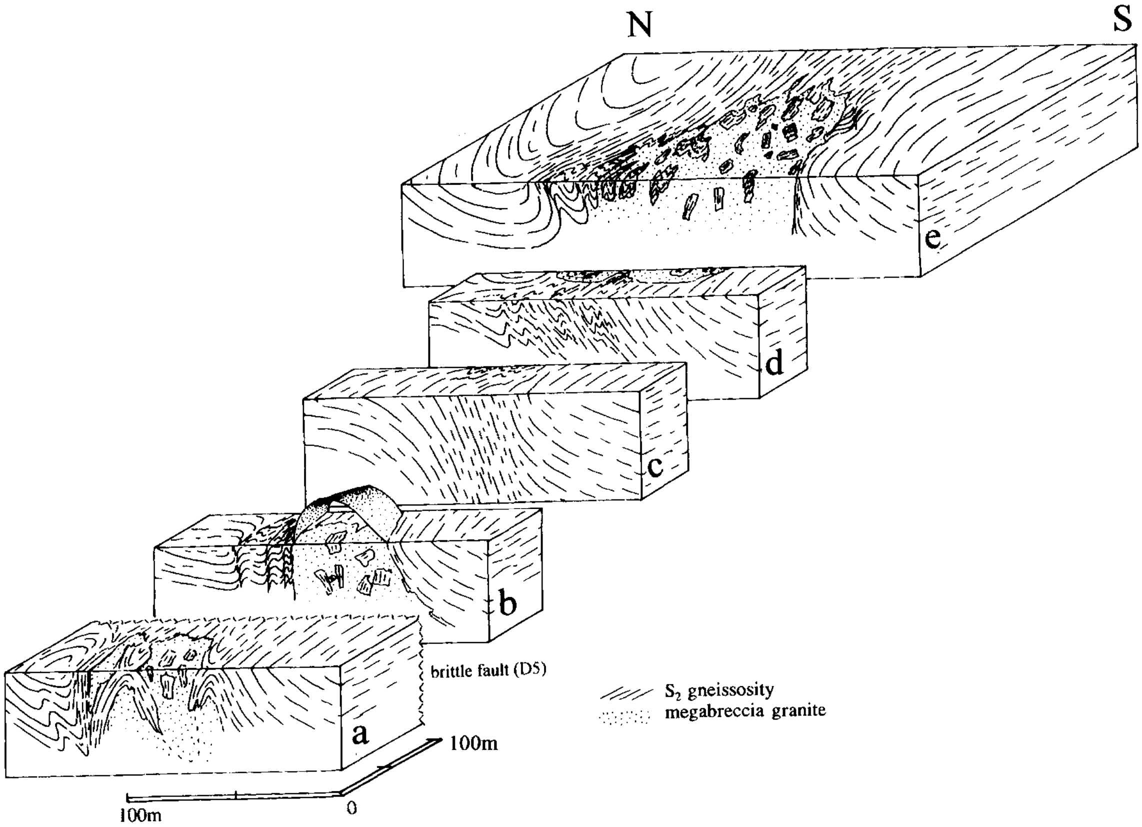

Fig. 7. Schematic block diagrams illustrating the occurrence of three melt bodies along a steep structure in the Hester Malan Nature Reserve [the megabreccia body in block diagram (e) is depicted in detail in Fig. 5]. The steep structure is developed as a south-facing monoclinal warp of the S_2 gneissosity. Antiformal upwarps are superimposed onto the monoclinal steepening of the gneissosity (a, b & e). Large-scale melting in the form of megabreccia formation (i.e. breccia granite including wall-rock fragments) occurs preferentially in the hinge zones of the antiformal upwarps.

of the enveloping steep structures, where they are developed as foliation-parallel and cross-cutting stringers of up to 15 cm in width. The second type of pegmatite involves stringers and pods of graphically intergrown K-feldspar and quartz that show both sharp and gradational contacts with the surrounding breccia granite. This type of pegmatite occurs also as thin (1–2 cm) rims around country-rock fragments that 'float' within the leucocratic breccia granite.

The breccia granite is commonly devoid of macroscopically visible tectonic fabrics. In some occurrences, however, it contains a subvertical, easterly trending foliation defined by the preferred grain-shape orientation of flattened quartz grains or quartz-grain aggregates. This fabric is parallel to the subvertical S_3 fabric of the enveloping steep structure. Deformation of the breccia granite is also indicated in thin section by the formation of subgrains around feldspar crystals and bands of subgrains that transect quartz and feldspar grains.

MEGABRECCIA MORPHOLOGIES

Based on the contact relationships with their surrounding wall rocks, their fragment population, and the amount and distribution of the breccia granite, four different morphologies of megabreccias can be distinguished (types 1–4). The various morphologies describe a continuum from essentially *in situ* generated melts, showing little evidence of migration, to melts that have migrated for hundreds of metres from their source, representing intrusive granitoids.

Type 1 megabreccias are characterized by gradational contacts with their wall rocks (Fig. 5). These gradational contacts are expressed as a progression from intensely sheared and folded country-rock gneisses along the margins of megabreccias, where the orientation of the wall rocks is largely intact, to zones of intense disruption of the host-rock sequence leading into the chaotic, highly dismembered textures that typify the central parts of megabreccias (Kisters, 1993). Near the margins of megabreccias quartz–feldspar leucosomes are developed as thin, discontinuous stringers and pockets along shear bands and in boudin necks, parallel to the gneissosity and/or to the axial planes of folds defined by the sigmoidally folded S_2 gneissosity (Figs 8 & 9). Closer to the migmatite bodies, shear bands are developed in closely spaced arrays or conjugate pairs that divide the subvertical gneisses into decimetre- to metre-sized lozenge-shaped blocks. Leucosomes form a semi-

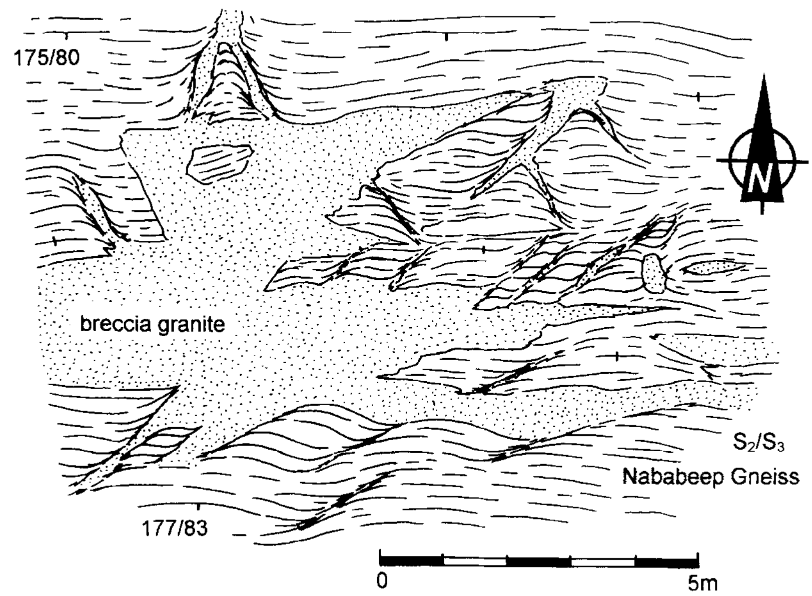

Fig. 8. Detailed sketch (plan view) of the structural development of parts of the eastern margin of the Hester Malan Nature Reserve megabreccia (Fig. 5). Leucosomes occur along oblique shear bands, boudin necks, and parallel to the subvertical S_2/S_3 fabric in the steep structure core. The progressive widening and coalescence of leucosomes leads to the formation of larger melt pockets (breccia granite) and to the gradual separation of wall-rock fragments.

continuous network along the shear bands, producing a diktyonitic migmatite texture (e.g. McLellan, 1988). Mafic selvedges are rarely developed along the leucosomes. The progressive widening and coalescence of leucosome stringers towards the central parts of the megabreccias results in the gradual separation of blocks so that the structural coherence of the wall rocks is gradually lost (Figs 5 & 8). The gradational separation of wall-rock fragments is also expressed in the fragment population of type 1 megabreccias that are mainly derived from the surrounding country rocks.

The sizes of fragments in the migmatites range from centimetre-sized inclusions to blocks of several tens of metres in diameter. The orientation of the gneissosity in adjoining fragments is highly variable, indicating a rotation of blocks. The fragments in the megabreccias show clear evidence of the intense deformation that has affected the gneisses in the adjacent steep structures. This deformation includes, most prominently, the highly strained gneissosities together with shear bands, foliation boudins and rare intrafolial folds (see also Lombaard and Schreuder, 1978). The internal foliation that parallels the long axes of fragments is commonly straight, but the blocks are sharply truncated at their terminations along

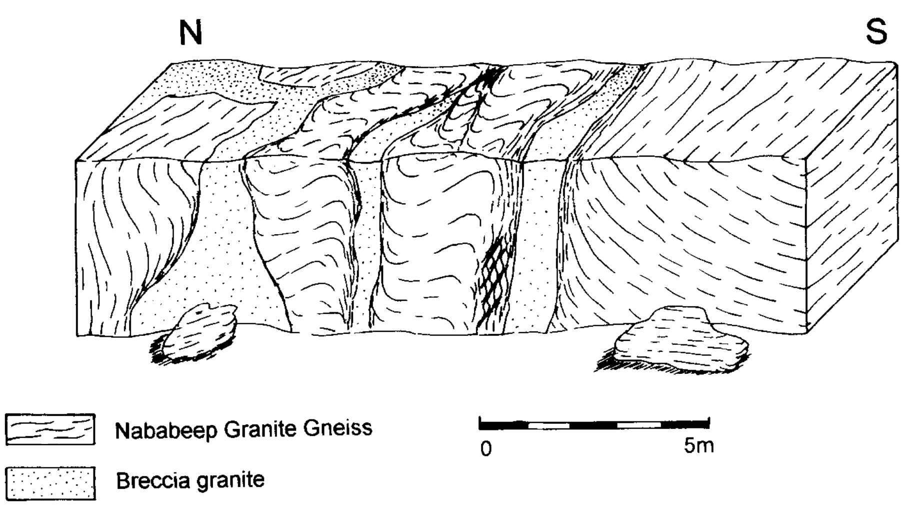

Fig. 9. Field sketch of an outcrop along the southern margin of the Narrap Valley megabreccia body (Fig. 6), illustrating the sigmoidal folding of country-rock gneisses between shear zones. The shear zones are invaded by a coarse-grained leucrocratic phase (breccia granite) consisting of K-feldspar, plagioclase, quartz, biotite and hypersthene. The progressive widening of the stringer-like breccia granite towards the centre of the megabreccia body leads to a separation and rotation of wall-rock fragments.

hook-like drag folds (Fig. 5). Hook structures along the margins of fragments reflect the original localization of melt in shear bands and/or boudin necks (Figs 4 & 8). Many fragments contain sigmoidally folded foliations and are bounded by zones of intensely developed foliations (Fig. 9). In contrast to the fragments of granite gneiss that show evidence of ductile deformation along their margins (i.e. shear bands, boudin necks), fragments of the metapelitic Wolfram Schist have angular outlines that indicate brittle fracturing during fragmentation.

Although most fragments display clearly discernable sharp boundaries, partial or nearly complete assimilation of country-rock fragments by the breccia granite has occurred locally. During the advanced stages of assimilation, the only distinction between the mineralogically similar granitic matrix of the megabreccia and country-rock fragments is provided by the preservation of a faint relict compositional layering and/or quartz fabric in the fragments. This fabric represents the original gneissose banding, augen texture or gneissosity of the former granite gneisses.

In contrast to type 1 megabreccias, the contacts of type 2 megabreccias are sharp. Type 2 megabreccias are, furthermore, characterized by variable proportions of exotic fragments that cannot be correlated with the surrounding wall-rocks.

Country-rock fragments in type 2 megabreccias can include all the high-grade rock types of the Copper District. As the sequence is subhorizontal and well stratified, this implies significant vertical movement of blocks. Based on the stratigraphic column of the Okiep Copper District, a predominantly downward (but also upward in some cases) displacement of blocks is indicated (Lombaard and Schreuder, 1978). The amount of vertical movement is commonly in the order of tens of metres, but may exceed 100 m. The largest known vertical transport distance of fragments is indicated for isolated blocks of the Rietberg Granite that are found some 700 m below their normal stratigraphic position in the 'Victory Lease Megabreccia' situated at the base of the Concordia Granite (Fig. 2). However, the fragment population is still dominated by the immediately adjacent country rocks. This is in contrast to type 3 megabreccias (see below). The amount of breccia granite is variable and ranges from <10 to $>50\%$ of the outcrop areas of individual megabreccias.

Type 3 megabreccias are composed mainly of angular- to subangular, highly disoriented, mainly exotic, country-rock fragments that are in mutual contact. The breccia granite constitutes $<5\%$ of the outcrop area and is mainly present as an interstitial phase between fragments or along the margins of the megabreccias where it is commonly developed as a pegmatitic phase. The contacts between the megabreccias and surrounding wall rocks are sharp, and the megabreccias occur as structurally highly discordant, pipe-like bodies, although the megabreccia contacts can still display evidence of minor shearing. As for type 2 megabreccias, the fragment populations suggest a mainly downward displacement of blocks with respect to surrounding rocks (Fig. 10). In the 'Henry's House' megabreccia (Fig. 10), closely packed fragments of Mixed Zone Gneiss, Wolfram Schist and Concordia Granite occur some 150 m below their normal stratigraphic positions in underlying Nababeep Gneiss. These 'exotic' fragments constitute $>70\%$ of the total outcrop of the 'Henry's House' megabreccia, whereas blocks of the surrounding Nababeep Gneiss are subordinate. In places, directly adjoining fragments have perpendicular internal foliation trends and there appears to be no correlation between the amount of breccia granite and the orientation of fragments. That is, although very little matrix is preserved in the megabreccias, fragments that are in mutual contact are highly disoriented.

Type 4 megabreccias are represented by compositionally homogeneous bodies of granitic composition that contain no or only very few country-rock fragments. They have abrupt, highly discordant contact relationships with the wall rocks, and Lombaard and Schreuder (1978) suggest an intrusive origin for these bodies. In contrast to type 1–3 megabreccias, the spatial relationship between type 4 megabreccias and steep structures is unclear, and the megabreccia bodies may terminate abruptly against the regional, subhorizontal country-rock gneisses. Although the typical megabreccia textures are largely absent and the structural control by steep structures is not evident, the granitic composition of the bodies (akin to that of the breccia granite of type 1–3 megabreccias) together with their elliptical shape, steeply inclined orientation and sharply transgressive nature are features that support a common origin for all four types.

DISCUSSION

Spatial and temporal relationships between deformation and melting

The close spatial association between megabreccias and steep structures has been known for a long time (Benedict *et al.*, 1964), but their relationship and the position of megabreccias within the regional geology of the Okiep Copper District have remained largely enigmatic (Lombaard and Schreuder, 1978; Lombaard *et al.*, 1986). The extensive disruption of the country-rock gneisses that yield the breccia-like, chaotic appearance was previously explained in terms of an explosive origin due to degassing mechanisms at mid-crustal levels (Lombaard *et al.*, 1986; Andreoli and Hart, 1987). Due to their sharply transgressive nature with respect to the enveloping steep structures, together with the presence of breccia fragments that contain the imprint of steep structure deformation (e.g. highly attenuated S_2/S_3 gneissosity and shear bands), megabreccias were also believed to post-date steep structure formation (Lombaard and Schreuder, 1978; Lombaard *et al.*, 1986).

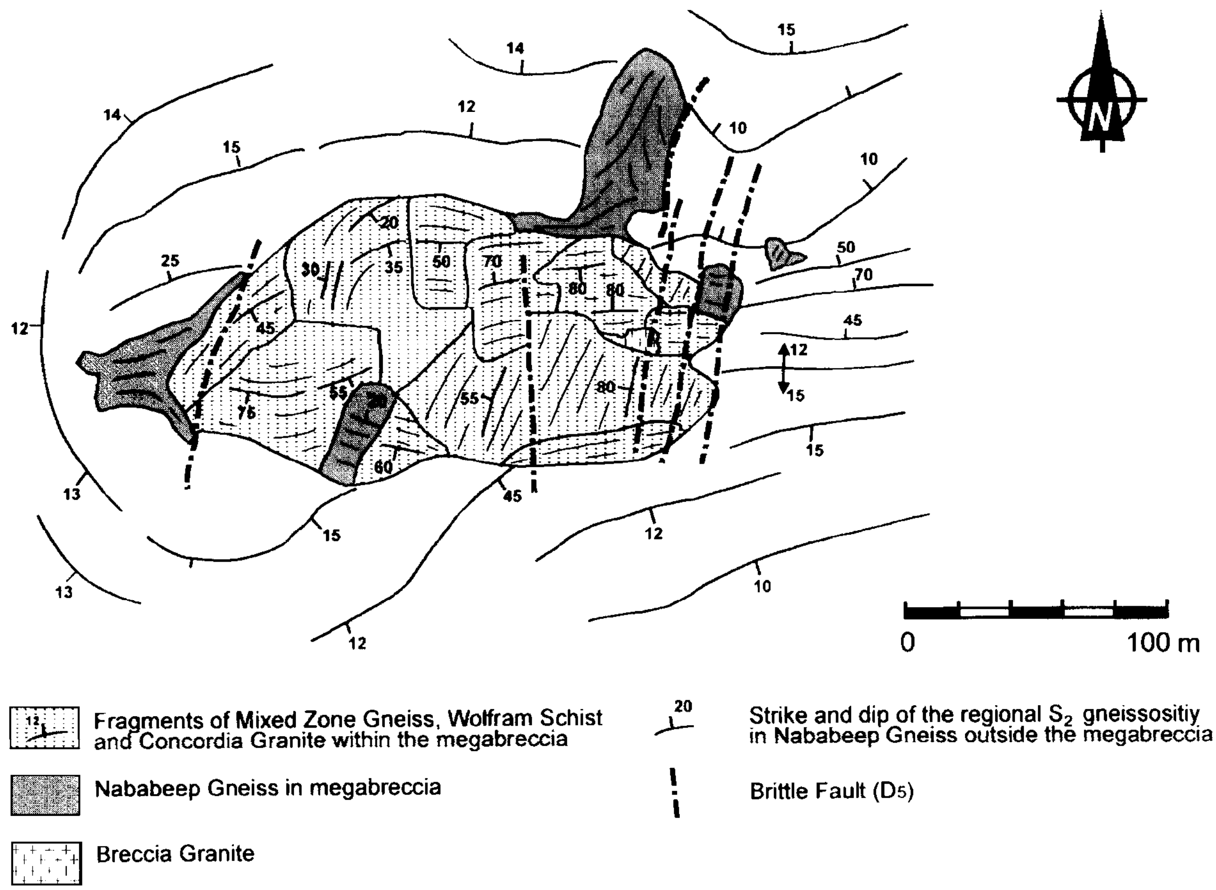

Fig. 10. Structural map of the 'Henry's House' megabreccia (modified after Lombaard and Schreuder, 1978). The regional gneisses (Nababeep Gneiss) describe an antiformal configuration around the megabreccia body, illustrating that the megabreccia is located in the core of the antiformal upwarp at the initiation of the steep structure which is developed east of the megabreccia. Note that the majority of fragments is not derived from the adjacent Nababeep Gneiss but consists of predominantly blocks of Mixed Zone Gneiss, Concordia Granite, and Wolfram Schist. These lithologies are exposed approximately 150 m above the present level of erosion, suggesting an overall downward movement of blocks. Note also the highly disorientated internal foliation trends of fragments that are in mutual contact and the small amount of breccia granite (see text for further description).

Based on the the structural and textural development outlined in the previous paragraphs, it appears that the megabreccias are temporally and genetically closely associated with the formation of steep structures. Structurally controlled, initial, small-scale segregation of melt occurred initially in shear bands and boudin necks that formed during the advanced stages of steep structure development (Figs 4, 8 & 9). Larger-scale melt bodies are located at the steep structure extremities (Figs 6, 7 & 10). The presence of the subvertical, E-trending S_3 steep structure fabric in small-scale leucosomes and in the breccia granite of some megabreccias (Kisters *et al.*, 1996b) indicates that steep structure deformation locally outlasted megabreccia formation. Hence, a syn-steep structure (i.e. syn-D_3) timing during or close to peak metamorphic conditions is suggested for the formation of the megabreccias.

Positive-feedback mechanisms between strain and anatexis

Numerous field and experimental studies have demonstrated a positive-feedback mechanism between deformation and melting in high-grade metamorphic rocks (Dell'Angelo and Tullis, 1988; Sawyer, 1994; Rushmer, 1995; Brown *et al.*, 1995). Grain-size reduction during crystal plastic flow and dynamic recrystallization in ductile deformation zones may result in enhanced reaction kinetics, which promotes initial melting along grain boundaries or grain-boundary triple junctions. The presence of melt during ductile deformation may, in turn, enhance both ductile deformation processes such as melt-assisted diffusion creep and brittle fracturing associated with high strain-rates and/or near-lithostatic melt pressures (e.g. Rushmer, 1995; Rutter and Neumann, 1995). This creates additional permeability. Dipple and Ferry (1992) have suggested permeabilities in ductile deformation zones to be two to five orders of magnitude greater than those of rocks undergoing regional metamorphism under static conditions. The envisaged enhanced permeability development in steep structures would thus have created pressure gradients and, consequently, melt would have migrated along this hydraulic gradient into the system. Additional melt would, in turn, have promoted ductile and ductile–brittle deformation processes in the steep structures, further enhancing the partitioning of the bulk strain during D_3 back into the steep structure zones.

An additional feature of steep structures that is significant for melt segregation is their subvertical attitude transecting the regionally subhorizontal granite-gneiss sequence of the Okiep Copper District. Considering the enhanced permeabilities in the steep structures compared to the regional gneisses, the steep structures provide a connection between two different lithostatic regimes. Assuming a normal geobarometric gradient of 30 MPa km^{-1}, two levels separated by a vertical distance of 300 m, i.e. the average vertical extent of steep structures, are characterized by an effective pressure gradient of approximately 10 MPa. This pressure gradient along steep structures could facilitate melt migration in addition to buoyancy and, together with the enhanced permeability in the deformation zones, would focus further melt migration. Hence, the complementary mechanisms of strain localization and partial melting in steep structures create the drainage system of upright anisotropies that facilitate the segregation of melts.

Melt generation and segregation in megabreccias

Steep structure formation plays a key role in the accumulation and segregation of melts. The segregation process can be subdivided into four stages:

(1) structurally induced small-scale formation and local migration of melts;
(2) melt accumulation of larger pods in low-stress sites along steep structures;
(3) subsequent vertical melt migration confined to the subvertical steep structure fabric; and
(4) melt migration independent of the steep structures to form discordant intrusive granitoids.

Stage 1. The small-scale segregation of melts can be observed in predominantly extensional structures that are associated with the initial stages of steep structure formation. Initial melt segregation occurs in shear bands and boudin necks, but also parallel to the gneissosity or along fold axial planes. The scarcity of mafic selvedges around leucosomes probably indicates that the melts have migrated for some distance into the predominantly extensional sites. Isolated pockets and stringers of melt may coalesce to form a semi-continuous network (Figs 4, 8 & 9).

Stage 2. Large melt bodies, now in the form of megabreccias, occur preferentially along the terminations of steep structures and/or the transitions between monoclinal and antiformal steep structure geometries (Figs 6, 7 & 10). In both structural settings, megabreccias are developed in the hinge zones of the antiformal upwarps of the S_2 gneissosity. The occurrence of megabreccias in the cores of these structural sites is interpreted to reflect the strain compatibility problem that arises as a consequence of the folding of the gneissosity above detachments represented by shallowly dipping thrust zones or the subhorizontal regional S_2 gneissosity (Kisters *et al.*, 1996a). The localized dilation accompanying the strain incompatibility in these sites results in a lowering of the local mean stress, setting up a hydraulic gradient. The dilational component in the core of the antiformal upwarps is clearly indicated by the textures in megabreccias (i.e. fragments cemented by interstitial granite). The hydraulic gradient triggers the migration of partial melts contained in the high-grade metamorphic country rocks. Similar mechanisms of melt redistribution and migration have been described from other migmatitic terrains (e.g. Allibone and Norris, 1992), where they are referred to as 'melt pumping' (e.g. Robin, 1979; Percival, 1989; Sawyer, 1991, 1994; Brown, 1994 and references therein), and from hydrothermal systems in which fluids are expelled from areas of higher pressure to regions of reduced mean stress ["dilatancy pumping" after Sibson *et al.* (1975) and Oliver *et al.* (1990)].

Evidence for a largely *in situ* formation of megabreccias showing little removal of melt or restite in the dilational sites associated with the initial stages of steep structure formation is provided in type 1 megabreccias by (1) fragment populations that reflect the adjacent wall rocks, indicating little vertical displacement of blocks; (2) local variations in the composition of the breccia granite (e.g. the localized occurrence of garnet in the breccia granite around blocks of peraluminous Wolfram Schist); and (3) the only gradual disruption and incorporation of fragments from their wall-rock gneisses (Fig. 5). Minor brittle fracturing evidenced by the angular outlines of blocks of the Wolfram Schist may indicate either competency contrasts between the granite gneisses and metasedimentary units or possibly higher internal fluid (melt) pressures and hydraulic fracturing as a result of fluid-absent melting reactions in the biotite-rich metapelitic schists.

Stage 3. The vertical mobilization of melt from accumulation sites is illustrated in type 2 and 3 megabreccias and is indicated by (1) the occurrence of megabreccias with exotic fragments that have experienced a downward or upward displacement of (locally) several hundreds of metres, and (2) the loss of structural coherence of *in situ* wall rocks and rotation of fragments to yield the typical schollen-and-raft textures of megabreccias.

The upward transport of blocks reflects entrainment by buoyant magma, which segregates from its source region together with parts of the restite. An overall downward movement of blocks is recorded in the Henry's House megabreccia (Fig. 10), where fragments within the megabreccia are derived from approximately 150 m above the presently exposed outcrop level. Moreover, the fragments in the Henry's House megabreccia are in mutual contact, displaying highly disorientated foliation trends with only small amounts of interstitial breccia granite in the eastern portions of the outcrop. Both the downward displacement of the fragments and the rotation of large, directly adjoining country-rock fragments are difficult to envisage without a framework of melt in which movement and rotation of blocks could have occurred. The predominant downward movement of blocks together with the rotation of directly adjoining country-rock fragments indicates that the melt (i.e. the breccia granite) has migrated out of the system, leaving behind a residuum consisting of fragments that have settled down from higher stratigraphic levels to compensate the space left by the buoyantly rising melt. "Melt compaction" (after McKenzie, 1984) caused by (1) the settling of wall rocks, and (2) deformation-enhanced compaction during ongoing deformation (i.e. shortening normal to steep structure lines) is likely to have assisted melt segregation in the type 3 megabreccias.

The occurrence of country-rock xenoliths several hundred metres below their normal stratigraphic position indicates the presence of open magma conduits through which the metre-scale blocks could settle. Considering that the largest known vertical dimensions of megabreccias are in excess of 1000 m, megabreccias represent melt bodies of a considerable size (up to 0.5 km^3). The settling of isolated wall-rock fragments in the melt column over hundreds of metres also implies considerable density contrasts between the anatectic melts and the granitic country rocks. This indicates that buoyancy was a major driving force for the ascent of the melts, even though they remained confined to the subvertical steep structure zones. Ascent of the melts predominantly by buoyancy is also likely, considering the hot and dry (i.e. orthopyroxene-bearing) nature of the melts. Heat loss from the magmas to the wall rocks during their ascent would be minimal considering the high ambient temperatures of the country rocks undergoing granulite-facies metamorphism at temperatures of about 850°C.

Stage 4. Type 4 megabreccias represent the intrusive end-members of megabreccias, i.e. granitoids that have migrated for several hundreds of metres from their sources and from the steep structure conduit. The lack of a structural link between type 4 megabreccias and the steep structures suggests that the advanced stages of upward melt migration were controlled predominantly by buoyancy.

CONCLUSIONS

The following conclusions can be drawn from the observations made on the structural development and occurrence of megabreccias in the Okiep Copper District.

(1) Megabreccias in the Okiep Copper District represent voluminous, structurally controlled, pipe-like schollen-and-raft migmatites that illustrate the deformation-enhanced generation and segregation of melt in a mid-crustal section undergoing high-grade metamorphism, associated regional-scale anatexis and coeval deformation. The presence of low volumes of melts on a regional scale is evidenced by the occurrence of small-scale leucosomes that are mainly confined to the subhorizontal gneissosity, showing little evidence of mobilization. The segregation and mobilization of melts is then structurally controlled (i.e. by the steep structures) indicating that strain is the catalyst for concentrating the melts. Different textural and structural types of megabreccia occurrences illustrate a continuum from (a) small-scale segregation of melt into predominantly extensional structures that are associated with the initial stages of steep structure formation; (b) the formation and accumulation of larger *in situ* melt bodies in hinge zones of steep structures (type 1 megabreccias); (c) partial segregation of melt and restite from its initial accumulation sites (type 2 megabreccias); (d) advanced stages of melt migration that have left behind a residuum (type 3 megabreccias); and (e) homogeneous granitic bodies which are intrusive into higher structural levels (type 4 megabreccias).

(2) A variety of different melt segregation processes appear to have operated during different stages of megabreccia and associated steep structure formation, including (a) initial melt segregation in extensional structures; (b) melt accumulation as a result of dilatancy pumping associated with strain incompatibilities developed during the initial stages of steep structure formation; (c) subsequent melt migration due to buoyancy, deformation-enhanced melt compaction during ongoing deformation, melt compaction due to the settling of fragments from higher stratigraphic levels and minor brittle fracturing; and (d) large-scale melt migration due to mainly buoyancy to form intrusive granitoids. Melt migration is largely confined to the subvertical fabric in steep structures, indicating that the subvertical anisotropies provided preferential pathways for the granitic melts. Synanatectic deformation is interpreted to have provided increased permeabilities for melt migration and hydraulic gradients along which melt could migrate since the subvertical fabric in steep structures represents a connection between two different lithostatic pressure regimes. Despite the variety of melt migration processes, melt ascent of the hot, water-undersaturated magmas is inferred to have been largely controlled by buoyancy.

(3) A positive feed-back mechanism between deformation and melting is indicated by the close spatial association between steep structures and megabreccias. Melting in steep structures was promoted by the formation of strain incompatibilities during deformation, and enhanced permeabilities in steep structures undergoing ductile deformation. Melting, in turn, partitioned the bulk strain during D_3 back into steep structures, which then provided the upright structural network for vertical melt migration in a

terrain otherwise characterized by subhorizontal lithologies and fabrics.

(4) Vertical transport of fragments over distances of up to 700 m indicate that open, vertical, interconnected magma conduits must have existed at the mid-crustal levels of the Okiep Copper District during deformation and megabreccia formation. Taking the largest dimensions of megabreccias into account, they represent discordant, steeply inclined bodies of considerable size and indicate that large, continuous melt bodies can exist in ductile regimes at high temperatures.

(5) The absence of megabreccias from the high-grade terrain to the immediate south of the Okiep Copper District, where steep structure deformation is not observed, underscores the significance of deformation for the processes of melt generation and segregation. It also indicates that the granite magma productivity of a crustal segment is dependent not only on the 'fertility' of crustal lithologies (e.g. Clemens and Vielzeuf, 1987), but also on its deformational style.

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REFERENCES

Allibone, A. H. and Norris, R. J. (1992) Segregation of leucogranite plutons during syn-anatectic deformation: an example from the Taylor Valley, Antarctica. *Journal of Metamorphic Geology* **10**, 589–600.

Andreoli, M. A. G. and Hart, R. J. (1987) Explosive KREEP-norite from Namaqualand, South Africa, with implications for the Sudbury irruptive. *International Workshop on Cryptoexplosions and Catastrophes in the Geological Record*, Parys, South Africa, abstracts, 1–8.

Benedict, P. C., Wiid, D. de N., Cornelissen, A. K. and Staff (1964) Progress report on the geology of the O'okiep Copper District. In *The Geology of Some Ore Deposits in Southern Africa*, ed. S. H. Haughton, pp. 239–302. Geological Society of South Africa, **2**.

Brown, M. (1994) The generation, segregation, ascent and emplacement of granite magma: the migmatite-to-crustally derived granite connection in thickened orogens. *Earth Science Review* **36**, 83–130.

Brown, M., Rushmer, T. and Sawyer, E. W. (1995) Introduction to special section: Mechanisms and consequences of melt segregation from crustal protoliths. *Journal of Geophysical Research* **100**, 15551–15564.

Clemens, J. D. and Mawer, C. K. (1992) Granite magma transport by fracture propagation. *Tectonophysics* **204**, 339–360.

Clemens, J. D. and Vielzeuf, D. (1987) Constraints on melting and magma production in the crust. *Earth and Planetary Science Letters* **86**, 287–306.

Clifford, T. N., Gronow, L., Rex, D. C. and Burger, A. J. (1975) Geochronological and petrogenetic studies of high grade metamorphic rocks and intrusives in Namaqualand, South Africa. *Journal of Petrology* **16**, 154–188.

Clifford, T. N., Stumpfl, E. F., Burger, A. J., McCarthy, T. S. and Rex, D. C. (1981) Mineral- chemical and isotopic studies of Namaqualand granulites, South Africa: a Grenville analogue. *Contributions in Mineralogy and Petrology* **77**, 225–250.

Clifford, T. N., Barton, E. S., Retief, E. A., Rex, D. C. and Fanning, C. M. (1995) A crustal progenitor for the intrusive anorthosite–charnockite kindred of the cupriferous Koperberg Suite, O'okiep District, Namaqualand, South Africa; New isotope data for the country rocks and intrusives. *Journal of Petrology* **36**, 231–258.

Cruden, A. R. (1988) Deformation around a rising diapir modelled by creeping flow past a sphere. *Tectonics* **7**, 1091–1101.

Dell'Angelo, L. N. and Tullis, J. (1988) Experimental deformation of partially molten granitic aggregates. *Journal of Metamorphic Geology* **6**, 495–515.

Dipple, G. M. and Ferry, J. M. (1992) Metasomatism and fluid flow in ductile fault zones. *Contributions in Mineralogy and Petrology* **112**, 149–164.

D'Lemos, R. S., Brown, M. and Strachan, R. A. (1992) The relationship between granite and shear zones: magma generation, ascent and emplacement within a transpressional orogen. *Journal of the Geological Society of London* **149**, 487–490.

Emerman, S. H. and Marrett, R. (1990) Why dikes? *Geology* **18**, 231–233.

England, R. W. (1990) The identification of granite diapirs. *Journal of the Geological Society of London* **147**, 931–933.

Gibson, R.L., Robb, L.J., Kisters, A.F.M. and Cawthorn, R.G. (1996) Regional setting and geological evolution of the Okiep Copper District, Namaqualand, South Africa. *South African Journal of Geology* **99**.

Hand, M. and Dirks, P. H. G. M. (1992) The influence of deformation on the formation of axial- planar leucosomes and the segregation of small melt bodies within the migmatitic Napperby Gneiss, Central Australia. *Journal of Structural Geology* **14**, 591–604.

Hartnady, C., Joubert, P. and Stowe, C. (1985) Proterozoic crustal evolution in southwestern Africa. *Episodes*, 236–244.

Hollister, L. H. and Crawford, M. L. (1986) Melt-enhanced deformation: A major tectonic process. *Geology* **14**, 558–561.

Hutton, D. H. W. (1988) Granite emplacement mechanisms and tectonic controls: inferences from deformation studies. *Transactions of the Royal Society of Edinburgh Earth Sciences* **79**, 245–255.

Joubert, P. (1986) The Namaqualand metamorphic complex—a summary. In *Mineral Deposits of Southern Africa*, eds C. R. Anhaeusser and S. Maske, Vol. 2, pp. 1395–1420. *Geological Society of South Africa.*

Kisters, A. F. M. (1993) Structural relationships of economic orebearers in the Okiep Copper District, Namaqualand, NW Cape. Ph.D. thesis, University of the Witwatersrand, Johannesburg.

Kisters, A. F. M., Charlesworth, E. G., Anhaeusser, C. R. and Gibson, R. L. (1996a) Steep structure formation in the Okiep Copper District: Bulk inhomogeneous shortening of a high-grade metamorphic granite-gneiss sequence. *Journal of Structural Geology* **18**, 735–751.

Kisters, A. F. M., Charlesworth, E. G., Gibson, R. L. and Anhaeusser, C. R. (1996b) The relationship between antiformal and monoclinal steep structures in the Okiep Copper District, Namaqualand: A case study. *South African Journal of Geology* **99**, 185–195.

Kisters, A. F. M., Gibson, R. L., Charlesworth, E. G. and Anhaeusser, C. R. (1992) Megabreccia formation in the Okiep Copper District. *Abstract Geocongress '92, Geological Society of South Africa*, Bloemfontein, 228–230.

Kisters, A. F. M., Potgieter, J. E., Charlesworth, E. G., Anhaeusser, C. R., Gibson, R. L. and Watkeys, M. K. (1994) Emplacement features of cupriferous noritoids in the Okiep Copper District, Namaqualand, South Africa. *Exploration and Mineral Geology* **3**, 297–310.

Lombaard, A. F. and Schreuder, F. J. G. (1978) Distribution pattern and general geological features of steep structures, megabreccias and basic rocks in the Okiep Copper District. In *Mineralization in Metamorphic Terranes*, ed. W. J. Verwoerd, pp. 269–295. Special Publication of the Geological Society of South Africa, **4**.

Lombaard, A. F. and the Exploration Department Staff of the O'okiep Copper Company Ltd (1986) The copper deposits of the Okiep Copper District, Namaqualand. In *Mineral Deposits of Southern Africa*, ed. C. R. Anhaeusser and S. Maske, Vol. 2, pp. 1421–1445. Geological Society of South Africa.

McCaffrey, K. J. W. (1992) Igneous emplacement in a transpressive shear zone: Ox Mountains igneous complex. *Journal of the Geological Society of London* **149**, 221–235.

McIver, J. P., McCarthy, T. S. and Packham, B. de. V. (1983) The copper-bearing basic rocks of Namaqualand, South Africa. *Mineralogia Deposita* **18**, 135–160.

McKenzie, D. P. (1984) The generation and compaction of partially molten rock. *Journal of Petrology* **25**, 713–765.

McLellan, E. L. (1988) Migmatite structures in the Central Gneiss Complex, Boca de Quadra, Alaska. *Journal of Metamorphic Geology* **6**, 517–542.

Oliver, N. H. S., Valenta, R. K. and Wall, V. J. (1990) The effect of heterogeneous stress and strain on metamorphic fluid flow, Mary Kathleen, Australia, and a model for large-scale fluid flow circulation. *Journal of Metamorphic Geology* **8**, 311–331.

Paterson, S. R. and Fowler, T. K. (1993) Re-examining pluton emplacement processes. *Journal of Structural Geology* **15**, 191–206.

Percival, J. A. (1989) Melt-induced fluid pumping and the source of CO2 in granulites. In *Fluid Movements — Element Transport and the Composition of the Deep Crust*, ed. D. Bridgewater, pp. 61–69. Kluwer, Dordrecht, The Netherlands.

Petford, N. (1995) Segregation of tonalitic–trondhjemitic melts in the continental crust: The mantle connection. *Journal of Geophysical Research* **100**, 15735–15744.

Petford, N., Kerr, R. C. and Lister, J. R. (1993) Dike transport of granitoid magmas. *Geology* **21**, 845–848.

Raith, J. G. and Prochaska, W. (1995) Tungsten deposits in the Wolfram Schist, Namaqualand, South Africa: Strata-bound versus granite-related genetic concepts. *Economic Geology* **90**, 1934–1959.

Robb, L. J., Armstrong, R. A. and Waters, D. J. (1998) Timing and duration of low-pressure granulite-facies metamorphism and crustal growth in Namaqualand, South Africa: Evidence from single-zircon U–Pb geochronology. *Journal of Petrology* (in press).

Robin, P.-Y. F. (1979) Theory of metamorphic segregation and related processes. *Geochimica et Cosmochimica Acta* **43**, 1587–1600.

Rushmer, T. (1995) An experimental deformation study of partially molten amphibolite: Application to low-melt fraction segregation. *Journal of Geophysical Research* **100**, 15681–15696.

Rutter, E. H. and Neumann, D. H. K. (1995) Experimental deformation of partially molten Westerly Granite under fluid-absent conditions, with implications for the extraction of granitic magmas. *Journal of Geophysical Research* **100**, 15697–15716.

Rutter, M. J. and Wyllie, P. J. (1988) Melting of vapour-absent tonalite at 10 kbar to simulate dehydration melting in the deep crust. *Nature* **331**, 159–160.

SACS (South African Commitee for Stratigraphy) (1980) Stratigraphy of South Africa. L. E. Kent (compiler), Part 1. *Handbook of the Geological Survey of South Africa* **8**, 690.

Sawyer, E. W. (1991) Disequilibrium melting and the rate of melt-residuum separation during migmatization of mafic rocks from the Grenville Front Quebec. *Journal of Petrology* **32**, 701–738.

Sawyer, E. W. (1994) Melt segregation in the continental crust. *Geology* **22**, 1019–1022.

Sibson, R. H., Moore, J. McM. and Rankin, A. H. (1975) Seismic pumping—a hydrothermal mechanism. *Journal of the Geological Society of London* **131**, 653–659.

Stevens, G., Clemens, J. D. and Droop, G. T. R. (1995) Hydrous cordierite in granulites: experiments and phase relationships. *Contributions in Mineralogy and Petrology* **117**, 375–393.

Van der Molen, I. and Paterson, M. S. (1979) Experimental deformation of partially-melted granite. *Contributions in Mineralogy and Petrology* **70**, 299–318.

Waters, D. J. (1988) Partial melting and the formation of granulite facies assemblages in Namaqualand, South Africa. *Journal of Metamorphic Geology* **6**, 387–404.

Waters, D. J. (1989) Metamorphic evidence for the heating and cooling path of Namaqualand granulites. In *Evolution of Metamorphic Belts*, pp. 269–275. Special Publication of the Geological Society, **43**.

Waters, D. J. (1990) Thermal history and tectonic setting of the Namaqualand granulites, Southern Africa: Clues to Proterozoic crustal development. In *Granulites and Crustal Evolution*, ed. D. Vielzeuf and Ph. Vidal, pp. 243–256. Kluwer Academic, Dordrecht.

Waters, D. J. and Whales, C. J. (1984) Dehydration melting and the granulite transition in metapelites from southern Namaqualand, S. Africa. *Contributions in Mineralogy and Petrology* **88**, 269–275.

Weinberg, R. F. (1993) Drops, surface tension and diapir models. *Journal of Structural Geology* **15**, 227–232.

Wickham, S. M. (1987) The segregation and emplacement of granitic magmas. *Journal of the Geological Society of London* **144**, 281–297.

Williams, M. L., Hanmer, S., Kopf, C. and Darrach, M. (1995) Syntectonic generation and segregation of tonalitic melts from amphibolite dikes in the lower crust, Striding-Athabasca mylonite zone, northern Sasketchewan. *Journal of Geophysical Research* **100**, 1995.