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Progressive adjustments of ascent and emplacement controls during incremental construction of the 3.1 Ga Heerenveen batholith, South Africa

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Abstract

The Heerenveen batholith is part of a suite of areally extensive, shallow-crustal granitoid plutons intruded during the last regional phase of tectonism and NW-SE subhorizontal shortening recorded in the Mesoarchean Barberton granitoid-greenstone terrain of South Africa at 3.1 Ga. Intrusive relationships allow at least four main successively emplaced intrusive stages to be distinguished. Each of these shows distinct geometries and intrusive styles that provide evidence for the progressive change of emplacement controls during the incremental construction of the Heerenveen batholith. The earliest sheet-like granitoids intruded as foliation-parallel sills along the shallowly dipping basement gneissosity, emphasizing the role of favourably inclined pre-existing wall-rock anisotropies for granite emplacement during the early stages of pluton assembly. Continued sheeting and coalescence of sheets provided the thermal ground preparation that led to the formation of larger, coherent magma bodies and the main phase of homogeneous, commonly megacrystic granites. These megacrystic granites form the central parts of the Heerenveen batholith, and are interpreted to represent steady-state magma chambers. The introduction of the rheologically weaker melt bodies into the shallow crust resulted in the nucleation of conjugate synmagmatic transpressive shear zones around the central granites. The shear zones correspond to several km-wide zones of shear zone-parallel granite sheeting. This stage marks a dramatic switch in emplacement styles. While the initial stages of magma emplacement were largely determined by factors external to the magma, most importantly the pre-existing wall-rock anisotropies, subsequent stages are dominated by factors intrinsic to the magma, namely strain localization and partitioning along melt-bearing zones during syntectonic plutonism. The associated melt transfer along these zones is independent of pre-existing structures and mainly related to buoyancy- and strain-induced melt ascent. The last granites of the Heerenveen batholith are post-tectonic. They intrude as either plugs or stocks of seemingly random orientation, but display a clear control by wall-rock anisotropies where they are in contact with the country rocks.

On a regional scale, the different phases of the Heerenveen batholith describe an overall zonation of central homogeneous granites enveloped by composite, sheeted and sheared margins. This pattern is typical for most of the large 3.1 Ga granite batholiths in the Barberton granitoid-greenstone terrain. We suggest that the sequence of progressively changing emplacement controls and the formation of steady-state magma chambers described here for the Heerenveen batholith may be of wider application to other zoned and/or incrementally assembled batholiths.

Keywords: *Archean granites*; Barberton terrain; Sheeted granites; Incremental emplacement; Magma chamber formation

1. Introduction

Large and seemingly homogeneous granite plutons are increasingly recognized as being constructed through the assembly of discrete melt batches that often take the form of sheet-like bodies (e.g. Ingram and Hutton, 1994; Wiebe and Collins, 1998; Miller and Paterson, 2001; Mahan et al., 2003; Archanjo and Fetter, 2004). Geochronological data on many of these sheeted granites have confirmed that pluton growth is incremental and may occur over up to several million years rather than representing short-lived single-stage events (e.g. Johnson et al., 2003; Coleman et al., 2004; Glazner et al., 2004; Westraat et al., 2005).

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The formation of granites is almost invariably linked to orogenic environments and the close correlation between deformation zones and regions of melt transfer and granite emplacement are well documented (e.g. D'Lemos et al., 1992; Ingram and Hutton, 1994; Brown and Solar, 1998). The presence of low-viscosity melts in a deforming crustal section may lead to strain localization that may not only lubricate but also trigger shear zones resulting in deformation rates in the melt-bearing zones that are substantially higher than average crustal strain rates (e.g. Davidson et al., 1994; Rutter and Neumann, 1995; Tommasi et al., 1995; Gerbi et al., 2004). Similarly, zones of magma transfer and granite emplacement may also result in strain partitioning, and magmatic arcs of e.g. transpressional orogenic belts can often be shown to localize the non-coaxial component of the bulk strain (Fitch, 1972; Tikoff and Teyssier, 1994; De Saint-Blanquat et al., 1998; Vigneresse and Tikoff, 1999).

Given the effects of strain partitioning and localization around magmas in conjunction with the progressive assembly of many granitoid plutons, one must expect progressive adjustments or transient switches of the controls and styles of emplacement in and around the sites of emplacement or zones of melt transfer (e.g. Marsh, 1982; Furlong and Myers, 1985; Cruden, 1990; Bergantz, 1991). There are numerous cases documenting the positive feedback effect between melting and deformation (e.g. Karlstrom et al., 1993; Ingram and Hutton, 1994; Brown and Solar, 1998; De Saint-Blanquat et al., 1998; Neves et al., 2000). However, examples where earlier granite phases can be shown to modify the emplacement styles and controls of ascent of later granite batches of composite plutons are only rarely documented. This may be expected in large plutonic bodies where the intrusion of subsequent magma batches is likely to obscure the emplacement controls of earlier granite phases.

The purpose of this paper is to examine and document the systematic changes and adjustments of intrusive styles and emplacement controls recorded by successive granitic magma batches during the incremental construction of a large, composite batholith. This study focuses on the 3.1 Ga Heerenveen batholith in the Barberton granitoid-greenstone terrain. The Heerenveen batholith is composed of a number of texturally and compositionally distinct granitic phases, comprising more massive granitoids in the centre, surrounded by km-wide zones of heterogeneous sheeted granites. The paper starts by describing the intrusive and relative age relationships between different granite phases, their geometries and magmatic and solid-state fabrics. The distinct intrusive styles and fabric developments in the different granite phases are then discussed in terms of the progressive modification of emplacement styles induced by earlier granite phases.

2. Regional geology

The Heerenveen batholith is one of the several areally extensive 3.1 Ga plutons located in the Mesoarchean (3.5–3.1 Ga) Barberton granitoid-greenstone terrain in South Africa. Individual plutons range from several 100 to >5000 km^2 in size, covering in total, an area in excess of 24 000 km^2 (Fig. 1). The plutons show a broad compositional range from trondhjemites to syenites (Anhaeusser and Robb, 1983), but the most common rock types are granodiorites, monzogranites and syenogranites, collectively referred to as the GMS suite (Yearron, 2003). Geochemically, the batholiths are medium to high potassium, calc-alkaline, metaluminous to slightly peraluminous I-type granitoids (Hunter, 1973; Anhaeusser and Robb, 1983; Anhaeusser et al., 1983; Robb et al., 1983; Yearron, 2003). In outcrop the batholiths have thin (<1000 m), generally tabular geometries, and based on textural characteristics and the low-grades of metamorphism recorded in e.g. the adjacent Barberton greenstone belt, relatively shallow (<5 km) emplacement levels are suggested (Hunter, 1973; Anhaeusser et al., 1983; Robb et al., 1983). Internal contacts between different intrusive phases reveal an overall sheeted architecture. Granite sheeting is particularly well developed along the margins of the batholiths, consisting of a multitude of compositionally distinct, subvertical and/or shallowly dipping sheets. These up to several km-wide sheeted margins surround a core of more massive granitoids (Anhaeusser et al., 1983; Westraat et al., 2005; Belcher and Kisters, 2006).

Available age data indicate that the composite GMS batholiths have intruded over a time span of approximately 15 Ma between ca. 3100 and 3115 Ma (Kamo and Davis, 1994; Westraat et al., 2005). Traditionally, the 3.1 Ga granitoids have either been interpreted as having intruded into an extensional and/or transtensional setting (De Ronde and De Wit, 1994; Kamo and Davis, 1994) or forming anorogenic granitoids emplaced after the tectonic assembly of the Barberton granitoid-greenstone terrain (e.g. Anhaeusser et al., 1983). More recent structural work has highlighted the presence of pervasive magmatic- and solid-state fabrics, synmagmatic shear zones and the progressive deformation of the granitoids of the GMS suite (Westraat et al., 2005; Belcher and Kisters, 2006), first described by Jackson and Robertson (1983). The fabric development, orientation and kinematics of the synmagmatic shear zones, and folding and/or boudinage of intrusive phases all point to the emplacement of the GMS suite during regional NW-SE subhorizontal contraction (Belcher and Kisters, 2006). Both the intrusive ages and synmagmatic deformation of the batholiths show that the GMS suite plutonism was concurrent with the last phase (D3; 3126–3084 Ma, De Ronde et al., 1991) of regional NW-SE shortening and associated folding and thrusting documented in the Barberton greenstone belt (De Ronde and De Wit, 1994; Kamo and Davis, 1994).

3. Heerenveen batholith

The Heerenveen batholith is exposed as an elongate, approximately 30 km long and 15 km wide, NNE-SSW orientated body along the main eastern escarpment in South Africa that offers a topographic relief of some 600 m. The granitoids are intrusive into older 3225–3450 Ma TTG gneisses and supracrustal greenstones that underwent regional deformation and mid-amphibolite facies metamorphism at ca.

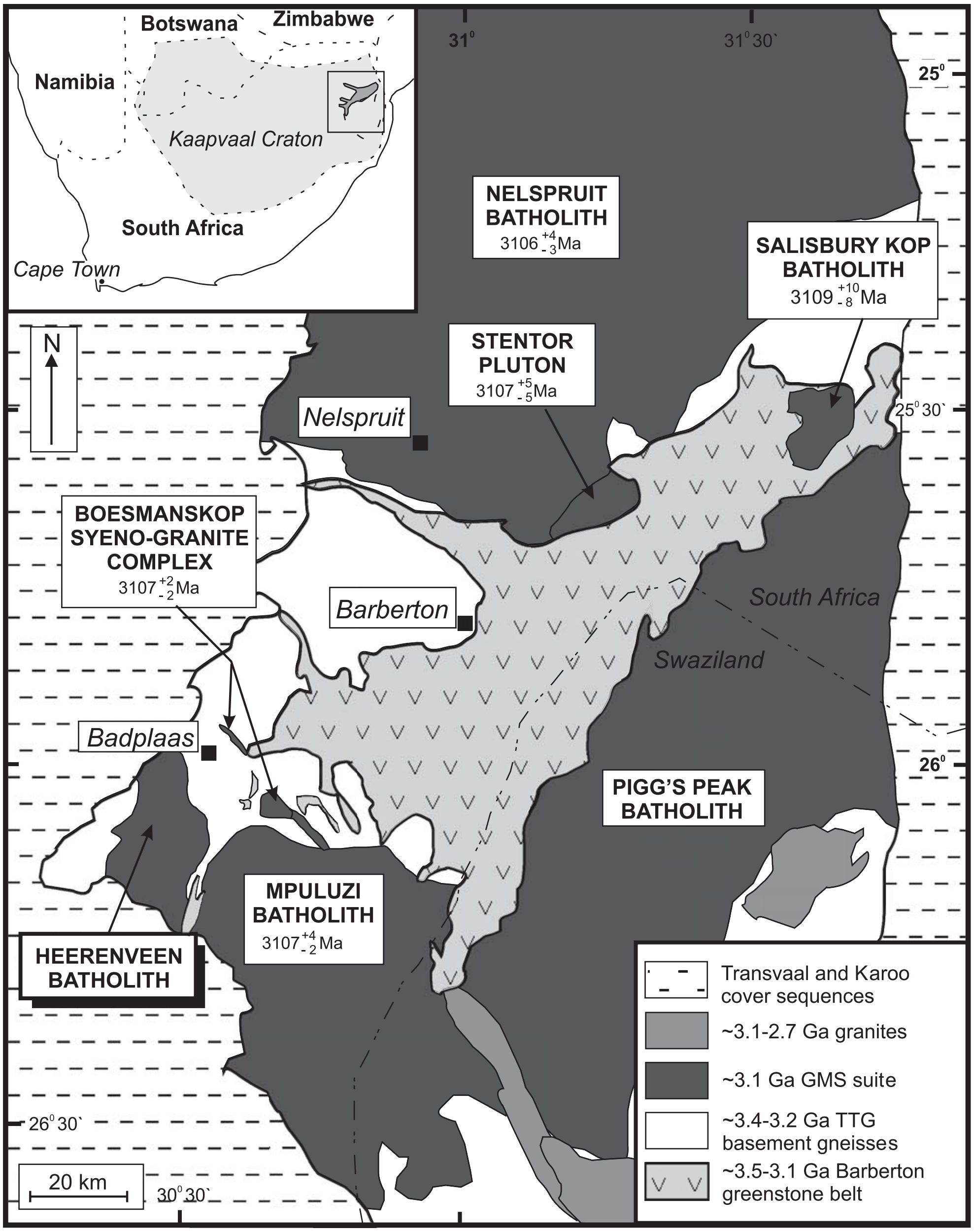

Fig. 1. Simplified geological map of the Mesoarchean Barberton granitoid-greenstone terrain (after Anhaeusser et al., 1981) showing the distribution of intrusives of the 3.1 Ga granodiorite–monzonite–syenogranite (GMS) suite. Age data for the GMS suite plutons are from Kamo and Davis (1994). Inset: location of the Barberton granitoid-greenstone terrain on the Archean Kaapvaal Craton in southern Africa.

3225 Ma (Stevens et al., 2002). The northern and southern extents of the Heerenveen batholith are concealed by younger cover sequences. The roof rocks of the pluton are nowhere exposed, while the floor of the pluton is locally transected along the eastern and southeastern margins of the Heerenveen batholith, exposing shallowly dipping gneisses of the Badplaas basement. In the west, the Heerenveen batholith is intrusive into E-trending subvertical TTG gneisses and minor amphibolitic remnants of the older, trondhjemitic Rooihoogte basement. Within 1–2 km of this contact, the basement gneisses are rotated into parallelism with the curvilinear western margin of the batholith (Fig. 2). This contact and the transition from country-rock gneisses via sheeted granites and intrusive breccias into more homogeneous, central granites occur over a 500–1500 m wide zone. The eastern margin of the batholith consists of a several km-wide zone in which a multitude of m-wide granitoid sheets intrude the shallow SE-dipping gneisses in a lit-par-lit fashion (Fig. 3). This zone corresponds to the ''marginal migmatite zone'' originally mapped by Anhaeusser et al. (1981) and Anhaeusser and Robb (1983). An exception to this rather gradational contact occurs in the SE, where the granitoids abut sharply against the subvertical NE-trending Schapenburg schist belt (Anhaeusser, 1983; Stevens et al., 2002).

Several texturally and mineralogically distinct phases are recognized in the Heerenveen batholith, each of which has characteristic internal geometries and fabrics (Table 1). Four main intrusive phases can be distinguished that, based on

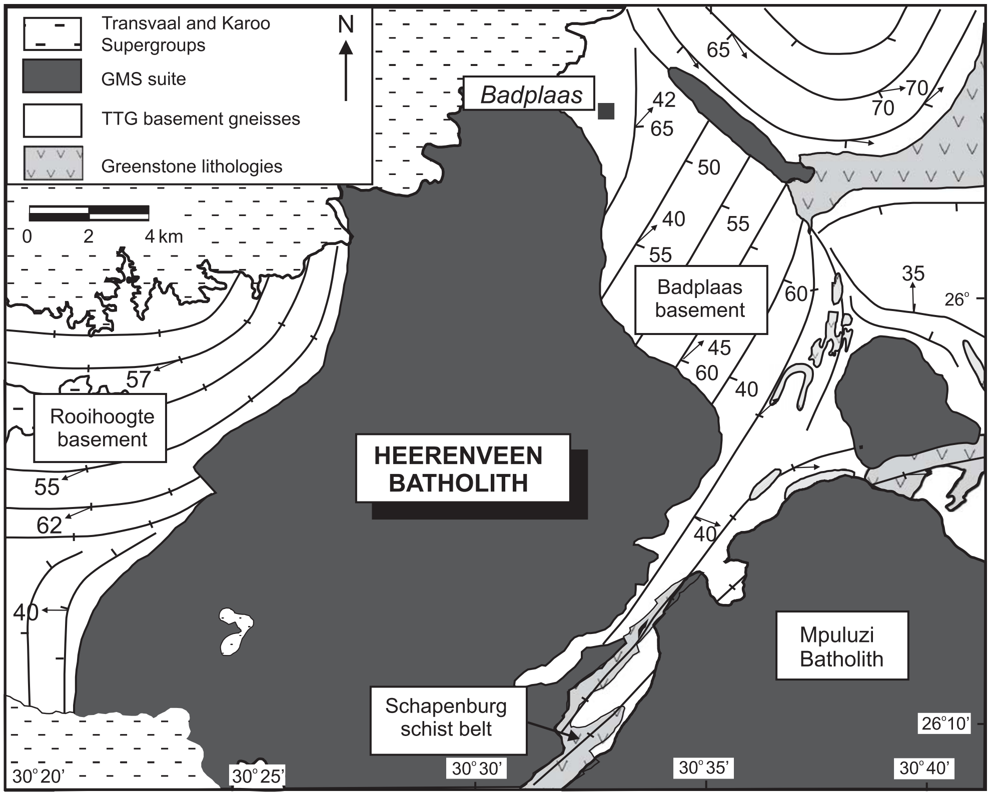

Fig. 2. Simplified geological map of the Heerenveen batholith intrusive into older basement granitoids and supracrustal greenstones. The northern and southern contacts of the Heerenveen batholith are unconformably overlain by rocks of the Paleoproterozoic Transvaal Supergroup in the north and the Phanerozoic Karoo Supergroup in the south. Form lines show the general trend and dips of the basement gneissosity and stretching lineations.

cross-cutting and fabric relationships, appear to have succeeded each other (Figs. 3 and 4). The first three phases contain only locally developed magmatic, but pervasive solid-state fabrics with regionally consistent ENE- to N-trends, indicating the syntectonic timing of these granitoids. The last granite phases cross-cut all earlier granitoids and are devoid of solid-state fabrics. The classification of the fabrics present within the Heerenveen batholith into magmatic and solid-state fabrics is based on the criteria outlined by Paterson et al. (1989) and described in greater detail in Belcher and Kisters (2006). The magmatic fabric in the Heerenveen batholith is defined by the preferred alignment of euhedral tabular K-feldspar megacrysts and is interpreted to signify the re-orientation and alignment of phenocrysts normal to the principal shortening direction during cooling and crystallization of the crystal mush, but with melt still present in the system (e.g. Paterson et al., 1998; Benn et al., 2001). The solid-state foliation is defined by the plastic deformation and elongation of minerals normal to the principal shortening direction after cooling and crystallization below the solidus (e.g. Paterson et al., 1989).

The four main stages include (from old to young): (1) sheet-like granitoids forming m-scale lit-par-lit injections into the shallowly dipping basement gneisses, best preserved along the eastern margin of the Heerenveen batholith. This shallowly dipping sheeted complex, henceforth referred to as the eastern lit-par-lit complex, can be traced for over 20 km along strike (Fig. 3); (2) relatively homogeneous, commonly megacrystic granites. These granites form the volumetrically dominant phases in the central parts of the batholith; (3) several 100 m to 2 km wide, ENE- to N-trending linear belts made up of highly strained, subvertical sheeted granites that bound the central megacrystic granites in the east and west. These belts are compositionally the most heterogeneous zones within the batholith and (4) late-to post-tectonic sheets and/or plug-like, pink to grey homogeneous granites, mainly restricted to the SE parts of the batholith.

The spatial distribution, internal architecture and fabrics within the four main phases are described below.

3.1. Eastern lit-par-lit complex

The eastern lit-par-lit complex is composed of leucogranites, pegmatites, and aplites. It represents the earliest recognized intrusive phase of the batholith being intruded by the homogeneous, megacrystic phases of the central Heerenveen batholith in the northeast and bound and cross-cut by subvertical sheeted granites in the west (Fig. 3). The complex is best preserved along the eastern margin of the batholith where the granitoids intrude as foliation-parallel, cm- to m-wide sheets parallel to the shallow to moderate SE dipping (25–45°) gneissosity of the banded TTG country-rock gneisses (Table 1). A similar complex is not developed along the western margin of the batholith where the granitoids intrude subvertical basement gneisses (Fig. 4). The eastern lit-par-lit complex is a between 1 and 6 km wide zone and is exposed over a vertical

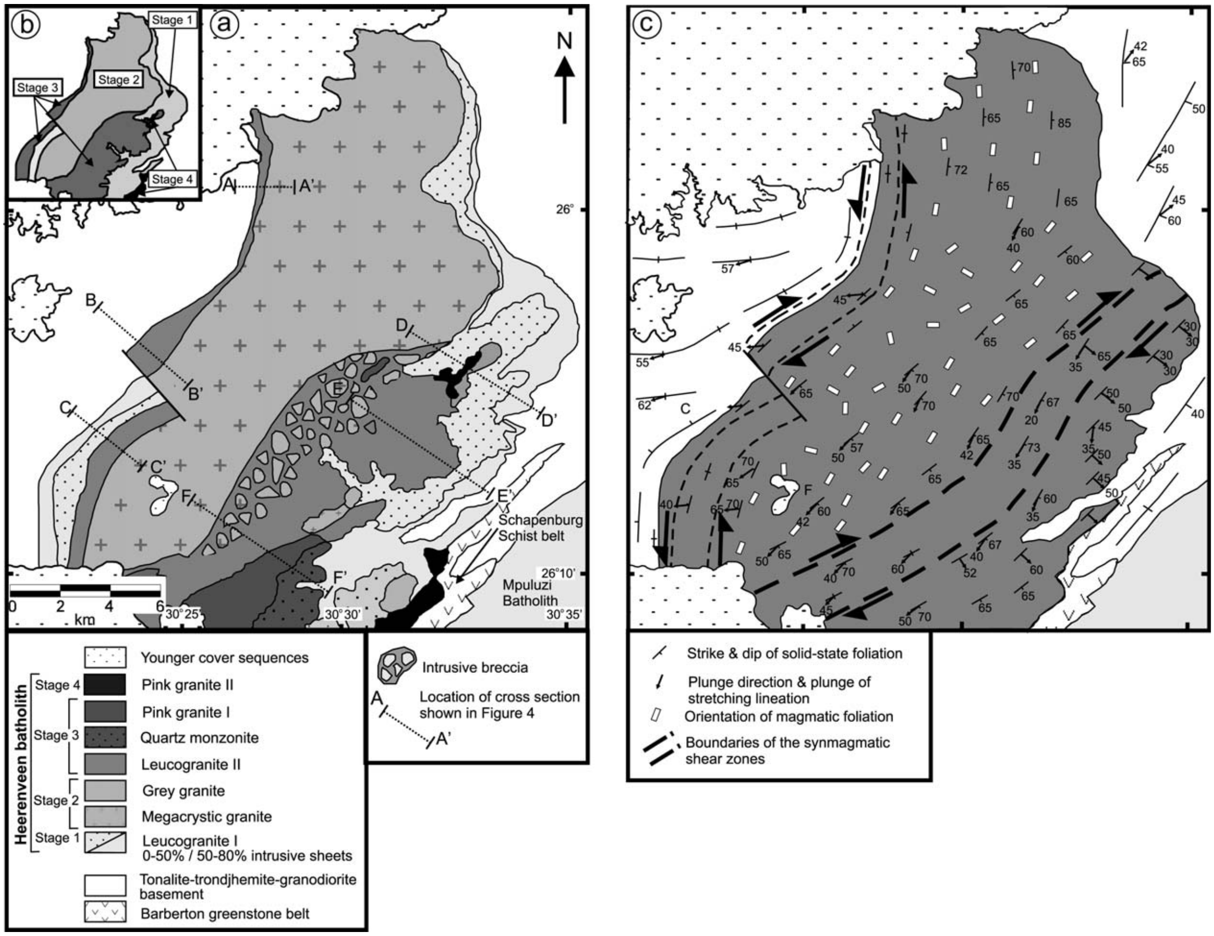

Fig. 3. Geological map of the Heerenveen batholith showing: (a) The main intrusive phases and their distribution, reflecting the overall zonation of the batholith, consisting of a central core of relatively homogeneous megacrystic granite, bound by compositionally heterogeneous marginal zones. (b) The four assembly stages (stage 1 – oldest, to stage 4 – youngest) based on mainly cross-cutting relationships, but also fabric development and internal geometry. The correlation between the compositionally different phases and their timing is detailed in Table 1. (c) The distribution of magmatic and solid-state fabrics in the batholith and gneissosities in the surrounding basement. Note the magmatic foliation in the central, homogeneous megacrystic granite and the solid-state foliation and associated lineation in the surrounding granites. The margin of the central megacrystic granites is bound by two synmagmatic shear zones and corresponds to the zones of heterogeneous granite sheeting.

extent of ca. 350 m showing a crude vertical, internal zonation. The base of the complex is characterized by isolated sheets (1–2 cm and up to 2 m thick) that intrude parallel to the shallowly dipping gneissosity and compositional banding of the TTG gneisses (Fig. 5a). This basal zone can be traced for over 20 km at approximately the same elevation along the eastern margin of the Heerenveen batholith. At this structural level, intrusive sheets constitute between ca. 5 and 25% of the outcrop. Most of the sheets are pegmatitic with up to 10 cm large, euhedral K-feldspar crystals intergrown with quartz and minor muscovite. Fine-grained aplites are also common, while leucogranitic sheets are rare. At higher structural levels, within ca. 100 m from the basal zone, granitic sheets become more abundant and may constitute 50–60% of the outcrop. The dm- to m-wide sheets form a branching and coalescing network of foliation-parallel sills and cross-cutting low-angle sheets that engulf rafts of the TTG basement (Fig. 5b). Fine- to medium-grained leucogranites increase in abundance, while pegmatites become subordinate. At the highest structural levels exposed, within ca. 250 m from the basal zone, granitic sheets dominate and constitute >80% of the outcrop. Significantly, isolated country-rock screens between the intrusive granitoids retain their shallow SE dips with only little evidence of rotation compared to country-rock gneisses outside the eastern lit-par-lit complex.

The shallowly dipping granitoid sheets contain a well developed, sheet-parallel, high-temperature, solid-state foliation, particularly in the lower parts of the lit-par-lit complex, defined by the grain-shape preferred orientation of quartz and quartz–feldspar aggregates and the orientation of phyllosilicates, mainly muscovite. Associated with the gneissosity is a down-dip lineation defined by stretched quartz- and quartz–feldspar aggregates and muscovite. Both the solid-state foliation and stretching lineation in the intrusive sheets are parallel to the planar and linear fabrics of the older country-rock gneisses (Figs. 3c and 6a, b). It is clear that, on a regional scale, the country-rock gneisses have acquired their fabric during the main phase of tectonism in the granitoid-greenstone terrain at ca. 3230 Ga (Dziggel et al., 2002; Stevens et al., 2002). This suggests an almost coaxial overprint of these older

Table 1
Summary of the main granite intrusive phases that compose the Heerenveen batholith

	Phases	Occurrence	Age relationships
Stage 4	Pink granite II	Randomly orientated sheets and plug-like bodies	Undeformed (post-tectonic) cross-cutting pink granite I, leucogranite I (centre) and TTG basement (southeast)
Stage 3	Granodioritic dykes (not on Fig. 3)	Predominantly intruded as a series of sheets confined to within the synmagmatic shear zones	High-temperature solid-state gneissosity (syntectonic). Co-magmatic with pink granite I
	Quartz monzonite	Predominantly intruded as a series of sheets confined to within the synmagmatic shear zones	High-temperature solid-state gneissosity (syntectonic). Co-magmatic with pink granite I
	Pink granite I	Predominantly intruded as a series of sheets confined to within the synmagmatic shear zones	Within the shear zones: high-temperature solid-state gneissosity (syntectonic). Randomly orientated intrusions: weak foliation to undeformed (late- to post-tectonic). Both styles intrude into the megacrystic granite and TTG basement
	Leucogranite II	Intruded as a series of sheets within and along the margins of the synmagmatic shear zones	High-temperature solid-state gneissosity. Intrudes into the megacrystic granite and TTG basement
Stage 2	Grey granite	Limited outcroppings in south-central parts of the batholith	Well-developed solid-state gneissosity (syntechtonic). Intruded by the leucogranite, pink granite and quartz monzonite (stage 3). Co-magmatic with megacrystic granite
	Megacrystic granite	Volumetrically the dominant phase forming a large central homogeneous body	Magmatic foliation superimposed by high-temperature solid-state foliation (syntectonic). Intruded by the leucogranite and pink granite (stage 3) along margins of the phase
Stage 1	Leucogranite I	Lit-par-lit intrusion of sheets and dykes found predominantly along the eastern margin of the batholith	Strong solid-state gneissosity. Intrudes into underlying TTG basement. Intruded and crosscut by the megacrystic granite

Based on their relative age relationships and distinct emplacement styles the granites can be subdivided into four emplacement stages, as discussed in the text.

fabrics by 3.1 Ga fabrics recorded in the younger granitoid sheets.

3.2. Central, megacrystic granites

The central parts of the Heerenveen batholith are made up of relatively homogeneous K-feldspar megacryst-bearing granitoids that underlie an area of ca. 200 km^2 forming the volumetrically dominant phases of the pluton (Fig. 3a). The megacrystic granites are bounded and intruded by subvertical granite sheets along their western and eastern margins, but are intrusive into the eastern lit-par-lit complex (Fig. 4). Quartz, K-feldspar, and plagioclase are the main components of the mainly leucocratic granites with accessory amounts of muscovite, biotite, chlorite, apatite and zircon. The commonly euhedral and tabular-shaped K-feldspar megacrysts reach lengths of up to 7 cm and show magmatic zoning. In places, quartz forms rounded, up to 2 cm large, interstitial aggregates that result in a distinct studded weathering pattern of the rocks. The K-feldspar megacrysts may either occur sporadically, as evenly distributed phenocrysts, as irregularly shaped clusters, or as trains of closely packed phenocryst aggregates. Transitions between megacryst-rich and megacryst-poor zones are commonly gradational and intrusive relationships within the megacrystic granitoids are only rarely observed. As such, contacts between different phases are cryptic or non-existent so that the internal geometry and architecture of the central granites remains unclear. A fine- to medium-grained, but volumetrically subordinate homogeneous grey granite phase is intrusive into the megacrystic granitoids, particularly in the southern parts of the batholith. The only other intrusions are cm- to m-wide leucogranite and pegmatite dykes that intrude both the grey and megacrystic granitoids. The mainly subvertical dykes show predominantly N- (350–035°) or ENE- (050–090°) trends. Subhorizontal leucogranite sheets also occur, but are volumetrically subordinate (Belcher and Kisters, 2006). The floor of the central megacrystic granitoids is not exposed. However, basement gneisses exhibiting subhorizontal lithological and structural layering occurring along the eastern margin of the granitoids may indicate the continuation of the shallowly dipping basement gneisses from the east and below the central parts of the Heerenveen batholith.

Closely packed feldspar megacrysts locally occur in cm- to dm-wide bands that can be traced for several tens of metres, outcrop permitting, defining a magmatic layering (Fig. 5c). This layering is commonly steep and shows consistent (E)NE trends across the central parts of the batholith (Figs. 3c and 6c). A magmatic foliation is regionally developed although it is relatively weak to absent in the central parts of the megacrystic granitoids (Fig. 5d). The foliation is defined by the preferred orientation of tabular feldspar megacrysts, showing (E)NE trends in the southern and central parts of the megacrystic granitoids, assuming more N-trends in the north (Belcher and Kisters, 2006). The magmatic foliation dips steeply to the SE and E. A high-temperature solid-state foliation is subparallel to the magmatic foliation. The solid-state foliation is defined by elongate quartz-grain aggregates, the grain-shape preferred orientation of quartz–feldspar aggregates and the preferred orientation of phyllosilicates. Cross-cutting pegmatite and aplite dykes are symmetrically folded about the NE-trending fabric, indicating deformation during mainly coaxial shortening (Belcher and Kisters,

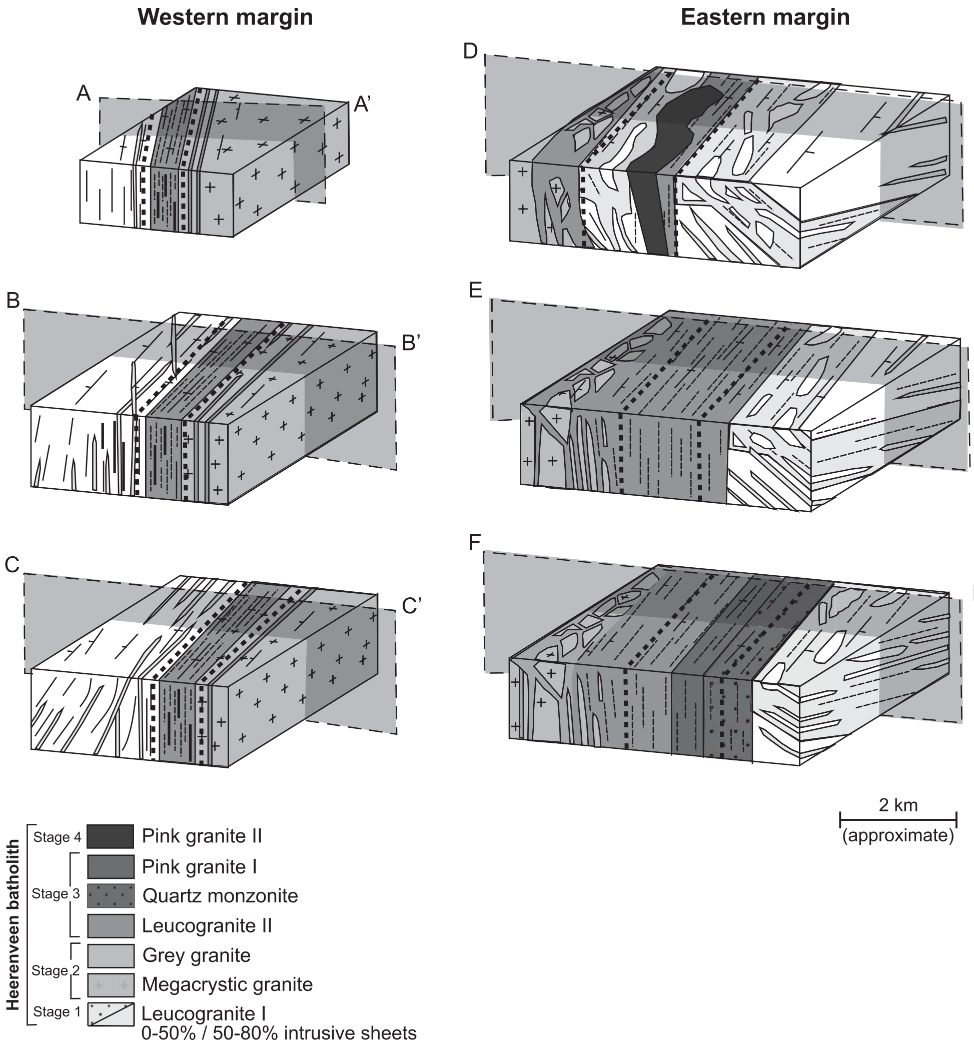

Fig. 4. Simplified cross-sections of the western and eastern margins of the Heerenveen batholith highlighting the characteristic asymmetry of the intrusive phases of the batholith shown in Fig. 3a.

2006). This solid-state foliation records a gradual increase in strain intensity towards the western and, in particular, the eastern margin of the megacrystic granitoids. The higher fabric intensities are manifested by quartz ribbons and the formation of a pervasive gneissosity that grades into protomylonitic textures. These highly strained textures along the margins of the central megacrystic granitoids are associated with a distinct change in intrusive style, and the homogeneous granitoids are intruded and bounded by subvertical granite sheets.

3.3. Subvertical sheeted granites: synmagmatic shear zones

Two ENE- to N-trending, curvilinear belts of subvertical sheeted granites bound the eastern and western margins of the megacrystic granitoids. These sheeted domains can be followed for over 25 km along strike ranging from ca. 500 m to 2–3 km in width (Fig. 3a).

The most characteristic feature of these zones is the abundance of subvertical, mainly ENE-trending granite sheets (Fig. 6f). Individual sheets range in width from several cm to >10 m and can be followed along strike for >100 m, outcrop permitting. Multiple sheet-in-sheet intrusions are common, indicated by low-angle intrusive contact relationships (Fig. 7). Given the width of the subvertical sheeted domains of up to 2 km, probably several hundred sheeting events are recorded within these domains. Northerly striking granite sheets are confined to the northern and southern extents of the western margin of the Heerenveen batholith (Belcher and Kisters, 2006). Sheet-in-sheet intrusive contacts range from being sharp to gradational, probably reflecting the relative time gap between the full crystallization of earlier sheets and the intrusion of subsequent magma batches. The domains of subvertical granite sheeting are compositionally the most heterogeneous zones within the Heerenveen batholith. Fine- to medium-grained leucogranites are most common. Other phases are, in decreasing order of abundance, pegmatites, fine-grained, pink granites, quartz monzonites, megacrystic granites and greyish granodiorites and diorites (Table 1, Fig. 3a). Along the southern extent of the eastern sheeted domain, the steeply dipping sheets envelop large rafts of banded, subhorizontal basement gneisses. The basement gneisses are gently folded

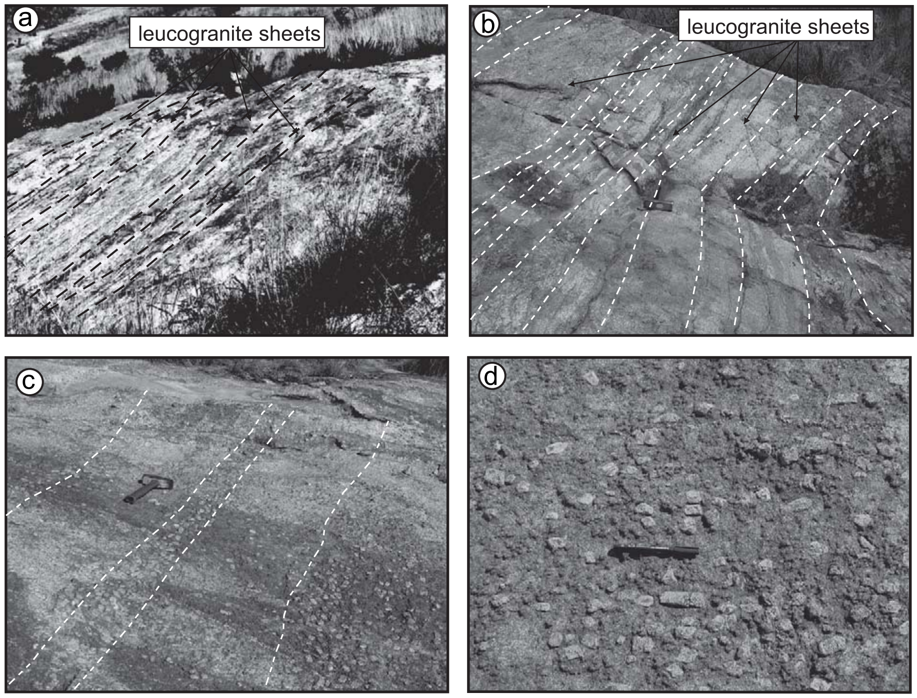

Fig. 5. Photographs of field relationships between intrusive phases of the Heerenveen batholith showing: (a) and (b) Lit-par-lit intrusion of leucogranite and pegmatite sheets along the shallow dipping gneissosity of the TTG basement in the east of the Heerenveen batholith forming the eastern lit-par-lit complex. (c) Plan view of the NE-trending magmatic layering defined by variations in the number of K-feldspar megacrysts within the central megacrystic granites. (d) ENE-trending, steeply dipping magmatic foliation defined by the preferred orientation of tabular cm-long K-feldspar megacrysts from the central megacrystic granites.

into upright, NE- to N-trending, subhorizontal folds so that the intrusive sheets have an axial planar orientation with respect to the folds.

The second characteristic feature of these domains is the development of pervasive solid-state fabrics, parallel to subparallel to the sheet margins (Fig. 6e, f). The fabric comprises a high-temperature solid-state foliation and lineation. The foliation is defined by quartz ribbons that alternate with recrystallised quartz–feldspar domains, locally resulting in the formation of banded gneisses. Where present, the preferred orientation of mica accentuates the foliation. Protomylonitic and mylonitic fabrics are common and quartz ribbons may show axial ratios of >20:1 in horizontal sections. Significantly, the sheet-parallel gneissosity of earlier sheets is truncated by subsequent sheets that intrude at low angles (Fig. 7c, d) indicating the synmagmatic timing of fabric development. Large K-feldspar phenocrysts are marginally recrystallised and form augen-shaped mantled porphyroclasts (Fig. 8a, b). The feldspar megacrysts also undergo brittle deformation shown by large bookshelf-type clasts that are transected by microfaults with quartz in the strain shadows. Intrusive sheets may also be folded into m-scale intrafolial, isoclinal folds, indicating progressive layer transposition (Fig. 8c). Stretching lineations are defined by elongated quartz- and quartz–feldspar aggregates. The plunge of the stretching lineations ranges from subhorizontal to subvertical even within individual sheets. The fabric intensity recorded in individual sheets by e.g. the aspect ratios of quartz ribbons or the degree of recrystallisation and grain-refinement is highly variable. It is not uncommon to find intrusive sheets with considerably higher strain intensities compared to the wall-rocks or older sheets they intrude into (Fig. 8d). This is a common feature also observed in other batholiths of the GMS suite (Jackson and Robertson, 1983; Westraat et al., 2005), indicating the strain localization into the intrusive sheets. Since the high-strain textures are defined by solid-state fabrics, strain localization must have continued during the early stages of subsolidus cooling of the sheets. The features described above underline the syntectonic emplacement of the granite sheets and the positive feedback between deformation and melt-bearing zones (Brown and Solar, 1998; Vigneresse and Tikoff, 1999). This led Belcher and Kisters (2006) to suggest that the linear belts of subvertical sheeted granites represent synmagmatic shear zones. Notably, the high-strain fabrics of the synmagmatic shear zones are not developed outside the confines of the Heerenveen batholith (Fig. 3c).

Non-coaxial fabrics and shear-sense indicators are common and include σ-type clasts, and S-C and S-C′ fabrics as well as bookshelf-structures in fractured feldspar megacrysts, particularly common in pegmatitic sheets. In the ENE-trending subvertical sheeted complexes, predominantly dextral strike-slip kinematics are recorded. However, sinistral shear-sense indicators are also observed and may occur in close spatial association with dextral strike-slip indicators. The N-trending segments along the western sheeted margin, in contrast, show mainly sinistral strike-slip. As such, the ENE- and N-trending belts form a conjugate set of synmagmatic shear zones (Belcher and Kisters, 2006). Shear-sense indicators are only observed on horizontal or near-horizontal sections, irrespective of the plunge of the stretching lineations, which suggest that the

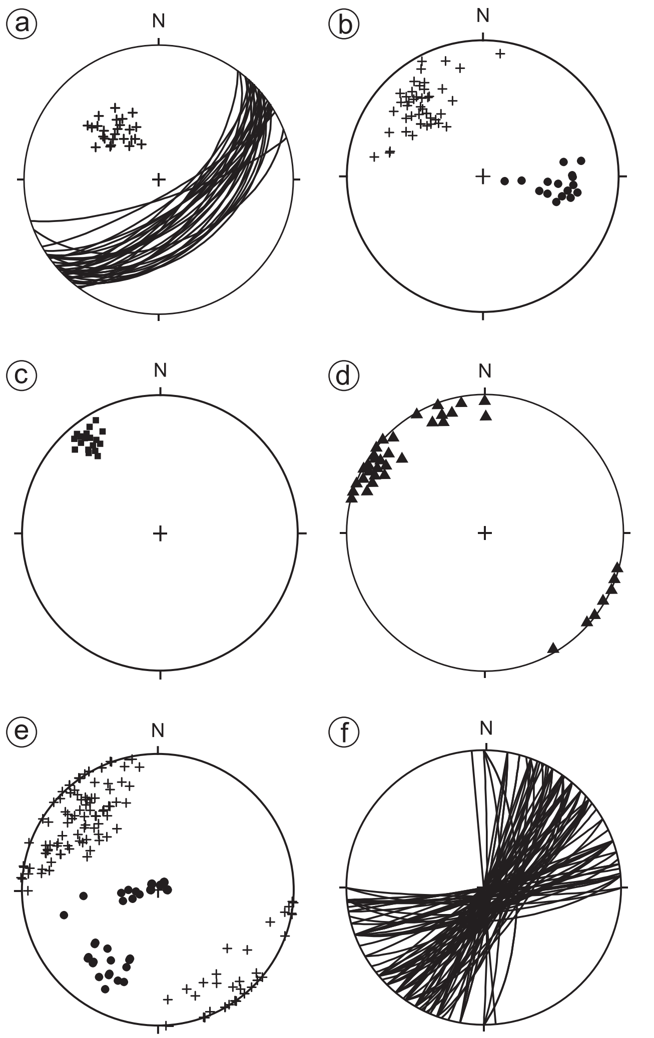

Fig. 6. Lower hemisphere, equal area projections of the orientation of intrusive and/or structural elements discussed in the text. (a) Great circles ($n = 23$) to the sills of the eastern lit-par-lit complex and poles to the gneissosity (crosses, $n = 29$) of the basement along the eastern margin of the Heerenveen batholith. (b) Poles to high-temperature solid-state foliation (crosses, $n = 67$) and mineral stretching lineation (dots, $n = 18$) within leucogranite and aplite sheets of the eastern lit-par-lit complex (stage 1) illustrating the shallow and sheet-parallel dip of the foliation, parallel to the basement gneissosity. (c) Poles (squares, $n = 17$) to magmatic layering of the central megacrystic granites (stage 2) illustrating the preferred NE trend. (d) Poles (triangles, $n = 43$) to the magmatic foliation of the central megacrystic granites (stage 2) mainly defined by the preferred orientation of euhedral K-feldspar megacrysts. (e) Poles to the high-temperature solid-state foliation in megacrystic granites (stage 2) and the bounding synmagmatic shear zone associated sheeted margins (stage 3) (crosses, $n = 98$). Dots ($n = 30$) illustrate the considerable scatter of mineral stretching lineations in the synmagmatic shear zones. (f) Great circles ($n = 103$) to intrusive sheets from the subvertical synmagmatic shear zones.

high-strain zones are transpressional shear zones. The conjugate orientation and shear sense are consistent with the subhorizontal, NW-SE directed shortening strain during the emplacement of the Heerenveen batholith.

The contacts between the subvertical sheeted domains and the central megacrystic granites are developed as intrusive breccias. These breccia zones are up to 4 km wide, such as along the contacts between the central granites and the eastern sheeted domain (Fig. 3a). The breccias are composed of dm- to m-scale, angular fragments of megacrystic granites intruded by subvertical leucogranite and granite sheets. The intrusive sheets still show mainly ENE trends (parallel to those in the synmagmatic shear zones) forming a network of branching and coalescing dykes (Fig. 8e). Locally, intrusive stockworks are developed. Up to six separate intrusive phases and brecciation events can be identified on individual pavements, testifying to the multiple intrusive relationships. Both the intrusive granites as well as the fragments of megacrystic granites contain the regionally developed ENE-trending solid-state gneissosity, although at lower strain intensities compared to the subvertical sheeted granites, also suggesting very little rotation of the fragments during brecciation.

3.4. Post-kinematic granitoids

Post-kinematic granitoids truncate all earlier phases and are devoid of any macroscopic fabrics. The mainly fine- to medium-grained, pink to greyish granitoids are confined to the SE and E margin of the batholith (Fig. 3). In the SE, the granitoids abut sharply against the steeply dipping, NE-trending supracrustal Schapenburg schist belt that is made up of amphibolites, ultramafic talc-carbonate schists, serpentinites and minor metasediments. In the eastern exposures, the pink granitoids intrude the subvertical sheeted granite complex as seemingly randomly orientated sheets and plug-like bodies. They sharply truncate the earlier fabrics and large, rotated rafts within the pink granitoids show the typical sheeted nature and penetrative gneissosities characteristic for the marginal synmagmatic shear zones (Fig. 8f).

4. Discussion

Two main features are pertinent for an understanding of the assembly and emplacement controls of the Heerenveen batholith. Firstly, the Heerenveen batholith was assembled through episodically emplaced magma batches, and at least four main geometrically distinct intrusive stages can be identified. Two of these show well-preserved sheeted geometries (stages 1 and 3). Cross-cutting relationships in these sheeted domains record a multitude of sheeting events documenting the continued addition of melt to the batholith. Secondly, magmatic and solid-state fabrics in the composite pluton point to its emplacement during regional NW-SE directed subhorizontal shortening (Belcher and Kisters, 2006). The penetrative fabrics formed during crystallization of the different magma batches and continued to develop during the early stages of subsolidus cooling. On a regional scale, the fabrics in the batholith correspond to the NE trend of folds and thrusts in the Barberton greenstone belt having formed during the D3 tectonism at ca. 3.1 Ga (e.g. De Ronde and De Wit, 1994; Kamo and Davis, 1994). This underlines the regional extent of crustal shortening and the syntectonic emplacement of the Heerenveen batholith. The following discussion is presented with respect to the above background.

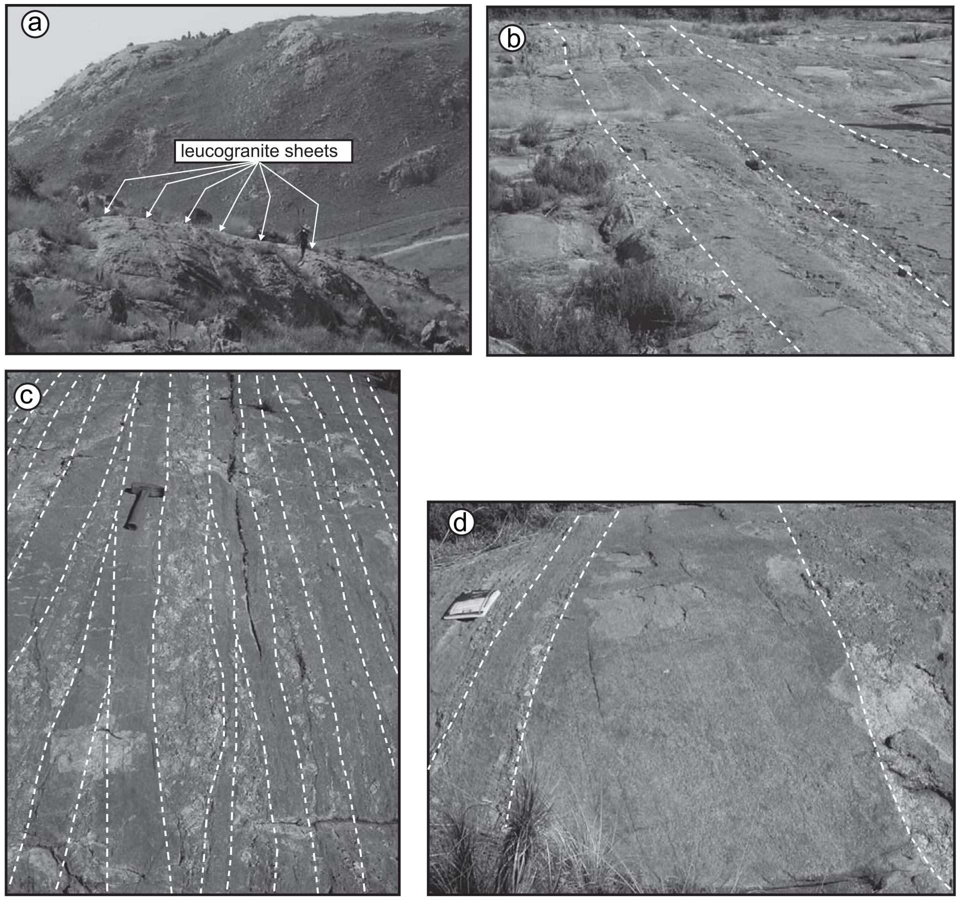

Fig. 7. Photographs of field relationships between different intrusive phases of the Heerenveen batholith showing: (a) Whaleback outcrops, in the foreground, containing m-wide, steep easterly dipping sheets along the western margin of the Heerenveen batholith. The zone of sheeted granites along the western margin of the Heerenveen batholith is up to 500 m wide, building up much of the seemingly massive granite slopes in the background. Field of view is ca. 30 m wide in the foreground, looking towards north. (b) Heterogeneous zone of subvertical sheeted granites along the eastern margin of the central megacrystic granites. Sheets are between 5 cm and 2 m wide and are continuous along strike across the outcrops for up to 200 m. Field of view ca. 15 m (foreground). (c) Centimetre-scale, NE-trending granite and pegmatite sheets from the eastern subvertical sheeted margin (plan view). Low-angle cross-cutting relationships are common, testifying to the multiple intrusion of the granitoid sheets; sheet margins are annotated for clarity. All sheets contain a pervasive solid-state foliation, subparallel to the sheet margins. (d) Oblique plan view of the low-angle cross-cutting relationships between a foliated medium-grained leucogranite (centre of the photograph) and later, medium-to coarse-grained, foliated granites bounding the central leucogranite; sheet margins annotated for clarity; A5 notebook for scale. This feature is common throughout the sheeted margins and can be followed in outcrops for several hundred metres.

4.1. The progressive development of emplacement controls

The emplacement of the sills of the early lit-par-lit complex (stage 1) was determined by the gneissosity and lithological banding of the TTG basement gneisses, suggesting that it was mainly differences in the tensile strengths parallel to and across the pre-existing anisotropies that controlled the localization of the sills (e.g. Brisbin, 1986; Lucas and St-Onge, 1995). In their present orientation, the sills and enveloping TTG gneisses show shallow- to moderate-SE dips. It is conceivable that the sills were originally emplaced as subhorizontal sheets, parallel to the then subhorizontal basement foliation, as is locally preserved in the more central parts of the batholith. In this scenario, the sheets intruded along the $\sigma1-\sigma2$ plane during subhorizontal shortening, occupying tensile fractures in addition to being emplaced along the gneissosity (Fig. 9a). The abundance of pegmatites and, as such, the volatile-rich nature of the intruding sheets suggest that the emplacement of the sills was aided by volatile-driven intrusion and wall-rock translation (Weinberg and Searle, 1999). The preservation of the original orientation of basement rafts and screens within the injection complex corroborates the largely non-rotational wall-rock translation during sheet emplacement. During ongoing shortening the initially subhorizontal TTG gneisses and intrusive sills were folded about a NE-trending axis and steepened to moderate (25–45°) SE dips, i.e. into an orientation where maximum shear stresses would be resolved during NW-SE directed, subhorizontal shortening (Fig. 9b). This may explain the formation of the sheet-parallel gneissosities and down-dip stretching lineations in the intrusive sheets that are confined to the sills of the eastern lit-par-lit complex and that are not found in any other phases of the Heerenveen batholith. In summary, both the sheet-like geometry and lit-par-lit style of emplacement argue for a strong control of these earliest intrusive phases by pre-existing wall-rock anisotropies and the orientation of the wall-rock structures with respect to regional strains.

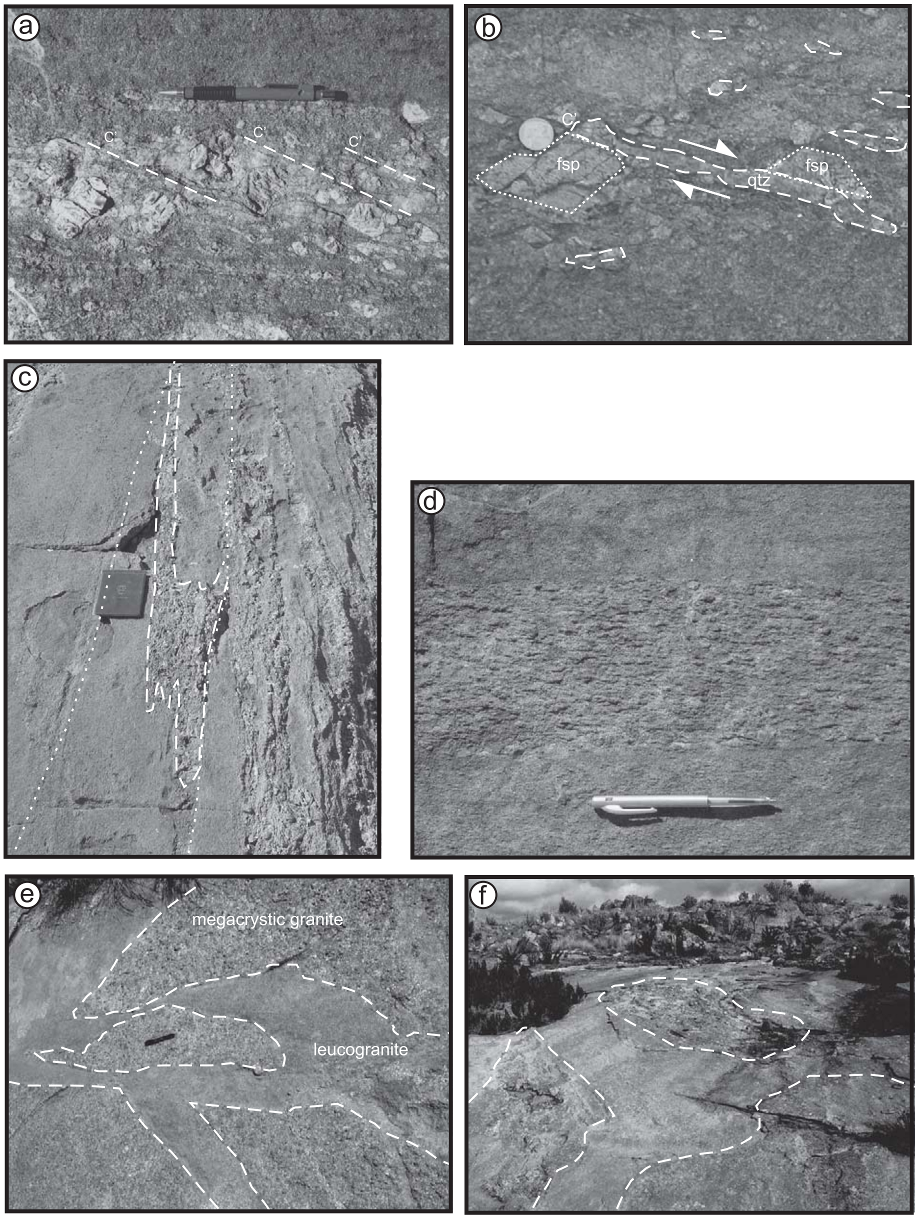

Fig. 8. Photographs of field relationships between different intrusive phases of the Heerenveen batholith showing: (a) Intense marginal recrystallisation of large feldspars separated by quartz ribbons from a pegmatite sheet illustrating the development of high-temperature, high-strain solid-state fabrics in intrusive sheets. Quartz ribbons run at low angles through the sheet delineating C′ planes of a S-C′ fabric, indicating dextral sense of shear (plan view, eastern synmagmatic shear zone). (b) K-feldspar phenocrysts fractured and displaced along a small-scale fault, occupied by a quartz stringer (qtz). The fault has the orientation of a C′ plane indicating dextral sense of shear. Flattened quartz aggregates define a grain-shape preferred orientation (plan view). (c) Isoclinal folding of a pegmatite sheet (centre of photo) within subvertical granite sheets of the eastern bounding synmagmatic shear zone (oblique plan view, A5 notebook for scale). (d) Subvertical sheet-in-sheet intrusion (plan view) from the eastern synmagmatic shear zone. This illustrates the strong, sheet margin-parallel gneissosity defined by positively weathering quartz ribbons (central granite sheet) intruded into a finer-grained leucogranite sheets (bottom and top of photo) and the effects of strain partitioning into the intrusive sheet. (e) Metre-scale intrusive breccia of medium-grained leucogranite intruding coarse-grained megacrystic granite. These breccias are developed over widths of up to 4 km. Both the megacrystic granites (stage 2) and the intruded leucogranite sheets (stage 3) contain a well developed NE-trending gneissosity, running approximately parallel to the top to the photo (oblique plan view, eastern breccia zone, annotations for clarity). (f) Metre-scale rotated rafts of sheeted leucogranites (annotated by dashed lines) and granites (stage 3) intruded by late-stage undeformed pink granites (stage 4) in the northeastern margin of the Heerenveen batholith.

Only little can be deduced about the emplacement controls or even the geometry of the central megacrystic granites, the next younger phases of the Heerenveen batholith (stage 2). Intrusive contacts within the granites and wall-rock relationships are only rarely exposed and the granites are commonly massive in appearance. The parallelism between magmatic and solid-state foliations is not unusual in granite plutons, and has been suggested to represent the transition from magmatic to solid-state flow during the continued cooling and crystallization of the plutons during regional deformation. The presence of melt allows for the rotation of the phenocrysts, without internal or marginal solid-state deformation, while the interlocking crystals of the

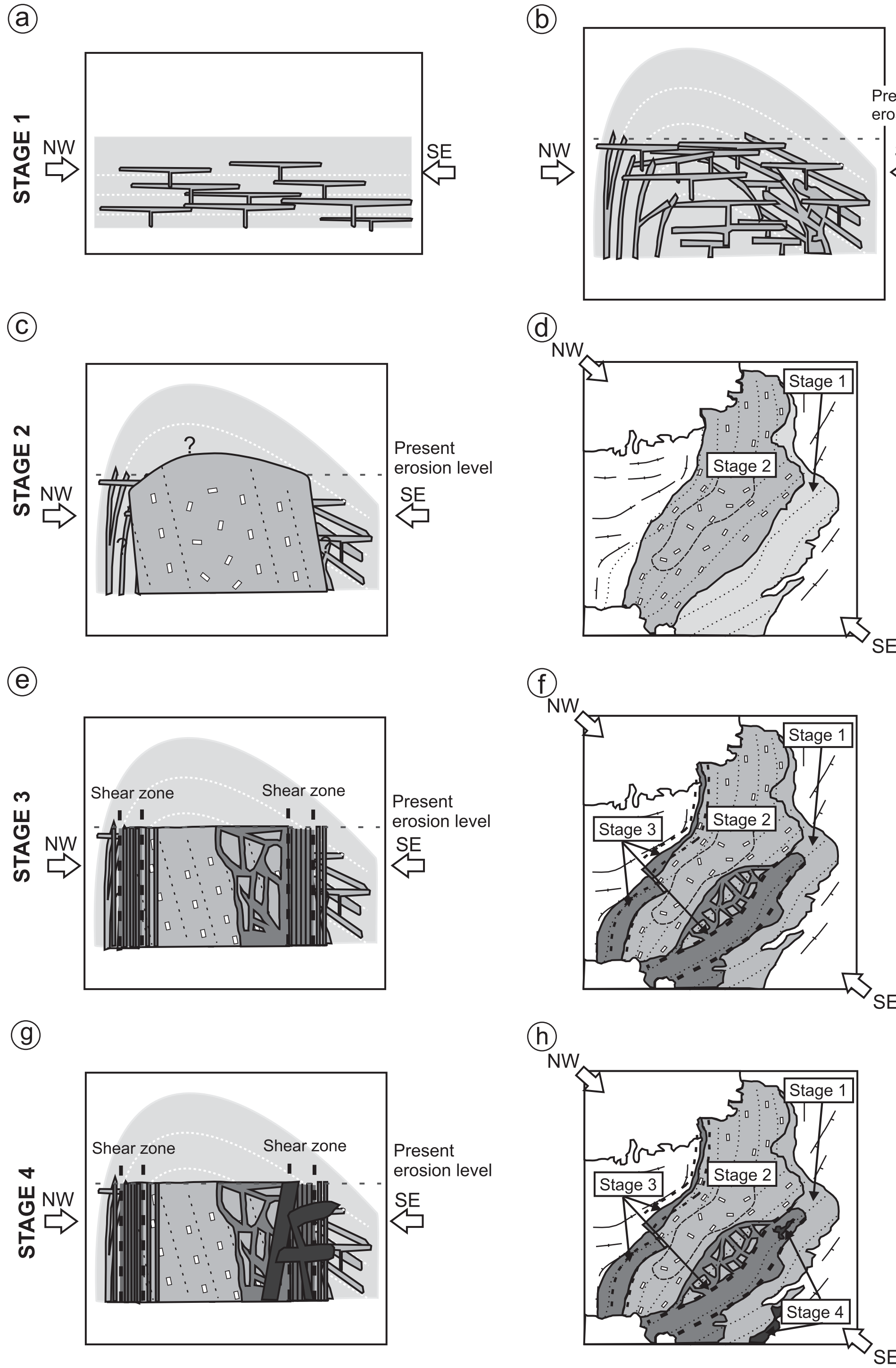

Fig. 9. Schematic diagrams showing the incremental construction of the Heerenveen batholith through the four main intrusive stages outlined in the text: (a) Stage 1: cross-sectional view showing the intrusion of the early leucogranite, aplite and pegmatite sheets along the subhorizontal gneissosity of the TTG basement during subhorizontal NW-SE shortening. The emplacement is controlled by the regional strain and pre-existing wall-rock anisotropies of the basement. (b) Folding of the basement about a NW-SW orientated axis leads to the rotation of the eastern lit-par-lit complex. During this stage, the sills develop the layer-parallel solid-state foliation and down-dip lineation, while low-angle cross-cutting dykes testify to the continued granite sheeting. (c) Stage 2: The formation of the homogeneous central granites as steady-state magma chambers is envisaged to have been facilitated by the thermal ground preparation provided by the earlier lit-par-lit intrusions. (d) Map view showing the central megacrystic granites truncating the wide eastern margin of the eastern lit-par-lit complex. (e) Stage 3: Following the formation of a steady-state magma chamber (stage 2), strain localization and partitioning along the margins of the central magma chamber during the regional NW-SE subhorizontal contraction leads to the initiation and development of the bounding synmagmatic shear zones. This results in the profound change in the construction style of the batholith, from predominantly wall-rock anisotropy controlled emplacement (stage 1) to melt controlled emplacement (stage 3). The shear zones represent melt conduits for melt ascent which fed and inflated the now eroded, higher structural levels of the batholith. (f) Map view of stage 3 showing the temporal and spatial link between the shear zones and the heterogeneous granite sheeting along the margins of the megacrystic granite. (g) Stage 4: The final, post-tectonic stage in the construction of the batholith sees the emplacement of randomly orientated, smaller sheet- and plug-like intrusions. The sharp termination of the late-stage intrusive against wall rocks, suggests an emplacement controlled by pre-existing anisotropies. (h) Map view of stage 4.

crystallizing magma form a load-bearing framework that is sufficiently strong to transmit regional stresses (Vigneresse and Tikoff, 1999). Progressive deformation after full crystallization of the granite then leads to the formation of high-temperature solid-state fabrics (e.g. Paterson et al., 1989). The subvertical orientation of both the magmatic and solid-state foliations throughout the Heerenveen batholith tracking the shortening (*XY*-) plane of the finite strain ellipsoid, is consistent with the emplacement and cooling of the pluton during ongoing subhorizontal shortening (Fig. 9c, d).

The next main stage in the assembly of the Heerenveen batholith (stage 3) is represented by the subvertical sheeted domains along the margins of the central granites, and is associated with striking changes in the emplacement controls of subsequent granite phases (Fig. 9e, f). The discrete, multiple granite sheets contained in the synmagmatic shear zones no longer exhibit any controls by wall-rock anisotropies that have largely determined the emplacement of earlier phases. In contrast, the multiple additions of melts to the marginal zones of batholith points to the significance of earlier magmas for the localization of subsequent melt batches. In other words, at this advanced stage in the assembly of the Heerenveen batholith it is factors intrinsic to the pluton that govern the emplacement of subsequent granite phases, while the influence of external controls, primarily wall-rock anisotropies, becomes subordinate (Fig. 10).

Both experimental and field studies (e.g. Grujic and Mancktelow, 1998; Walte et al., 2005) have documented the nucleation and progressive growth of conjugate shear zones around rheologically weaker melt-bearing zones during coaxial shortening of mixed rock-melt systems. The conjugate sets of non-coaxial shear zones typically surround lower strained pods that record near-coaxial pure shear deformation. This deformation pattern closely mimics the location, conjugate arrangement and kinematics of the bounding synmagmatic shear zones around the central megacrystic granites of the Heerenveen batholith (Belcher and Kisters, 2006). One of the prerequisites for this to occur is that the central megacrystic granites or at least parts thereof, were partially molten for the bounding shear zones to nucleate.

Granite-sheeting in the km-wide synmagmatic shear zones and adjoining breccia zones have contributed to the progressive construction of the Heerenveen batholith. However, the abundance and subvertical orientation of the shear zone-parallel sheets suggest that the synmagmatic shear zones, at their present level of exposure, have most likely represented melt transfer zones and ascent conduits, rather than the final emplacement sites of the granites. Melt transfer and the positive feedback between melt transfer zones and deformation, i.e. shear zones, is a widely documented feature (e.g. Hutton, 1982; McCaffrey, 1992; Brown and Solar, 1998). Recent models for magma transfer in transpressional and contractional shear zones invoke magma overpressuring as the main driving force for melt ascent. Magma overpressuring occurs as a result of the buoyancy of the melt, the increase of vapour pressures during the late stages of melt ascent and tectonic pressures, i.e. deviatoric stresses in actively deforming environments (e.g. Ingram and Hutton, 1994; Hogan and Guilbert, 1995; De Saint-Blanquat et al., 1998). Significantly, the upward movement of melt is facilitated by vertical pressure gradients that are greatest in vertical structures, i.e. structures representing the shortest connection to the free boundary of Earth's surface. Thus, the mainly shallowly dipping basement gneissosity that determined the emplacement and orientation of earlier phases of the Heerenveen batholith had an unfavourable orientation for a buoyancy-driven melt ascent, rather leading to the ponding of magmas along the pre-existing anisotropies. The subvertical synmagmatic shear zones, in contrast, provided favourably inclined conduits for a vertical melt transfer. The subvertical orientation of the shear zones also means that a potentially larger variety of sources may have been tapped in the subhorizontal basement complex, which is possibly reflected in the fact that the geochemical heterogeneity previously documented for the Heerenveen batholith (e.g. Anhaeusser et al., 1983; Yearron, 2003) is almost exclusively confined to the subvertical sheeted domains.

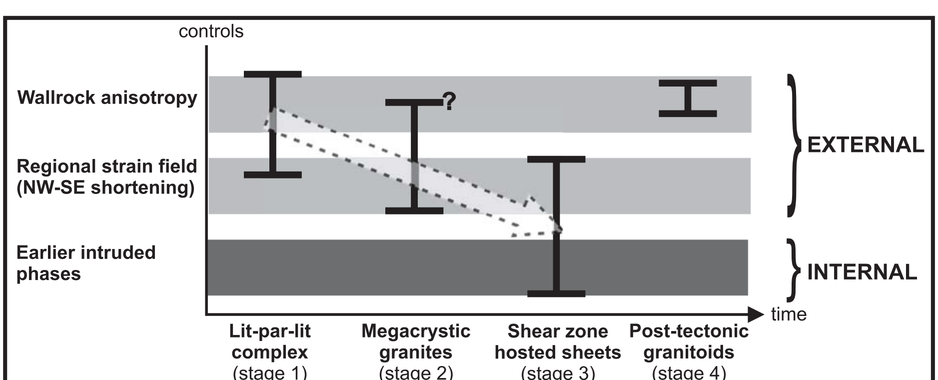

Fig. 10. Diagrammatic synopsis of the changing emplacement styles and controls during the incremental construction of the Heerenveen batholith. Controlling factors can be grouped into pre-existing factors unrelated to the pluton itself (external) and those related to the pluton, i.e. melt related (internal). Early intrusive phases are predominantly controlled by the wall-rock anisotropy and the regional strain field (external factors). With the introduction of more melt, the influence of the wall-rock anisotropy is reduced, and conversely, controls by previous intruded melts and the effects of strain localization determine the emplacement of subsequent melt batches (internal factors). In the absence of a deviatoric stress field, post-tectonic granite factors are again controlled by the wall-rock anisotropy.

Alternative interpretations of the synmagmatic shear zones as, e.g. bounding structures that accommodate the volume of the intruding magma and inflation of the pluton (Tobisch and Cruden, 1995; Cruden, 1998) or as already present regional shear zones that guided and facilitated melt migration or emplacement (e.g. Brown and Solar, 1998) appear unlikely. The sinistral and dextral transpressive kinematics of the conjugate shear zones record the regional shortening, rather than accommodating wall-rock displacement as a result of either roof uplift, floor depression or the lateral translation of wall rocks (e.g. Cruden, 1998; Cruden and McCaffrey, 2001). Similarly, regionally developed shear zones with comparable orientations and kinematics are not found in the surrounding basement gneisses and the high-strain fabrics are only developed within the confines of the Heerenveen batholith.

The lack of magmatic and solid-state fabrics in the final intrusive phases of the Heerenveen batholith is interpreted to indicate their post-tectonic timing (stage 4). These granites intrude the earlier phases of the Heerenveen batholith as seemingly, randomly orientated sheets or plugs, in stark contrast to the dominant ENE- and N-trends of granites in large parts of the pluton (Fig. 9g, h). However, in places where the late-stage granites intrude and are in contact with the surrounding basement rocks, pre-existing wall-rock anisotropies exert a strong control on the geometry of the granites. This is the case in the SE parts of the Heerenveen batholith, where the fine-to medium-granites sharply terminate against the metasediments and metavolcanics of the schist belt. The post-tectonic phases also indicate the prolonged intrusion history and that magmatic activity outlasted the regional D3 tectonism.

4.2. The role of sheeting for pluton construction and steady-state magma chamber formation

The pattern of marginal zones of sheeted granites enveloping cores of more massive granites is typical for most of the GMS suite plutons in the Barberton granitoid-greenstone terrain (Anhaeusser and Robb, 1983). On regional maps, this zonation is delineated by what was then referred to as the “marginal migmatite zones” surrounding the main plutons of e.g. the Heerenveen, Mpuluzi or Nelspruit batholith (e.g. Anhaeusser et al., 1981; Anhaeusser and Robb, 1983; Robb et al., 1983). We suggest that this zonal distribution of granite phases with distinct internal architectures and geometries and their relative timing with respect to each other outlined in this study, point to some of the underlying mechanisms through which the large batholiths of the GMS suite were emplaced. A number of recent works that have modelled the thermal evolution and emplacement of large plutonic complexes at shallow-crustal levels emphasize the significance of sheeted margins for the construction of steady-state magma chambers (Furlong and Myers, 1985; Hanson and Glazner, 1995; Yoshinobu et al., 1998). Considering the shallow emplacement level of the Heerenveen batholith (Hunter, 1973; Anhaeusser and Robb, 1983; Robb et al., 1983), the earliest intrusions of the eastern lit-par-lit complex were intruded into presumably cool wall rocks. This corresponds to the well-preserved sheeted architecture, particularly at lower structural levels of the lit-par-lit complex pointing to the relatively quick cooling of the narrow intrusions below their solidus. Given a sufficiently high magma supply rate and a high-rate of sheeting, the repeated addition of heat associated with multiple intrusions will increase the ambient wall-rock temperature (Furlong et al., 1991). Continued sheeting, preserved by the coalescing sills and low-angle dykes at higher structural levels in the eastern lit-par-lit complex will result in slower cooling rates of newly added sheets as the ambient wall-rock temperatures will increase. This has the effect that larger steady-state magma chambers may be constructed through the continued addition of relatively small melt batches, provided that the ambient temperatures are elevated above the intrusions’ solidi (e.g. Hanson and Glazner, 1995; Fleck et al., 1996). The formation of a steady-state magma chamber by this process of progressive sheeting also implies that the crystallization front within the chamber may migrate (Marsh, 1996; Yoshinobu et al., 1998), depending on the site of new magma additions. As a consequence, the crystallization front will not necessarily track the original geometry of the granites, so that the intrusive contacts between different granite phases may be homogenized and obliterated. This leads to the commonly observed cryptic contacts in the centres of large granite batholiths (e.g. Glazner et al., 2004). A similar process is invoked here for the development of the central megacrystic granites, which lack clear internal contacts. Thus, the early stage of multiple granite sheets preserved in the several km-wide lit-par-lit complex along the eastern margin of the Heerenveen batholith represent the thermal ground preparation for the development of the subsequent central, more massive megacrystic phases. The introduction of the rheologically weaker steady-state magma chambers, in turn, is a prerequisite for the nucleation of the bounding synmagmatic shear zones, which are similarly documented for the adjoining Mpuluzi batholith (Jackson and Robertson, 1983; Westraat et al., 2005). The synmagmatic shear zones, in turn, not only contribute to the incremental construction of the batholith, but also to the thermal insulation and maintenance of a central steady-state magma chamber, by providing a buffer between the central granites and the surrounding cold wall rocks. The degree of preservation of the internal sheeted geometry in the synmagmatic shear zones indicates that crystallization rates of individual sheets were faster than the emplacement rates (compared to the central megacrystic granites where crystallization rates were slower than emplacement rates). This inhibited post-emplacement textural or chemical homogenization along the boundaries between the cooler wall rocks and the central granites, preserving the distinct sheeted nature of granitic intrusive phases.

The example of the 3.1 Ga Heerenveen batholith illustrates how emplacement controls of syntectonic plutons undergo progressive adjustments in response to the incremental construction and successive addition of melt batches. The emplacement controls can be conceptualized into external factors, i.e. those that are independent of the magmas, and internal factors intrinsic to the magmas (Fig. 10). The latter involve mainly rheological changes as a consequence of granite plutonism, either as a result of the introduction of rheological heterogeneities in the form of melts, associated strain localization and strain partitioning as well as wall-rock heating during granite intrusion.

5. Conclusions

The emplacement of the successive phases of the Heerenveen batholith records a positive feedback loop between melt emplacement and deformation, resulting in transient changes in the controls and styles of emplacement of the magmas. The earliest phases of pluton emplacement are largely controlled by external factors, mainly determined by the regional strain field and the presence and orientation of pre-existing anisotropies. During the progressive assembly of the pluton, the emplacement of subsequent phases is increasingly influenced by factors intrinsic of the magmas (Fig. 10). Wall rocks are heated by continued granite sheeting to the stage when steady-state magma chambers can be established. At this stage, strain localization and partitioning around the steady-state magma chambers become the predominant factor. Melt transfer and emplacement are controlled by synmagmatic shear zones that nucleated around the central magma chambers. The thermal insulation of the steady-state magma chambers through continued addition of melt and heat to the bounding shear zones may lead to the homogenization of the originally heterogeneous central zones. This contributes to the development of the commonly observed homogeneous, massive granites in the central parts of the batholith, as is predicted through thermal modelling studies of incrementally constructed magma chambers (Yoshinobu et al., 1998). The fact that numerous large batholiths of the GMS suite show similar zonal architecture of marginal sheeted phases and more massive cores, suggests that similar processes to those described here may have a wider application to the construction of sheeted batholiths.

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