Field and microstructural observations of granulite facies rocks, Hamilton Downs, Mt. Hay Block, central Australia

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December 7, 2009

Submitted in partial fulfillment of the requirements for a Bachelor of Arts Degree from Carleton College, Northfield, Minnesota
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Abstract

This study reports the field and microstructural observations of a well-exposed, unretrogressed section of the lower continental crust in the Mount Hay Block, Central Australia. The Mount Hay Granulites (Mafic, Anorthositic, Intermediate, Quartzofeldspathic) experienced penetrative ductile deformation in the lower crust at ~800°C, ~8 kbar during the 1780-1720 Ma Strangways event. These rocks were later uplifted in the 1590-1570 Ma Chewings Event and the 400-300 Ma Alice Springs Orogeny. I studied the anorthositic granulites of Hamilton Downs, located on the far eastern margin of the Mount Hay Block. Compositions of the anorthositic granulites are distinct from the mafic/felsic granulites of Ceilidh Hill. In these rocks, lineation is steeply plunging and well developed. Foliation is variable. Fabrics including L=S, L>S, L>>S and L-tectonites are expressed in the shape-preferred orientation of pyroxene clots and segregated layers. The distribution of fabric types may indicate that Hamilton Downs is part of a larger sheath fold. A 1 km wide zone of high strain separates the lower strain anorthositic granulites of Hamilton Downs from the mafic granulites of the southeastern tongue of Ceilidh Hill. Transposition of compositional layering and foliation from Ceilidh Hill and Hamilton Downs indicates that the high strain zone is younger than surrounding exposures. Within the high strain zone, quartz and plagioclase deformed by grain-boundary sliding as inferred from microstructural observations including amoeboid grain boundaries and variable grain size.

Keywords: Granulite, central Australia, Mount Hay Block, Hamilton Downs
Introduction

The Mount Hay Block is a particularly good place to study deformation of the lower crust. Based on xenoliths (Chen et al., 2001) and seismic velocity analysis (Christensen and Mooney, 1995; Rudnick and Fountain, 1995) we know the lower crust is dominated by granulite facies rocks, consisting primarily of plagioclase and pyroxene. Within the Mount Hay block, granulites with various compositions and structural fabrics are preserved in a thick (~40 km laterally) nearly pristine structural section of the lower continental crust. The Mount Hay block is therefore ideal for assessing the broad pattern of deformation in the lower crust and for studying the variations in structural fabric as a function of lithologic composition.

The Mount Hay Block has been the subject of many studies (Waters-Tormey, 2004; Hallau, 2006; Waters-Tormey and Tikoff, 2007; Waters-Tormey et al., in press). Yet the compatibility of structural elements, the localization of strain and the significance of fabric variation continue to be poorly understood. In this study, I present preliminary results from field and microstructural observations of a largely unstudied exposure of anorthositic granulites in the south and eastern portion of the Mount Hay Block just north of the Hamilton Downs Cattle Station (Fig. 1C). Three important questions addressed in this study include: (1) How is the degree and development of structural fabric (i.e., lineation and foliation) expressed in the rocks of Hamilton Downs which are primarily of anorthositic composition? (2) How do the Hamilton Downs anorthositic granulites fit into the larger geological context of the Mount Hay Block mafic granulites including what is known of fabric formation on Ceilidh Hill just to the north (c.f., Hallau, 2006) (3) What do microstructures in these rocks say about deformation mechanisms in the lower crust?
In order to address these questions, structural and fabric domains were defined and identified in the field using a modification of the fabric classification criteria defined by Hallau (2006) on Ceilidh Hill but more applicable to the anorothositic compositions at Hamilton Downs. Mesoscale fabric intensity maps were constructed to illustrate the distribution and intensity of strain and the structural connections to the better-studied Ceilidh Hill to the north. Finally, microstructural observations in plagioclase and quartz are presented to assess the likely deformation mechanisms operating in the Hamilton Downs rocks, thereby providing important information on the mechanical characteristics of the lower crust.

Geologic Setting

The Mount Hay Block is located within the Arunta Inlier of central Australia (Fig. 1) and is part of a 160 x 50 km² EW oriented belt of granulites. (Shaw et al., 1984). Granulites within the Mount Hay Block experienced six major tectonothermal events (Shaw and Black, 1991; Dunlap and Teyssier, 1995; Hoatson et al., 2005). The protoliths of the Mount Hay Block granulites were gabbros and charnockites emplaced in the lower crust during the Stafford event (1810-1790 Ma) and subsequently deformed at granulite facies conditions during the Yambah and Strangeways events (1780-1745 Ma and 1730-1690 Ma) (Hoatson et al., 2005). Detailed geothermobarometric and isotopic studies (Collins and Shaw, 1995; Staffier, 2007; Waters-Tormey et al., in press) constrain peak metamorphic conditions of the Mount Hay granulites to conditions typical of the lower continental crust (>600°C, >7 MPa).
Figure 1. (A) General map of Australia showing location of Arunta Block. (B) Location of Mt. Hay Block within the Arunta Inlier. (C) Simplified geologic map of Mt. Hay Block. Study area (including Hamilton Downs and the southeastern portion of Ceilidh Hill) enclosed in box. Modified from Tikoff et al. (2001), Waters-Tormey et al. (2007).
The Mount Hay Block was partially exhumed during the Chewings event (1590-1570 Ma) and later during the Paleozoic Alice Springs orogeny (400-300 Ma) which resulted in the uplift and rotation of the entire Mount Hay Block along the Redbank thrust zone (Claoue-Long and Hoatson, 2005). Isotopic data suggests that the Mount Hay Block experienced amphibolite facies conditions during these major exhumation events, but the retrogression to lower metamorphic facies (e.g. greenschist) is restricted to discrete shear zones bounding the Mount Hay Block (Waters-Tormey et al., in press).

According to seismic reflection studies, tectonic motion along the Redbank thrust zone likely displaced the Moho by as much as 25 km vertically and at least 40 km laterally (Wright et al., 1990; Wright et al., 1993; Korsch et al., 1998; Biermeier et al., 2003). Therefore, in its present configuration, the Mount Hay Block displays a large, pristine structural section through the lower crust with depth increasing from northeast to southwest (Staffier, 2007).

Broadly speaking, the Mount Hay Block can be divided into four geologically distinct regions: Mount Hay, Capricorn Ridge, Ceilidh Hill, and Hamilton Downs (Fig 1C). The dominant lithologies in all four regions consist of mafic (pyroxenitic and gabbroic) and felsic (charnockitic) granulite with subordinate anorthositic, calc-silicate, quartzofeldspathic, and pelitic granulites also present.

**Mount Hay and Capricorn Ridge**

Mount Hay and Capricorn ridge are located in the west and north Portion of the Mount Hay Block and form the majority of granulite exposures (Fig 1C). Previous mapping of the Mount Hay Block relied on aerial photography, limiting structural
relationship analysis to color contrast recognition. These geologic and petrologic
descriptions were compiled into the 1:250,000 Hermannsburg geologic map and notes
(Glikson, 1984; Watt, 1992; Warren and Shaw, 1995). Detailed ground-based mapping
and fieldwork of the study area is limited to Mount Hay and Capricorn Ridge (Waters-
Tormey, 2004; Staffier, 2007; Waters-Tormey and Tikoff, 2007). These workers defined
qualitative, field-based assessments of L versus S fabric development. Distinctions were
based on the strength of lineation and foliation based on consistency in linearity and
planarity respectively, and mesoscopic shape-preferred orientation in the defining phase
(most often plagioclase). With these data, it is possible to make interpretations of relative
strain in Mount Hay and Capricorn Ridge.

Mount Hay is inferred to be a low strain lens with lineation and foliation displaying
a 10 km scale fold (Fig. 1C). Fabric development and intensity is dominated by L>S
fabric, with less common L>>S, and L=S, and rare L-tectonites constrained to
topographic high points (Staffier, 2007). This large-scale structure with fold closures on
the east and west ends of the ridge, is interpreted to be a antiformal sheath like fold
(Glikson, 1984; Shaw et al., 1984; Staffier, 2007).

In contrast, Capricorn ridge displays discrete lithologic domains that are thinner,
laterally continuous and more planar than those found on Mount Hay. While there is
some heterogeneity in the fabric development across the discrete lithologic domains,
found throughout Mount Hay, the compositional layering displayed at Capricorn ridge is
everywhere parallel to a single primary east/west trending foliation. (Waters-Tormey et
show that the consistently parallel orientation of the compositional layering reflects the transposition of older foliations in the Mount Hay block and thus, Capricorn ridge is inferred to be a 6 km wide zone high strain relative to Mount Hay.

Evidence that deformation of the Mount Hay Block occurred in the lower crust is abundant. Sheath folds, transposition of compositional domains into the foliation, the presence of L-tectonites, local boudinage and undulose to patchy extinction of plagioclase in thin section, all indicate high temperature ductile deformation typical of the lower crust (Waters-Tormey, 2004; Staffier, 2007; Waters-Tormey and Tikoff, 2007; Waters-Tormey et al., in press). Extensive thermobarometric analyses of samples throughout the Mount Hay Block constrain peak deformation conditions from 700-900 °C and 6.9-8.2 MPa (Collins and Shaw, 1995; Staffier, 2007; Waters-Tormey et al., in press). Despite the range in depth, there is no significant variation in temperature recorded in samples throughout Mt Hay and Capricorn ridge. The lack of systematic variation in temperature suggests that deformation in the lower crust occurred at relatively constant temperatures or that the mineral assemblage of Mount Hay re-equilibrated when the Capricorn Ridge shear zone was active. Assuming a lithostatic gradient of 27 MPa/km, constrained by the pressure calculations from Staffier (2007) of 690-820, MPa, Waters-Tormey et al. (in press) estimates that deformation of the Mount Hay Block occurred at a depth between 26 and 30 km, with a geothermal gradient of roughly 27-30°C.

Ceilidh Hill

Previous study of Ceilidh Hill and the southeastern portion of the Mount Hay Block
consists of structural mapping and a fabric study completed by Hallau (2006) as part of an undergraduate thesis project at the University of Wisconsin-Madison. The lithology of Ceilidh Hill is primarily fine-grained intermediate to mafic granulite, with a mineral composition consisting of pyroxene, plagioclase, K-feldspar, and quartz. Compositional layering is common and displayed as cm to m-scale compositional bands of charnockite within fine-grained gabbro. These compositional bands are classified as the $S_0$ fabric (Fig. 2).

Hallau (2006) identifies four primary fabric domains on Ceilidh Hill: L-tectonites, L$\gg$S, L$>$S and L$=$S. Fabric is characterized by the shape-preferred orientation of the plagioclase and quartz crystals found in the mm to cm-scale felsic segregations. Lineation is consistently well developed and is most commonly defined by the long axes of elongate quartz and plagioclase crystals of felsic segregations with up to 10:1 length to width ratios. $S_1$ foliation is defined by the consistency and planarity of shape-preferred orientation of the felsic segregations in the plane perpendicular to lineation. L$=$S domains display foliation and lineation that are approximately equally developed, with domains between compositional layers showing sharp, well-defined margins. L$>$S domains retain tabular margins between compositional layers, but display less well-developed flattening in plane perpendicular to foliation. L$\gg$S domains are characterized by a weak shape-preferred orientation in foliation plane and non-tabular compositional banding. Compositional layering and the shape-preferred orientation of felsic segregations are often folded. L-tectonites are defined by rods of felsic segregation with a shape-preferred orientation alignment almost exclusively in the direction of lineation. Compositional layering in L-tectonites of Ceilidh Hill is largely absent.
In general, the fabric type of Ceilidh Hill is dominated by L>S fabric, with less common L>>S and rare L-tectonites constrained to two topographical high points (Hallau, 2006). L=S fabric is found along the northern boundary with Capricorn Ridge and on the southeastern tip of along the boundary with Hamilton Downs. Foliation is generally NW-SE striking, but begins to swing to an E-W orientation towards the boundary with Hamilton Downs (Fig. 3). Lineation consistently plunges nearly vertically (an average of 84°). In contrast to Capricorn Ridge, changes in fabric type are most commonly gradual. Abrupt structural contacts between boundaries are rare (Hallau, 2006).

In the following sections, I add to this foundation of work with important detailed field mapping and both macro and microstructural observations of the South Eastern portion of Ceilidh Hill and Hamilton Downs. I attempt to integrate these data into previous work in order to provide a more detailed picture of this regions tectonic history. I build on Hallau’s (2006) preliminary work, focusing on a much smaller area encompassing the southeastern most tongue of Ceilidh Hill and a small 3.5 X 5 km exposure called Hamilton Downs. Structural and lithologic geologic mapping of Ceilidh Hill consisted of strike-perpendicular and strike-parallel traverses where significant fabric and lithologic variations were recorded. Detailed measurements were collected, documenting the orientation and degree of foliation, lineation, compositional layering and various mesostructures. These measurements were compiled and overlaid on a topographical map of the region (Fig. 2). Each site showing foliation and lineation was classified on a spectrum of fabric intensity modified from Hallau (2006) (Fig. 3).
Figure 2. Structural map of southeastern Ceilidh Hill and Hamilton Downs showing trends in lineation and foliation. Location shown in Fig 1. Topography from the Australia 1:50,000 Geological Survey. Stereonets in upper right correspond to Ceilidh Hill (top left), high strain zone (top right), and Hamilton Downs (bottom left). Foliation plotted as planes (blue lines), lineation as points (black dots).
Figure 3. A) Generalized map of L versus S fabric development adapted from Fig. 2. Fabric transitions gradual in Ceilidh Hill, abrupt in Hamilton Downs. Note concentration of L >> S and L-tectonite fabric in topographical highs of Hamilton Downs. B) Composite cross section after A) showing penetrative foliation inclination and boundary of high strain zone. No vertical exaggeration.
**Hamilton Downs**

The composition of Hamilton Downs contrasts that of the largely interlayered mafic and felsic granulites found on Ceilidh Hill to the north. Lithologies in Hamilton Downs range from almost pure anorthosite (>15 percent pyroxene) to gabbronorite (60/40 percent plagioclase/pyroxene) containing varying amounts of pyroxene but consistently dominated by plagioclase. The Hamilton Downs exposure reflects the weathering prone nature of plagioclase, exposing amphibole and orthopyroxene bearing bands, rods, clots and aggregates that represent the regular to patchy cm to m-scale compositional banding we define as the $S_{0a}$ fabric (Fig. 4). In addition to the $S_{0a}$ compositional layering, local compositional bands of 10 cm to meter scale pure, fine-grained anorthosites cut through pyroxene clotted anorthosites and gabbronorites. This compositional layering has been designated as the $S_{0b}$ fabric, which is most often oblique to the primary foliation ($S_1$). Additional lithologic domains are represented by rare 1 to 3 mm seams of pyroxenite and 50 cm dikes of pure fine-grained gabbro (Fig. 4).

Exposures of mafic pyroxene clotted gabbro/anorthosite similar to Hamilton Downs have been cited elsewhere within Mount. Hay Block, including the northern flank of Capricorn Ridge and in discrete horizons and layers throughout the fault bound Amburla Folds region between Mount Hay, Cap Ridge, and Ceilidh hill (Fig 1C). Both Glickson (1984) and Waters-Tormey (2004, 2007) refer to this unit as the Mount Hay Anorthosite (which Watt (1992) attempted to formally rename as the Amburla Meta-leuconorite). To avoid further confusion, we shall refer to this unit simply as the anorthositic granulites.
Figure 4. Photographs showing different types of compositional layering. (A) Original igneous compositional layering. (B) Strong shape-preferred orientation of feldspar segregations perpendicular to lineation make this an L>S fabric. (C) 8 mm seam of pyroxenite (S0c) cutting through L>S fabric defined by rod-like pyroxene cores (aussie dollar for scale). (D) 3-5 cm fine-grained, pure plagioclase band (S0b) cutting L>S fabric (pencil for scale), oriented parallel to lineation defined by shape-preferred orientation of pyroxene clots. (E) L=SL>>S lineation shown by meter thick mafic suture zone containing an isolated tabular layer of pyroxenite (pencil for scale). (F) 2 mm to 5 cm bands of charnockite within fine-grained gabbro (pencil for scale).
Given the significant difference in composition between the anorthositic granulites of Hamilton Downs and the mafic granulites of Ceilidh Hill, major changes to the fabric classification method developed by Hallau (2006) are necessary to accurately assess the degree and development of fabric throughout Hamilton Downs. Felsic segregations and compositional layering of charnockite and are absent in Hamilton Downs and the shape-preferred orientation of plagioclase grains, vital to fabric classification in Ceilidh Hill, is often weak to non-existent. The degree and development of the S₁ foliation within Hamilton Downs is primarily based on the shape-preferred orientation of pyroxene grains (Fig. 5). Lineation is likewise defined by shape-preferred orientation in pyroxene grains (and occasionally, polycrystalline ribbons of plagioclase).

As shown in Figure 6, there is substantial range in texture across Hamilton Downs, making it difficult to create a universal fabric classification scheme. We used the following classification method to make field based decisions of fabric development shown in Figure 3: L=S fabric are not found on Hamilton Downs. L>S fabrics are characterized by well-defined margins within the S₀a compositional layering and a clear shape-preferred orientation of pyroxene clots perpendicular to the plane of lineation (Fig. 4B). L>>S fabrics are defined by weak shape-preferred orientation of pyroxene perpendicular to plane of lineation. L-tectonites are difficult to classify, but are most often characterized by highly elongate pyroxene clots in the direction of lineation with a complete lack of shape-preferred orientation perpendicular to lineation (Fig. 5A and B, Fig 6B).
Figure 5. A) Photograph showing shape-preferred orientation perpendicular to lineation segregation in the plane perpendicular to lineation showing weaker shape-preferred orientation parallel to lineation. B) Photograph of same felsic segregations, defining an L-tectonites fabric. C) Photograph of much more strongly developed shape-preferred orientation of felsic segregations parallel to lineation on Ceilidh Hill. D) Photograph of same felsic segregations in the plane perpendicular to lineation showing weaker shape-preferred orientation perpendicular to lineation.
Figure 6. Various pyroxene and plagioclase textures found throughout Hamilton Downs. A) Photograph from the southwestern knob showing complete lack of fabric in both pyroxene and plagioclase (Aussie dollar for scale). B) Photograph from southeastern knob showing large 1-3 cm pyroxene clots with strong shape-preferred orientation parallel to lineation (black pencil for scale). C) Photograph from southwestern knob showing fine-grained pyroxene and plagioclase crystals, both with strong shape-preferred orientation parallel to lineation (pencil tip parallel to lineation for scale). D) Photograph from northern knob showing pyroxene clot segregation into pyroxene rich and pyroxene poor layers that define the S0a compositional layering (black pencil for scale).
The degree and development of foliation and lineation varies substantially across Hamilton Downs (Fig. 3, Fig 5A, B and C). In contrast to Ceilidh Hill, contacts between fabric types are occasionally gradual, but more often abrupt. The most southeastern portion of Hamilton Downs is defined by a weak L>>S fabric striking SW-NE and dipping steeply an average of 80° (Fig. 3). Fabric changes abruptly from an anorthosite rich L>S containing very limited, small <20mm pyroxene clots, to L-tectonite defined by large pencil like rods of pyroxene that range in size from 0.5cm to 6 cm parallel to lineation with no shape-preferred orientation perpendicular to lineation (Fig 4C). Further west, pyroxene clots show less overall strain, but display a definite shape-preferred orientation perpendicular to lineation, and are therefore classified as L>S. The primary foliation trend changes from a SW-NE orientation (in the L>>S and L-tectonite fabrics) to an EW orientation (in the L>S fabrics) with lineation plunging an average of 71°. As shown in Figure 2, this region displays both S₀a and S₀b compositional banding that is oblique to the S₁ primary foliation.

Near the topographical high point on the southwestern knob of Hamilton Downs, there are 5 m² regions that display little to no fabric at all (Fig 3). Crystals of pyroxene are not consolidated into clots and segregations, and are randomly oriented (Fig. 6A). Just 15 meters north of this knob, there is an abrupt change into course-grained gabbronorite with a clear shape-preferred orientation parallel and perpendicular to lineation in individual pyroxene crystals and plagioclase (Fig. 6C). This L>S fabric is cut by multiple consistently oriented 6.5 cm S₀b fine-grained anorthosite bands. The distribution and
consolidation of pyroxene crystals is highly variable along the ridge towards Ceilidh Hill. In a small area of 6m$^2$, it is possible to find randomly oriented, 20 mm clots, as well as substantially smaller 4-8 mm clots segregated into obvious layers defining the $S_{0a}$ fabric.

The northernmost knob of Hamilton Downs is characterized by an L>>S fabric defined most often by the shape-preferred orientation of large, 3-4 cm pyroxene clots (parallel to lineation) in $S_{0a}$ segregated layers. The trend of the primary foliation is oriented SW-NE, dipping steeply an average of $79^\circ$. Lineation is region is highly variable, trending NW to NE and plunging an average of $65^\circ$.

**High Strain Zone**

On the western boundary of Hamilton Downs, towards the southeastern most portion of Ceilidh Hill, S-fabric intensity begins to surpass lineation (Fig. 3). There is an extensive 1 km wide L=S domain located between the boundary of the southeastern portion of Ceilidh Hill and Hamilton Downs. This horizon of s-dominated fabric strikes southwest and dips steeply towards the northwest an average of $78^\circ$. Lineation is consistently well developed trending almost due east and plunging an average of $69^\circ$ (Fig. 3).

The lithology of this region differs from that of Hamilton Downs and Ceilidh Hill. Composition abruptly changes from a heavily weathered course grained gabbronorite (50/50 plagioclase/pyroxene) to a fine-grained (>1mm grain size) leucogranite, with no visible pyroxene, but with abundant quartz and large 5mm subhedral garnets (Fig. 7). The
steeply pitching lineation is defined by stretched quartz and plagioclase crystals. As shown in Figure 7, the compositional layering between plagioclase layers and quartz and k-spar layers is tabular and well defined, everywhere parallel to the primary foliation.
Figure 7. Photographs from the high strain zone separating Ceilidh Hill from Hamilton Downs. A) Shows strong lineation in highly stretched quartz and plagioclase polycrystalline ribbons. Note absence of pyroxene and large 8mm euhedral garnet to the right of pencil. B) Plane perpendicular to lineation, showing strong L=S fabric defined by highly stretched quartz and plagioclase crystals and tabular margins of S0 compositional banding parallel to primary foliation (pencil for scale). Note extreme reduction in grain size compared to grain size within Hamilton Downs and Ceilidh Hill.
Towards the topography of southeastern Ceilidh Hill, the lithology changes from sillimanite bearing gneiss to fine-grained gabbro containing the same centimetric felsic segregations and 3-5 cm charnockite layers that are found throughout Ceilidh Hill. Despite the gradual change in composition, these rocks continue to be dominated by a strong S-fabric, and are still classified as L=S. The shape preferred orientation of felsic segregations and 4 cm layers of S₀ charnockite are tabular, showing well defined margins parallel to the primary S₁ foliation. Orientation of foliation changes from southwest to nearly due west, and begins to dip more shallowly, an average of 68°.

**Microstructural and Mineralogical Characterization**

To compliment outcrop-scale observations, thin sections were made for microstructural and mineralogical analysis. Hand samples were collected from a variety of locations and fabric types within Hamilton Downs and the high strain zone. All thin sections were cut parallel to lineation and perpendicular to foliation so that the microstructural elements could be evaluated within the kinematic reference frame. Analysis of thin sections included detailed notes of mineral assemblage, grain shape and size, deformation textures, and grain-boundary relationships.

Deformation microstructures of plagioclase are generally in agreement with high temperature deformation textures described by (Lafrance et al., 1996). Undulose extinction, tapered deformation twins and healed microfractures are the most common microstructures indicative of deformation. The deformation twins, which follow the pericline and albite twin laws, are often gently curved, and terminate at grain boundaries, tapering to a fine point within the grain (Deer et al., 1992). Larger, primary plagioclase
grains are commonly more deformed than smaller recrystalized grains. These secondary recrystalized grains show straight extinction and are generally absent in deformation twins (Fig. 8 and Fig. 9). Grain boundaries throughout the study area range in texture, from very irregular (interlobate to amoeboid in HD09-27), to gently curved, with common triple point junctions (Fig. 9A and B). The presence of dihedral 120° anneals suggests that at a minimum, rocks in this region reached partial textural equilibrium (Lafrance et al., 1996; Passchier and Trouw, 2005). The highly interlobate grain boundaries and dissected recrystalized plagioclase grains shown in Figure 9 may be indicative of grain boundary migration. In order to confirm the presence of grain boundary migration, additional studies of lattice-preferred orientation are needed. According to (Passchier and Trouw, 2005) the most conclusive evidence of grain boundary migration is a complete lack of lattice-preferred orientation.

Hamilton Downs:

Field-based assessments of lithology are largely correct and are supported by the microstructural observations. The composition of samples from Hamilton Downs is largely anorthositic (containing 5-30% mafic materials), consistent with the field calls of lithology. Typical mineralogy consists of plagioclase + orthopyroxene + hornblende + illmenite (Fig. 8). In general, shape fabric in these samples is weak to nonexistent. Extinction families (groups of grains that are extinct in the same position under cross polarized light) are not observed (Waters-Tormey, 2004). The more abundant plagioclase grains are approximately equal in size (0.8-1.2 mm), with grain boundaries that are gently curved to interlobate. Shape-preferred orientation is weak to non-existent both
perpendicular and parallel to lineation. Larger plagioclase grains display undulose to sweeping extinction. Tapered deformation twins are ubiquitous and often smoothly bent. Plagioclase grains occasionally exhibit 120° triple junctions (Fig. 8).

Orthopyroxene grains are generally smaller than plagioclase, and range in size from 0.1-0.3 mm, with grain boundaries that are gently curved to interlobate (especially in contact with plagioclase grains). Rarely, there is a weak shape-preferred orientation of pyroxene parallel to lineation in the form of football shaped grains. Pyroxene grains exhibit 120° triple junctions but are less common than in plagioclase. Most pyroxene grains exhibit characteristic weak pink to green pleochroism. Smaller orthopyroxene grains commonly form subgrains within plagioclase and other, larger orthopyroxene grains. These subgrains may be evidence of dynamic recrystalization, and more specifically bulging recrystalization (BLG), or even high temperature grain boundary migration (GBM) (micro-tectonics, 2005).

Hornblende grains, like orthopyroxene, are much smaller than the dominant plagioclase crystals, ranging in size from 0.05-0.3 mm. Grain and phase boundaries are most commonly straight to gently curved. Hornblende is distinguished from other phases by its dark green pleochroism and high birefringence.
Figure 8. Photomicrographs of samples HD09-11 and HD09-04 cut parallel to lineation and perpendicular to foliation. A) HD09-11 under cross-polarized light showing interlobate grain boundaries and rare 120° anneals (red arrow). B) Same area as show in A) under plain-polarized light showing weak shape-preferred orientation in football shaped orthopyroxene parallel to lineation. C) HD09-04 under cross-polarized light showing gently curving tapered deformation twins and patchy to undulose extinction in large plagioclase grain (center). Note subgrains within larger orthopyroxene grains. D) Same area as shown in C) under plain polarized light showing pleochroism in orthopyroxene. Mineral abbreviations from Kretz (1983).
**High Strain Zone:**

Two hand samples were collected from the high strain zone separating Ceilidh Hill from Hamilton Downs. HD09-29 was taken from the transitional fabric on the southeastern boundary of Ceilidh Hill from what we designated a felsic segregated gabbro with a strongly developed L=S fabric. As shown in Figure 8A and B, the sample consists entirely of 50/50% plagioclase/pyroxene composition. Well-developed shape-preferred orientation is present in both phases, defined by elongate plagioclase grains and distinctive football shaped pyroxenes. Plagioclase crystals are largely equant size, ranging from 0.8-1.4 mm. Orthopyroxene crystals are smaller, ranging in size from 0.2-0.5 mm (lengthwise). Grain and phase boundaries are straight to gently curved, never interlobate. Grain boundaries are dominated by foam texture (abundant 120° triple junctions). In contrast to the samples from Hamilton Downs, patchy to undulose extinction in plagioclase is not observed.

Sample HD09-27 was taken from the middle of the high strain zone, from an exposure with a particularly well-developed s-fabric (L=S). As shown in Figure 9C and D), the average grain size is extremely reduced, with the largest quartz and plagioclase crystals rarely exceeding 0.05 mm. This sample is lithologically distinct from both Ceilidh Hill and Hamilton Downs, with a composition of quartz + k-feldspar + biotite + kyanite + (sillimanite) + orthopyroxene + plagioclase + garnet + ilmenite. Grain boundaries of quartz and plagioclase are interlobate to amoeboid, and exhibit patchy to undulose extinction. Subhedral garnets are strongly associated with sillimanite and biotite, and are most often found growing around stretched sillimanite and biotite grains.
Figure 9. Photomicrographs of samples HD09-29 and HD09-27, cut parallel to lineation and perpendicular to foliation. A) HD09-29 under cross-polarized light showing equant grain size and foam texture (120° anneals). B) Same area shown in A) under plain-polarized light showing football shape of orthopyroxene, indicative of shape-preferred orientation parallel to lineation. C) HD09-27 under cross-polarized light showing patchy to undulose extinction in quartz (upper right) and shape-preferred orientation of quartz parallel to lineation. D) Same area as C) under plain-polarized light showing elongate biotite. Note extremely reduced grain size and interlobate to amoeboid grain boundary in quartz and plagioclase. Note subhedral face of garnet. Mineral abbreviations from Kretz (1983).
Geothermobarometry

Preliminary work on sample HD09-27 was performed on the Carleton College Hitachi S-3000N Scanning Electron Microscope (SEM) with an acceleration voltage of 20 kV, and beam current of 98 μA equipped with an Oxford INCA microanalysis system. Microprobe analysis allowed for detailed mineral identification, confirming the assemblage identified in thin-section. The peak metamorphic mineral assemblage of HD09-27 is qtz + kfs + bt + ky + (sil) + opx + plag + grt (Kretz, 1983). The positions in P-T space of all calculated equilibria are made using the computer program TWQ 2.34 (Berman, 2007) and the thermodynamic database of (Berman, 1991) with revisions through February, 2007. Reactions were considered in the seven-component system K₂O-CaO-FeO-MgO- Al₂O₃- SiO₂- H₂O (KCaFMASH) (Table 1) allowing for the calculation of seven reactions, three of which are independent (Fig. 10). Taken together, these reactions suggest that peak metamorphic conditions recorded by sample HD09-27 range from ~8-13 kbar and 880-980°C. However, the well documented GASP (Spear, 1993) and garnet-biotite (Ferry and Spear, 1978) geothermometers intersect at 980°C and 11.9 kbar (Fig. 10).
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Figure 10. Geothermobarometry results for sample HD09-27. Mineral equilibria in the KCaF-MASH system calculated using TWQ (Berman, 1991). The yellow shaded area depicts the likely range of possible P-T conditions for this sample. Al2SiO5 phase diagram is shown for reference.
Discussion

The Hamilton Downs exposure is lithologically and structurally distinct from the neighboring Ceilidh Hill. Composition is dominated by plagioclase with varying amounts orthopyroxene (0-30%) and limited hornblend. In contrast to Ceilidh Hill, there is little to no quartz and no observed felsic segregations or compositional layers of charnockite. Shape fabric is defined most frequently by the shape-preferred orientation of orthopyroxene clots. Unlike what we see in Ceilidh Hill, shape-preferred orientation in plagioclase is weak to non-existent both in field observation and in thin section. Whereas lineation is mostly consistent in orientation and magnitude throughout Ceilidh Hill, there are 5 m² regions within Hamilton Downs that lack a visible macroscopic fabric measurable in the field. With this abundant evidence, it is reasonable to assert that the rocks of Hamilton Downs have experienced less deformation than the nearby exposure of Ceilidh Hill as well as the high-strain shear zone of Capricorn Ridge described by Waters-Tormey (2004) and Waters-Tormey et al. (2007, in press) and the Mount Hay sheath fold (Glikson, 1984; Shaw et al. 1984; Staffier, 2007).

The compositions and textures displayed at Hamilton Downs are most similar to the anorthositic granulites found in the northeastern portion of Capricorn Ridge and Amburla Folds region (Glickson, 1984; Watt, 1992; Waters-Tormey, 2004; Waters-Tormey et al., 2007, 2008 in review). Similar to what has previously been documented at Capricorn Ridge and Amburla Folds, Hamilton Downs displays no observable migmatization and intrusion by charnockitic compositional layers. The presence of distinct lithologies of anorthosite in the Mount Hay block that record different structural
fabrics likely indicates that compositional differences between the mafic granulites and the anorthosites also represent rheological differences between these rock types during deformation and thereby affect the fabrics they record during deformation.

Similar to previous interpretations of Mount Hay and Ceilidh Hill, the fabric types displayed throughout Hamilton Downs likely express different states and types of strain. Domains of L-tectonite and L>>S typically imply unidirectional stretching and constriction whereas L=S fabrics imply flattening and plain strain (Davis and Reynolds, 1996). The distribution of fabric types in the Hamilton Downs region suggests that plane strains dominated near the boundary with Ceilidh Hill and constrictional strains dominated the topographical highs found in the middle of Hamilton Downs. These spatial variations in fabric type may indicate that Hamilton Downs is part of a large-scale sheath fold.

Alternatively, fabric variation may be indicative of overprinting relationships of varying strain intensity. Throughout the study area, with the exception of regions showing little to no fabric, lineation is generally well developed. Relative strain is therefore estimated by the development of foliation. Regions with strong S-fabrics can be interpreted as zones of relative higher strain than L>>S and L-tectonite fabrics. The km wide L=S domain that separates Hamilton Downs from the southeastern tongue of Ceilidh Hill is therefore inferred to be the region of highest strain. Hallau (2006) suggests that there is significant overprinting of three separate foliations within Ceilidh Hill. In our focus area of the southeastern most tip of Ceilidh Hill, two of Hallau (2006) foliation trends are observed, one striking NE-SW, and a second striking WNW-ESE. The L>>S
fabric in the northwestern portion of our study area displays the latter foliation trend (Fig. 3). On the southeastern boundary of Ceilidh Hill, towards the high strain zone separating Ceilidh Hill from Hamilton Downs, foliation and compositional layering are transposed onto a single, strongly developed NE-SW trending S-dominated fabric. This complete transposition may indicate that the zone of high strain is younger than the surrounding exposures of Ceilidh Hill and Hamilton Downs.

The zone of high strain may be related to deformation structures of the (400-300 Ma) Alice Springs orogeny found elsewhere in the Mount Hay Block, including the amphibolite and greenschist facies mylonite zones bounding the northern and southern portions of Capricorn Ridge. It is important to note however that the mineral assemblage and geothermobarometry work within this zone of high strain is indicative of much higher-grade deformation.

Previous geothermobarometry work on the Mount Hay Granulites constrains peak deformation conditions from 700-900°C and 6.9-8.2 kbar (Collins and Shaw, 1995; Staffier, 2007; Waters-Tormey et al., in press). Preliminary geothermobarometric data on sample HD09-27 from the high strain zone records a range from ~8-13 kbar and 880-980°C, with the well-documented GASP and garnet-biotite geothermometer intersecting at 980°C and 11.9 kbar (Fig. 10).

Berman (1991) suggests that it is possible to reasonably assess the state of equilibrium given the convergence of all equilibria in a single P-T region. As shown in Figure 10, mineral reactions do not intersect at a single point. The intersection of the GASP and garnet-biotite geothermometer occurs at pressures and temperatures well
above peak deformation conditions found elsewhere in the Mount Hay Block. Faulty microprobe data may be to blame. As shown in Table 2, the mineral garnet in particular displays unusual cation sums: Si cations should be about 3.0 as opposed to the 3.38, Al should be 2.0 instead of 1.88, and total cations should add up to 8.0 instead of 7.68. Scattered reactions may also indicate that the mineral assemblage in sample HD09-27 is in a state of disequilibrium. Disequilibrium is supported by the presence of kyanite coexisting with sillimanite, which is difficult to account for, given that the calculated range of pressure and temperature conditions falls entirely within the sillimanite stability field (Fig. 10).

The deformation microstructures of samples throughout Hamilton Downs and the region of high strain are indicative of high-temperature, high pressure conditions present in the lower crust (Lafrance et al., 1996). Undulose extinction, tapered deformation twins and healed microfractures are the most common microstructures indicative of deformation. Microstructures such as the highly interlobate grain boundaries and dissected recrystallized plagioclase grains present in HD09-27 (Fig. 9C and D) have previously been used to classify high-temperature grain boundary migration (Passchier and Trouw, 2005; Staffier, 2007; Waters-Tormey et al., in press). If GBM is indeed the primary deformation mechanism, it would be an important contribution to the growing consensus that grain boundary sliding makes a more significant contribution to the bulk rheology of the lower crust than previously thought (Waters-Tormey, 2004).
Conclusions

The primary goals of this research are to fit the Hamilton Downs exposure into the larger geological context of the Mount Hay Block granulites, to explore how fabric variation is expressed in the anorthositic granulites of Hamilton Downs and to characterize the microstructural relationships in an attempt to better understand large-scale rheology of the lower continental crust. The following results presented in this paper provide valuable insight into this important question:

1. Hamilton Downs is more weakly deformed than Ceilidh Hill
2. Hamilton Downs is lithologically distinct from the neighboring Ceilidh Hill and is most similar in composition texture to the northernmost exposure of Capricorn Ridge, and the Amburla Folds region.
3. Based on the distribution of fabric types, with high strain S-fabrics on the outer boundaries and constrictional L-tectonites near the central topographical highs, Hamilton Downs may be part of a larger sheath fold.
4. Separating Hamilton Downs from Ceilidh Hill is a 1 km wide zone of solid state deformation that we describe as a high strain shear zone.
5. The shear zone is most likely younger than surrounding exposures given complete transposition of both compositional layering and primary foliation from Ceilidh Hill and Hamilton Downs onto a single L=S fabric trending SW-NE.
6. Preliminary geothermobarometry work on a sample within the shear zone indicates peak metamorphic conditions in the range of ~8-13 kbar and 880-980°C. However, presence of kyanite and interlobate grain boundaries is indicative of
chemical disequilibrium, thus providing an inaccurate estimation of P-T conditions. Further study on a professionally polished thin section is required.

7. Deformation microstructures such as interlobate to amoeboid grain boundaries and dissected recrystalized plagioclase grains may be indicative of grain boundary sliding, an important component in bulk rheology of the lower crust.

Acknowledgments

I offer my sincerest gratitude to my advisor Sarah Titus, without whom, I’d have never found my way to Australia. Despite being on leave, she couldn’t help but dispense wisdom and cheer. I thank Seth Kruckenberg for taking me on as a field assistant, preparing excellent meals, and telling great stories by the fire. Thank you Basil Tikoff for rustling up funding through the University of Wisconsin-Madison and for keeping me on track. To Bereket for patiently teaching me how to grind and polish thin sections, and perhaps more importantly, forever reminding of the important things in life. Thank you Cam Davidson for the five-minute questions turned to hour long, illuminating conversations. To Tim Vick for graciously putting up with late time cards and messy senior desks. And last but certainly not least, I am forever indebted to the entire Carleton Geology department and all of its students. Thank you for the backrubs, the fresh pressed cider, venison and the willingness to fruit golf. Truly, this experience has made me realize all that is good about Carleton College and it’s people.

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