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# Deformation within the Cannibal Creek Pluton and its aureole, Queensland, Australia: a re-evaluation of ballooning as an emplacement mechanism

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**Abstract**—Structures within the foliated Cannibal Creek granite and its deformed aureole indicate that the pluton appears to have been emplaced after a minimum of two strong regional deformation events ($D_1$, $D_2$), that contact metamorphic porphyroblast growth began during the early stages of a third aureole-centred event ($D_a$), and that a fourth weak deformation overprints all earlier structures, at least within the strain-softened aureole. The aureole deformation ($D_a$) is most strongly developed at the pluton contact, decreasing in intensity both inwards to the core, and outwards into the wall rock. Earlier interpretations linking $D_a$ strain to expansion (ballooning) of the pluton during emplacement are no longer favoured. Previously discussed diagnostic criteria of ballooning, such as closed elliptical trend lines for the aureole foliation, and new field evidence, such as radial magmatic lineations and moderate to high-temperature solid-state deformation of external sheath dykes, are either ambiguous or point strongly toward syn- to pre-tectonic emplacement of a piercement diapir. Less than 30% of the pluton volume appears to have been accommodated by wall rock shortening as the result of ballooning or diapiric ascent. The rest was likely accommodated by a combination of broad wavelength regional doming (1–5 mm year$^{-1}$) above the pluton, far field redistribution of mass into the source area plus or minus some component of diapiric backflow, stoping, assimilation and dilation in fault bends or fold hinges.

## INTRODUCTION

MUCH controversy still revolves around how room is made for large volumes of magma. Hypotheses advanced include fault-related transport and opening (Marsh 1982, Castro 1986, Glazner 1991), stoping (reviewed in Paterson & Fowler 1993), assimilation or wall-rock melting, diapirism (Dixon 1975, Cruden 1990) and the concept of ballooning plutonism (Sylvester *et al.* 1978, Brun & Pons 1981, Bateman 1984, 1985a, Ramsay 1989). In fact, different plutons may have markedly different emplacement histories, and may make room for themselves by different mechanisms. Detailed structural studies are needed, in many cases, just to distinguish between the effects of emplacement and the effects of syn- to post-emplacement regional deformation; these distinctions often rely on model predictions for emplacement-related and for tectonic structural patterns, but for some modes of emplacement, models are still lacking or overly simplistic.

In the case of plutons with deformed aureoles, the concept of ballooning (the radial expansion of magmatic bodies making room by solid-state deformation) has been increasingly cited as a dominant mechanism of intrusion. Examples include the Papoose Flat pluton (Sylvester *et al.* 1978), the Cannibal Creek pluton (Bateman 1984, 1985a), some zoned plutons in Japan and Baja, California (Schimizu & Gastil 1990) and numerous plutons in France (Brun & Pons 1981, Lagarde *et al.* 1990). In the ballooning model, progressive input of magma from below leads to radially-directed expansion of the pluton (outward normal to the contact), creating room by ductile shortening in the solid state of the host rock and early intrusive phases (Bateman 1985a, Ramsay 1989) or shortening in the solid state of the outer early-cooling rind and wall rock of a single-phase pluton (Sylvester *et al.* 1978).

The model of ballooning plutons needs to be examined in more detail, particularly because many of the so-called 'diagnostic features' of a ballooning pluton—for example, concordant foliations in the wall rock, flattening strains, wall rock attenuation, etc.—can be produced by diapiric processes (Cruden 1988, Schmeling *et al.* 1988) or by regional deformation around pre-existing plutons. This study will take a fresh look at a classic ballooning pluton, the Cannibal Creek granite of Queensland, Australia (Bateman 1984, 1985a), reassessing the ballooning hypothesis in light of new field and microstructural data. As discussed below in more detail, structural data from this study are fully consistent with diapirism and pre- and post-emplacement regional deformation, whereas some evidence, such as sheath dyke deformation, are inconsistent with ballooning. From shortening estimates in the wall rock and pluton, it appears that insufficient room could have been made for the pluton by ballooning, although very small distal strains which are not apparent in the field may cumulatively provide additional room of uncertain magnitude. A combination of mechanisms was likely responsible for emplacement, some possibilities of which will be discussed below.

## GEOLOGICAL SETTING AND PREVIOUS WORK

The Cannibal Creek pluton, located in north-central Queensland (Fig. 1), is a granitoid pluton of uncertain

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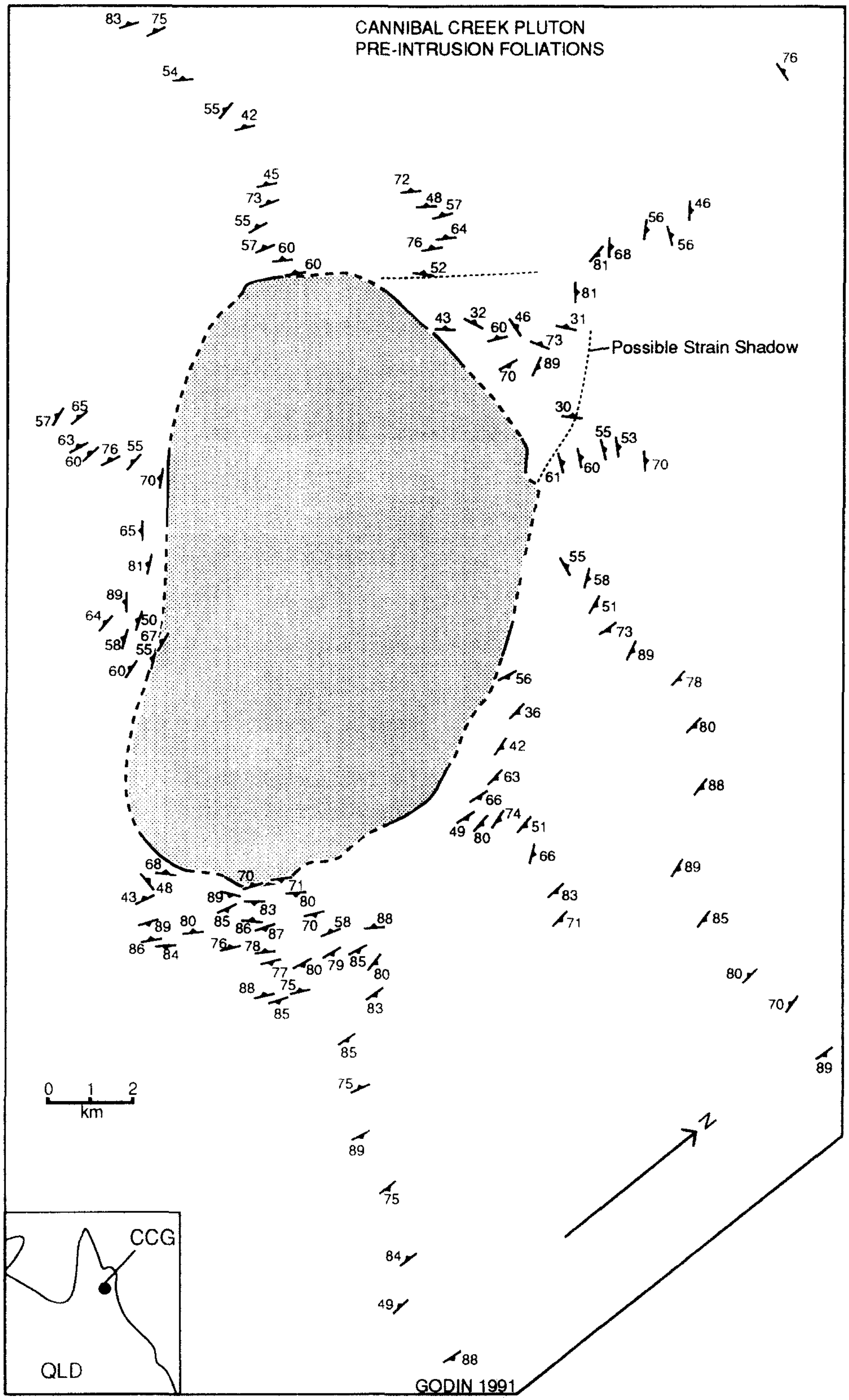


Fig. 1. Map of pre-intrusion (pre-$D_a$) structures around the Cannibal Creek granite, from this study only. Foliation attitudes (generally $S_2$) are shown by strike and dip. The pluton is shaded, and the surrounding wall rock is undifferentiated. Unfortunately, the southwest portion of the pluton was inaccessible. See Bateman (1985a) for comparison of structures.

age (Devonian or younger; Bateman 1985, B. Davis personal communication 1991), intruding undifferentiated turbidite–greywacke schists of the Silurian–Devonian Hodgkinson Province (Amos & de Keyser 1964, de Keyser & Lucas 1968, Arnold & Fawckner 1980). The 16 × 9 km pluton was interpreted by Bateman (1984, 1985a,b) as a classic example of a ballooning pluton, expanding radially outwards to deform a static aureole during the final stages of diapiric emplacement. This interpretation was later challenged by Paterson (1988, 1989), who proposed that the pluton and aureole structural patterns were equally (or more) consistent with emplacement of a piercement diapir without ballooning, followed by regional deformation.

Bateman (1985a) originally proposed the following history for the area:

(1) $D_1$ regional folding (forming $S_1$) in the lower Devonian;

(2) ascent of the Cannibal Creek pluton along fractures and then finally as a diapir, kinking the wall rock;

(3) radial expansion (flattening plane parallel to contact) of the diapir, *in situ*, as material continued to well up from below, leading to the major aureole deformation (forming $S_a$);

(4) late, brittle ring and sheath dyke emplacement, and;

(5) two late weak regional deformations ($D_2$ and $D_3$), described mainly indirectly from apparent folding of earlier fabrics (Bateman 1985a).

Post-tectonic *in situ* ballooning of a diapir was advocated by Bateman (1985a) as the emplacement mechanism based on a number of criteria, many of which are ambiguous with respect to other emplacement methods. His most relevant lines of evidence for such an emplacement include: (a) $S_a$ overprints early kinks formed during diapiric rise; (b) syn-kinematic (i.e. syn-$S_a$) contact porphyroblast growth; (c) solid-state deformation is superimposed on a magmatic foliation in the pluton; (d) closed elliptical contours for $S_a$ which are more circular than the pluton shape; (e) steeper dips for $S_1$ and bedding than for $S_a$, believed unlikely for diapirism; (f) increases in strain intensity and $S_a$ development as one approaches the pluton contact; and (g) the oblate (flattening) nature of the $S_a$-related strain.

Paterson (1988, 1989) pointed out, in contrast, that the structures are more consistent with piercement diapirism followed by later weak regional deformation. The arguments of Bateman (1984, 1985a,b) and Paterson (1988, 1989) will now be re-examined in light of more recent field and microstructural work in and around the Cannibal Creek granite.

## FIELD OBSERVATIONS

Mapping in both the pluton and the aureole has confirmed the presence of *at least* one major deformation in the wall rock prior to intrusion of the pluton (Bateman's 1985a pre-intrusion $S_1$). Although no direct truncation of those structures against the pluton was observed, the early foliation is overprinted and transposed in the contact aureole by $S_a$, the contact-parallel aureole foliaton. No evidence was observed for *pre-*$S_a$ diapirism-related kinking of the wall rock. Locally, minor kinking was seen, but in all cases, the kinked foliation was $S_a$ and not the earlier regional foliation; therefore, kinking formed after emplacement was well under way.

Microstructural work (to be discussed in more detail below) has shown that Bateman's (1985a) $S_1$ regional fabric is actually a pervasive $S_2$ cleavage (hereinafter referred to as such), crenulating an earlier $S_1$ cleavage that is no longer readily visible at the hand specimen or outcrop scale. The $D_2$ deformation was followed by $D_a$, which in turn was followed by a weak regional deformation, referred to in this study as $D_4$.

The $D_2$ and $D_a$ events produced strong spaced to pervasive cleavages, marked by dark selvage-like surfaces, crenulation planes and/or strong alignment of mineral grains parallel to the schistosity; the $D_1$ event may also have created a pervasive cleavage, but was not clearly seen in the field. The $D_4$ event, however, is definitely weak in comparison to the earlier ones, even where $S_4$ is best developed (see Fig. 2a), seen only as an axial plane to local folding or kinking of the $S_a$ foliation.

As seen in Fig. 1, the pre-intrusion $S_2$ regional fabric now wraps around the pluton, but regionally has a generally N- to NNW-strike and steep dip. A potential 'strain shadow' (an area in which early foliations did not undergo substantial re-orientation) with $S_2$ (or possibly $S_1$?) at a high angle to the pluton contact is seen north of the pluton, but its counterpart in the south end is not readily seen, perhaps largely because the southern tip of the pluton was inaccessible. Field evidence for $S_1$ is poorly defined, however, consisting of several outcrops with two fabrics that appear to pre-date $S_a$, based on cross-cutting and folding relationships.

Development of $S_a$ is marked by deformation of the earlier $S_2$ fabric, which is a pervasive cleavage defined by strong colour or compositional banding, axial planar to tight isoclinal folds of bedding (and/or pre-existing $S_1$ banding). Close to the pluton, $S_2$ may be nearly completely transposed into parallelism with $S_a$ (Fig. 2b), although local zones of heterogeneous strain confirm that $S_a$ post-dates $S_2$.

At distances of >5 km from the contact, $S_a$ is difficult or impossible to recognize, but as one approaches the contact, it increases in intensity. Approaching the pluton from several km away, the first evidence of $S_a$ is dark mm- to cm-spaced dissolution seams (that in thin section are seen to be crenulations of $S_2$) in pelitic layers. Within 2–3 km of the pluton, weak crenulations are observed macroscopically, which increase gradually in intensity towards the contact, grading into macroscopic open to moderately tight (60° interlimb angle) folds of bedding and/or $S_2$, with a mm-spaced axial-planar ($S_a$) crenulation cleavage (Fig. 2a). In the inner 1 km of the aureole, it becomes increasingly difficult to identify two fabrics as $S_2$ is transposed into parallelism with $S_a$ (Fig. 2b). Only a pervasive $S_a$ is usually visible within 100–500 m of the contact.

In terms of timing, $S_a$ appears to be syn-emplacement. Locally, undeformed granitoid dykes are seen which cross-cut both $S_a$ and folded $S_2$. On the other hand, deformed dykes with solid-state fabrics subparallel to $S_a$ in the wall rock are also seen. These contrasting field observations are consistent with $S_a$ being *broadly* syn-emplacement but do not provide conclusive evidence as there may be several generations of dyke emplacement.

Within the pluton (Fig. 2c), the foliation is generally defined by one or more of: elongate tabular megacrysts of K-feldspar, moderate to weakly aligned micas and mica clots, oblate mafic microdioritic layers and occasional xenoliths (close to contact), tabular plagioclase crystals, and elongate quartz grains/clots. Using the criteria reviewed by Paterson *et al.* (1989), the foliation observed has a largely magmatic origin, with alignment of magmatic megacrysts during magmatic to submagmatic flow. Quartz is mildly elongate or anhedral, particularly as one moves away from the contact, while plagioclase and tabular K-feldspar megacrysts are euhedral to subhedral. The magmatic foliation within the pluton is moderately strong in the south, east and north but relatively weaker in the western interior of the pluton, except close to the contact, generally orientated parallel to $S_a$ in the aureole.

Close to the contact zone, solid-state deformation is also seen within the pluton, generally subparallel to the magmatic foliation, but sometimes oblique to it (Fig. 2d). This solid-state fabric ranges from nearly homogeneous development of an anastamosing cleavage (Fig. 2d; near the contact), marked by the alignment of micaceous clots and ovoidal quartz and/or feldspar, to more heterogeneous development, with spaced shear surfaces separating less deformed zones. Towards the core of the pluton, solid-state deformation is generally weakly developed, if detectable at all, consistent with the observations of Paterson (1988). The formation of this solid-state overprint will be discussed in more detail along with microstructures.

Bateman (1985a) has described $S_a$ as forming closed elliptical trends with a more circular shape than the pluton itself, thus cross-cutting the boundary. Paterson (1988), using Bateman's (1985a) data, has shown that there appears to be a discordance between steep pluton foliations and shallower wall rock foliations.

This study has found that in general, $S_a$ strikes subparallel to the contact, both in the pluton and the wall rock (see Fig. 4), forming approximately elliptical closed trends without noticeably cross-cutting the pluton contact (Fig. 2e). The dip of $S_a$ varies up to 50° or more in any given radial transect, even within the pluton alone, and no *consistent* pattern of dip is seen; traverses across the contact included areas where the schistosity of the wall rock was actually 20° steeper than the pluton foliation. Magmatic and solid-state foliations in the pluton are generally parallel. Noticeable obliquities between the aureole foliation and the pluton foliation *were* observed, however, at one point on the contact (north end—wall rock foliation is 215/17°NW within 15 m of contact showing a strong magmatic foliation of 275/52°N), raising serious doubts about expansion of the pluton, but this effect may be related to strain heterogeneity, as it was the only observed case of such marked obliquity.

Magmatic lineations, defined by orientations of euhedral tabular K-feldspar megacrysts, were detected in several locations, forming a crudely radial pattern (nearly down-dip, except for one in the west-central portion of the pluton which was defined by mica alignment). More lineations might have been observed, but as Bateman (1989) pointed out, the outcrop style makes identification of such lineations difficult in the field. Such a radial pattern of magmatic lineations would be consistent with magmatic flow during diapiric ascent (Schmeling *et al.* 1988, Cruden 1990).

Stretching lineations in the wall rock are rarely observed *in situ* and show no consistent orientation or strength (see Figs. 2f and 4). Such lineations were observed on both the $S_2$ and the $S_a$ foliation plane.

The latest generation of structures observed in the field is the $S_4$ cleavage, a weak crenulation or kinking of $S_a$, observed only locally (Fig. 2a). Although only a dozen $S_4$ planes were measurable, they cluster weakly around an average orientation of 336/78°NE, similar to the orientation of regional $S_2$ structures. The origin of this event is difficult to pin down given the few instances in which $D_4$ structures were seen and measurable, but appears to be a weak post-$S_a$ deformation as it kinks the aureole foliation. More information on the relative timing and significance of the structures described comes from looking at microstructures.

## MICROSTRUCTURES

### *Wall rock*

Microstructures were examined from three complete radial transects (to the east, to the north and to the west) in the wall rock, one radial transect in the pluton (northern sector) and a selection of samples in the south and east (Fig. 5). The results were fairly consistent from all transects, indicating that the structural timing described above is probably correct.

Evidence for an $S_1$ cleavage comes mainly from the eastern transect, where three samples (CC29, CC33 and CC8) preserve evidence of $S_2$ crenulating an early pervasive cleavage ($S_1$) (Fig. 3a). The $S_1$ cleavage is defined by pervasive mineral grain alignment, and is found as relict lenses around which the $S_2$ cleavage anastamoses. As discussed above, field evidence in the northern part of the aureole also suggests that there may be two pre-intrusion cleavages.

In all pelitic samples examined, $S_2$ is a pervasive cleavage, defined by mica plus or minus quartz alignment (Fig. 3b). As one approaches the pluton, the $S_2$ cleavage is increasingly more intensely crenulated by the $S_a$ cleavage, with almost complete transposition of $S_2$ into parallelism with $S_a$ near the contact (e.g. CC104, CC106). Far from the pluton, the aureole cleavage is a mm- to cm-spaced crenulation, relatively weak and irregular in orientation. Close to the contact, the anastamosing $S_a$ has almost obliterated the $S_2$ cleavage by transposition, except in small lensoid domains and porphyroblasts.

As pointed out by Bateman (1985a, 1989), the wall rocks display some 'millipede structures' (Fig. 3b), which are believed by Bell & Rubenach (1980) to represent bulk inhomogeneous shortening of the rock. Some component of bulk inhomogeneous shortening was probably experienced by the rocks, but evidence of non-coaxial strain was equally or more abundant (Fig.

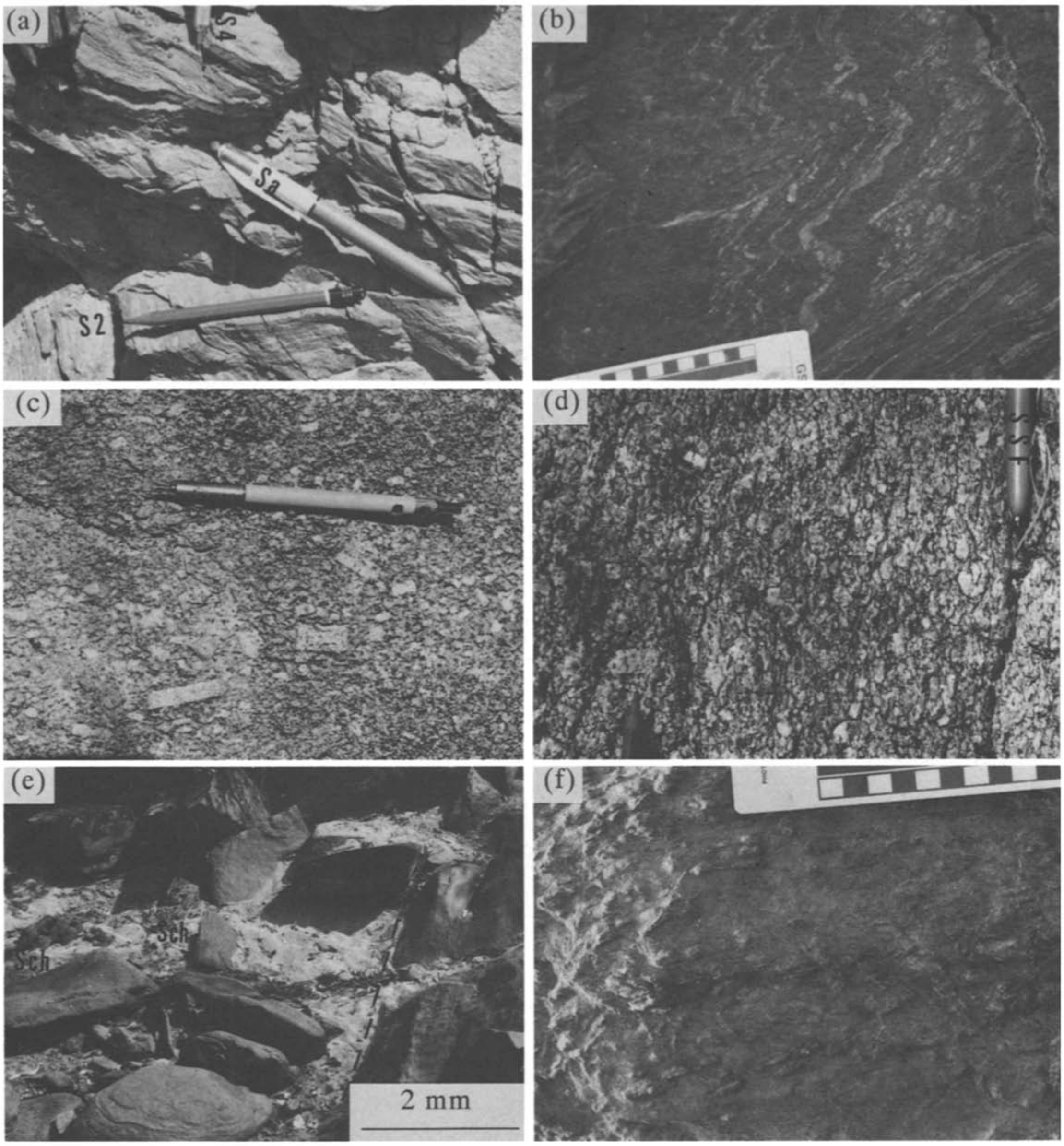


Fig. 2. (a) Three generations of structure. $S_2$ is a pervasive cleavage cut by the $S_a$ ($=S_3$) crenulation cleavage, which is in turn crenulated weakly by the $S_4$ plane in the upper left (parallel to pen tip). West side of pluton (near sample CC185 location). (b) $S_a$ (parallel to cm ruler) transposes $S_2$. Transposition is most highly developed in lower right. Close to western contact, near sample CC201. (c) Typical magmatic foliation, defined by aligned tabular euhedral megacrysts of K-feldspar (parallel to pen). (d) Solid-state foliation (SSF) cross-cutting magmatic foliation. SSF is defined by micaceous folia and ovoidal feldspar slots and is at almost right angles to the magmatic foliation measured in the field (parallel to base of photograph and megacryst). Near CC224. (e) At pluton contact (dashed; 130/55°SW), some xenoliths are seen in the first few metres of the pluton, with relatively oblate shapes. Wall rock schistosity (129/51°SW, seen at 'Sch') parallels contact; $S_a$ can also be seen on the contact surface. West side, southeast of CC156. (f) Lineation in the wall rock defined by porphyroblast alignment, parallel to cm ruler.

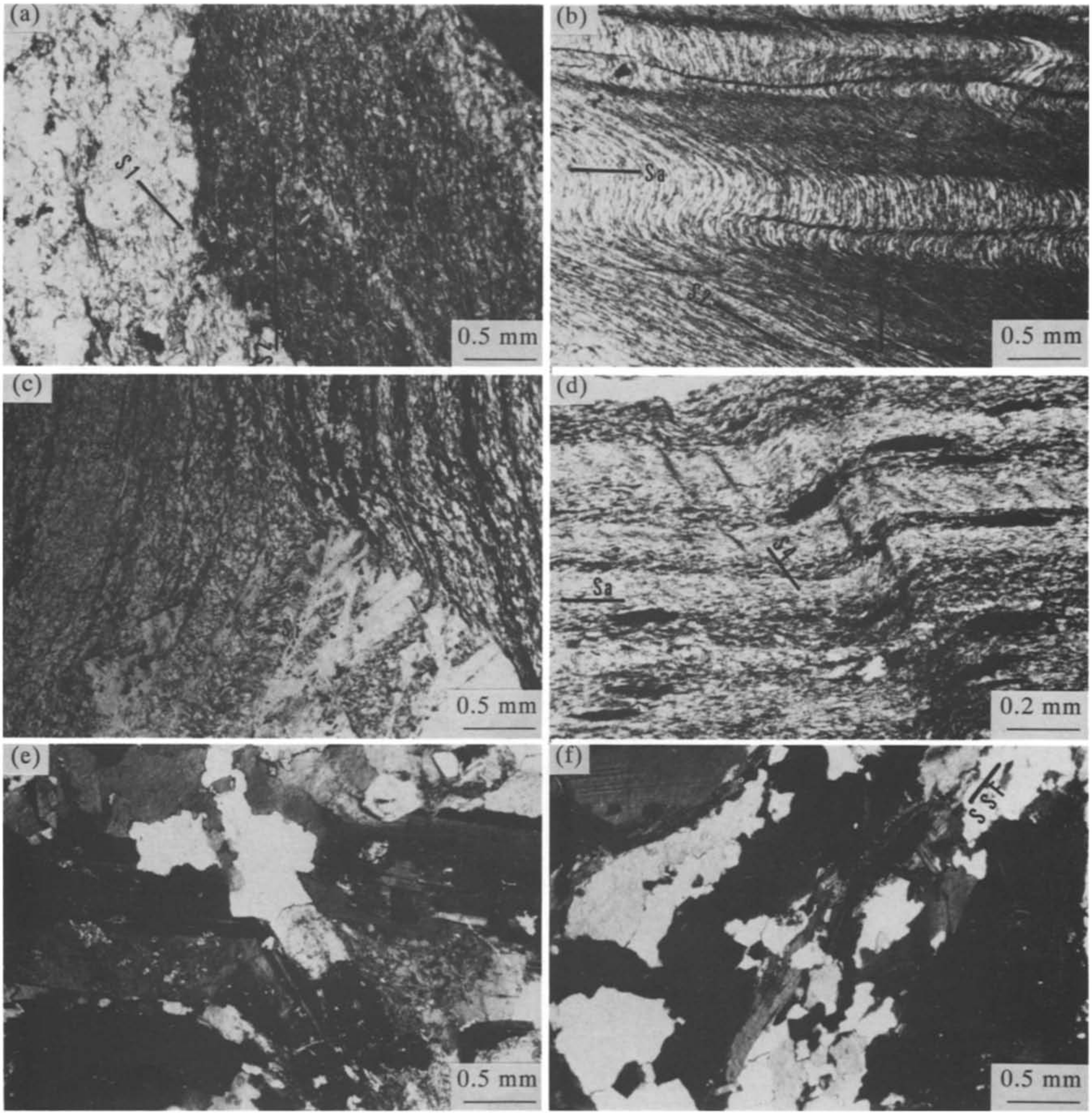


Fig. 3. Photomicrographs. (a) $S_1$ and $S_2$ cleavages in distal sample (CC29). Dominant foliation is $S_2$, a pervasive to sub-mm spaced cleavage in both the quartz-rich layers (light coloured) and the micaceous pelite layers (dark). $S_1$ is a pervasive cleavage seen only in the pelite, showing evidence of folding; plane polars. (b) Pelitic sample (CC180) showing crenulation of $S_2$ by $S_a$, and development of some millipede structures. $S_2$ is a pervasive cleavage, while $S_a$ is a sub-mm-spaced crenulation cleavage, defined by fold hinges and selvages. $S_a$ is itself overprinted by $S_4$, seen as dark banding in lower right. Plane polars. (c) Sericitized andalusite porphyroblast (bottom) in pelitic schist (CC49), showing inclusion trail geometries (see Fig. 6 for details). Within the porphyroblast, an earlier stage of crenulation is overgrown—a pervasive $S_i$ ($=S_2$) is crenulated by a spaced cleavage that is oblique to, but continuous with the matrix $S_a$. Porphyroblast growth appears to be early syn-$S_a$. Plane polars. (d) Pervasive $S_a$ ($S_3$) kinked by $S_4$ in pelitic sample (CC224). $D_4$ strain observed in thin section is minor; plane polars. (e) Igneous textures predominate in pluton core. Alignment of plagioclase growth twins (center) and biotite (lower left) indicate magmatic foliation. Quartz is anhedral and fairly equant in shape, with weakly granoblastic grain boundary shapes, but little recrystallization. Undulose extinction in K-feldspar (lower centre). Cross-polars. (f) Granitoid just inside northwest margin of main pluton. Possible relict magmatic alignment of plagioclase twins is cut by solid-state foliation (SSF). Cross-polars.

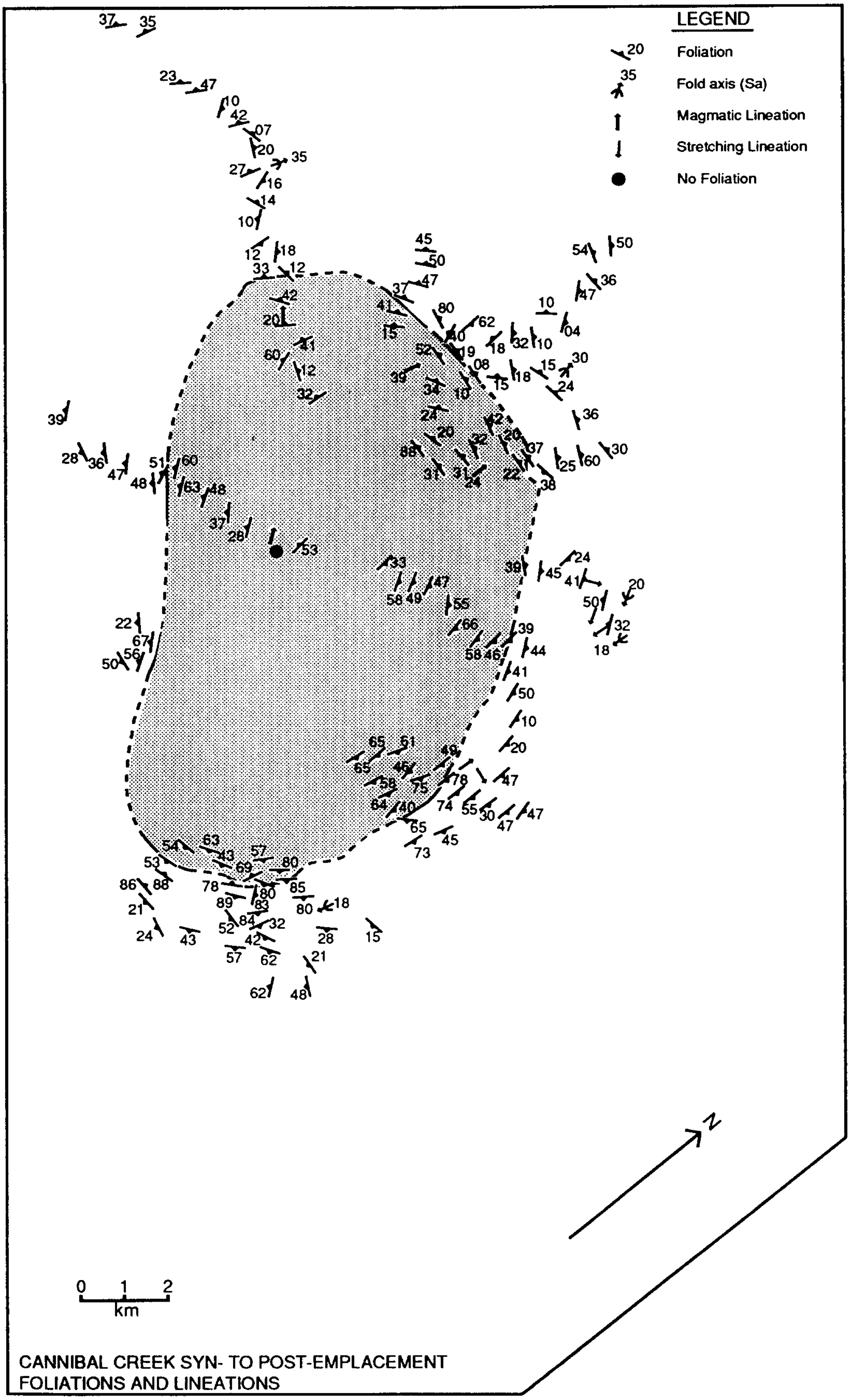


Fig. 4. Map of syn- to post-emplacement structures around the Cannibal Creek granite. The pluton is shaded, and the surrounding wall rock is undifferentiated. All pluton foliations and lineations which are shown appear to be the result of magmatic strain, although sub-parallel solid-state deformation was seen as well (see text). The shallow-dipping foliation patterns in the wall rock west-northwest of the pluton have been influenced by a sub-surface cupola of granite (either a subsurface irregularity of the CCG, or a separate but possibly related pluton) that has been detected in drill core (Bateman 1985a), and do not define kinks. The pluton contact was not fully surveyed in the field, due to the limited time available. See Bateman (1985a, fig. 2) for comparison of structures.

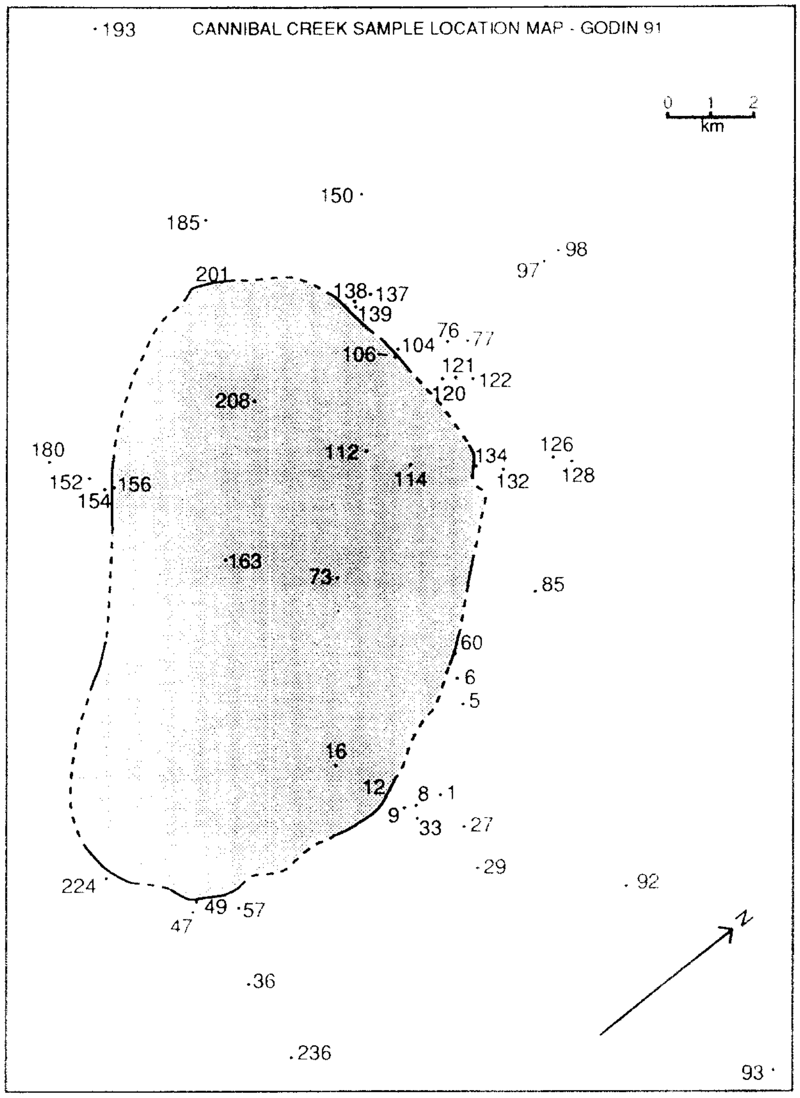


Fig. 5. Sample location map for the Cannibal Creek granite. Pluton is shaded. Samples are numbered as shown (e.g. station 224—CC224).

3b), indicating that there was likely a significant non-coaxial component of the strain as well.

Large (mm-scale) contact metamorphic porphyroblasts of andalusite (wholly or partly sericitized) overgrow the $S_a$ crenulation at an early stage of development, as described by Bateman (1985a, 1989). In samples with nearly pervasive development of $S_a$ in the matrix (Fig. 3c), inclusion trails in porphyroblasts show a sub-mm spaced crenulation of $S_2$, with the crenulation planes inclined at moderate or low angles to $S_a$ as shown in Fig. 3(c) and Fig. 6. This texture is seen in many samples (e.g. CC224, CC8, CC49). In the case of CC224 and CC2, the overgrown crenulation planes (Si) are apparently continuous with $S_a$, but at an angle to $S_a$ as seen in the matrix; distinct oxide horizons can be traced from the matrix into the porphyroblasts. $S_a$ in the matrix wraps around porphyroblasts. This combination of textures would seem to indicate that porphyroblasts grew syn-$S_a$, but after some aureole deformation ($S_i$ crenulations) had begun.

Spaced $S_i$-crenulation planes continuous with $S_a$ in the matrix in porphyroblasts have fairly consistent orientations throughout the samples considered (±20°), and $S_i$ crenulations with the same orientations are also seen in lensoid domains of less-deformed matrix, unrelated to porphyroblasts. For several reasons, the consistent $S_i$ crenulation orientation seems hard to explain with a model of porphyroblast and lensoid rotation during one co-axial or even one non-coaxial deformation (i.e. $D_a$) (Schoneveld 1977, Olesen 1978, Passchier *et al.* 1992). First, the range of sizes and shapes of porphyroblasts makes equal rotation of porphyroblasts unlikely. Second, $S_i$-bearing lensoid domains are elongate parallel to $S_a$ in the matrix, and do not appear to differ markedly in composition from the adjacent matrix which does not preserve $S_i$ trails. If the lenses had rotated to form the obliquity between $S_i$ and $S_a$, they would have to have been part of a larger microlithon that was rotated and later cut down in size and shape by $S_a$ development.

In any case, either the matrix or the porphyroblasts must have rotated during the later $D_4$ weak regional event because the $S_a$ trails in porphyroblasts have an orientation differing from that of $S_a$ in the matrix but the surfaces can be continuously traced from porphyroblast to matrix (see Fig. 6 and Fig. 3c); this texture is seen in most slides examined, including those with the $S_i$ crenulation textures described. The data appear to be most consistent with non-rotation of the porphyroblasts, for the reasons given above, but the evidence is not conclusive (Bell 1985, Bell *et al.* 1986, 1992, Passchier *et al.* 1992).

The latest deformation in all of the slides examined is a weak spaced crenulation or a locally-developed open folding kinking of the $S_a$ fabric, seen on all sides of the pluton (Figs. 3b & d). This axial-planar $S_4$ cleavage is at a high angle to $S_a$ in the sections observed (many from the south end of the aureole). In some samples, such as CC8, there appears to have been local re-activation of $S_2$ layering during the $D_4$ event. Although no macroscopic $D_4$ structures were noted on the western side of the aureole, a local $S_4$ is visible in thin section, crenulating $S_a$ (Fig. 3b; CC180).

*Pluton*

As discussed above, a magmatic foliation is seen throughout the pluton, with a solid-state overprint that increases in intensity towards the contact. Bateman (1985a,b) attributed the solid-state deformation to ballooning of the pluton after the critical melt percentage was passed (<30% melt; Arzi 1978). Paterson (1988, 1989), on the other hand, suggests that the solid-state deformation is a minor later overprint which could not account for the apparent strain estimated from xenoliths (55% shortening—Bateman 1985a; discussed in more detail below).

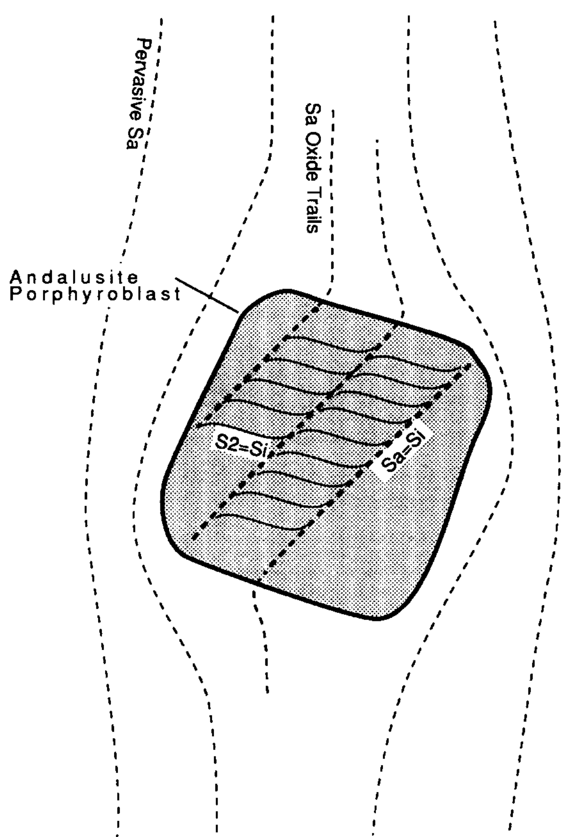


Fig. 6. Schematic diagram of common porphyroblast–matrix relationships seen in wall rock samples of the Cannibal Creek granite. Within the porphyroblast, two cleavages are preserved—an early pervasive $S_1$, which is crenulated by an early stage of $S_a$ development. Individual spaced $S_a$ crenulations can be traced into the pervasively cleaved matrix from porphyroblasts. The textures indicate that porphyroblasts probably grew during an early stage of development of $S_a$.

Within the core of the pluton, igneous crystallization textures predominate, with some low intensity solid-state deformation (Fig. 3e). Igneous textures include weak alignment of subhedral plagioclase grains (and growth twin planes), large subhedral to euhedral biotite and muscovite grains (>2 mm; weakly aligned if at all), large anhedral interdigitating quartz grains (with moderately granoblastic boundaries), and an absence of major recrystallization (Paterson *et al.* 1989). Evidence of weak solid-state overprinting includes: (1) reversion of orthoclase to microcline (Eggleton & Buseck 1980, Paterson *et al.* 1989); (2) minor growth of myrmekite (Simpson 1985, Vernon 1991); (3) biotite grains that show weak local bending or kinking, but very little healing or recrystallization (Paterson *et al.* 1989); (4) undulose extinction in quartz and feldspars, but rare subgrain development and rare grain-size reduction on grain boundaries (Simpson 1985, Knipe 1989). No evidence of strain shadow melt accumulations that might be expected in a submagmatic deformation environment (Hibbard 1987) was seen.

Moving closer to the contact, igneous textures are still dominant and relatively little increase is seen in the component of solid-state deformation until within several hundred metres of the contact. In this contact zone, there is far more recrystallization seen in thin section (Fig. 3f), and the solid-state foliation is defined by distinct anastamosing folia marked by recrystallized fine-grained biotite, muscovite and quartz (Fig. 3f). Dissolution of igneous grains along the solid-state foliation is visible, but no evidence for major non-coaxial deformation was noted. Stronger deformation is also indicated by increasing elongation of quartz grains, higher degree of subgrain formation in quartz, plagioclase and K-feldspar, recrystallization and grain-size reduction of much of the igneous mica, so that almost no kinking was seen, bending of plagioclase twin planes, and common myrmekite pockets on faces normal to the contraction direction rather than in strain shadow positions. The strain appears to have been ductile, with no major cataclasis of megacrysts. These textures point to solid-state deformation at moderate to high temperatures (>550°C; Simpson 1985; Tullis & Yund 1987, Evans 1988), possibly during or just after emplacement and crystallization. Sub-magmatic textures such as myrmekite in strain shadows and submagmatic fractures (criteria of Hibbard 1987, Paterson *et al.* 1989, Bouchez *et al.* 1992) were not observed.

Textures in the external contact-parallel sheath dyke that intrudes the wall rock are inconsistent with the model of deformation timing set out by Bateman (1985a). The sheath dyke, believed to be emplaced after ballooning by Bateman (1985a), shows textures that are the same as those of the contact zone, or if anything, even stronger in the intensity of solid-state deformation.

Here too, a magmatic flow foliation is seen, defined by plagioclase growth twin alignment (bent locally), overprinted by solid-state strain. It appears that intrusion of the sheath dyke occurred before the solid-state deformation that also affected the pluton. Bateman (1985a) concluded that the sheath dyke post-dated ballooning. If so, ballooning could not have produced the solid-state deformation observed. Alternatively, the dyke could pre-date ballooning, but if so, one would have to explain how extensional strains, permitting emplacement of these major contact-parallel dykes in the wall rock, could form in the aureole of a ballooning diapir. More likely is that the solid-state deformation in the pluton is late syn- to post-emplacement in timing.

## STRAIN ESTIMATES AND THE ROOM PROBLEM

Strain estimates in the Cannibal Creek aureole and pluton (Bateman 1985a) suggest that room for the pluton was made by a combination of pluton shortening (70%), wall rock shortening (30–100% present volume of pluton) and regional doming (to 10%). There are serious problems with several of the assumptions that went into these strain estimates, not the least of which is that strains were assumed to be wholly due to volume loss, ignoring any component of constant volume strain. I shall begin with a discussion of strains within the pluton.

### *Pluton*

In terms of pluton strain estimates, the main difficulty arises from the type of strain marker (xenoliths) used by Bateman (1985a), which is also used to reconstruct the 'initial volume' of the pluton. Xenoliths at the contact, with aspect ratios of 5:5:1 were used as evidence for 55% shortening (Bateman 1989), assuming (1) that all strain was by volume loss, and (2) that xenoliths began with aspect ratios of 1:1:1. Problems with assumption (1) are discussed below in reference to the wall rock. Assumption (2) is unrealistic given both the schistose nature of the wall rock, and the evidence for magmatic flow. The $S_2$ foliation is pervasive and wall rocks are strongly banded. If a xenolith were to fracture into the melt, it would most likely spall in with a strongly oblate initial shape, rendering strain estimates invalid (Paterson & Fowler 1993). In addition, for both xenoliths and schlieren layers, the possibility of strain during magmatic flow has been well documented (Vernon 1984, Vernon *et al.* 1988, Guglielmo 1993, Paterson & Fowler 1993). Almost all of the apparent flattening of xenoliths and schleiren layers could have taken place by spalling of disc-shaped xenoliths into the magma and by strain during circulation of the melt, without any expansion of the pluton.

A quick test of the validity of assumptions about xenolith strains is to look at the reconstructed model of the pluton's volume and radius based on xenolith data. Using this reconstruction, a radius of 9 km is attained (Bateman's fig. 11, 1985a), and the predicted dip of the contact at the present erosional level is measurable as 24°. In fact, the dip of the contact is generally 45–80° in the field, as measured from contact foliation attitudes and actual exposures. This discrepancy means that: (1) the xenolith strain estimates break down when used for reconstruction; and (2) the modeled pluton radius is probably too large.

Moreover, as Paterson (1988) has pointed out, the solid-state deformation observed in the pluton is too low in intensity to reconcile with 55% shortening. No evidence of massive volume loss is seen; selvages of dissoluble material are rare in thin sections.

### *Wall rock*

In terms of wall rock strains, Bateman (1985a) divided the aureole into four zones. (1) An inner zone of penetrative cleavage with an estimated 40% shortening, which is a reasonable hypothesis normally, except that the wall rock had already developed a penetrative cleavage in both $D_1$ and $D_2$, therefore the $D_a$ schistosity formation may involve more re-activation than new shortening. (2) A zone of folding and crenulation with shortening normal to the pluton of 15–25%, a value that is also reasonable (rough fold strains measured in this study ranged from 28 to 45% as *maximum estimates* in the inner km of the aureole). (3) A zone of kinking with 10% shortening is, I believe, an overestimate, given the minor post-Sa deformation seen in thin section, and the rarity of macroscopic kinking. (4) A zone up to 45 km away from the pluton averaging 1% shortening (invisible strain involving reactivation of $S_2$ cleavages), which I also find hard to accept. The fourth zone's existence is postulated on the basis of simplified theoretical studies (Marsh 1982), and is not based on field or microstructural evidence. Such a zone is inconsistent with the small width (<2–3 km) of strained structural aureoles observed around other plutons of similar size (Paterson & Fowler 1993; see also Guglielmo 1993 (4+ km)). These studies suggest that emplacement-related strain beyond 3–4 km of the contact is near zero. Theoretical modelling of emplacement-related strains by Guglielmo (in press) supports the possible existence of small surreptitious distal strains which may have been overlooked, but the importance of such strains in accommodating pluton emplacement is uncertain. Actual distal strains may dissipate somewhat closer to the pluton than in model estimates, due to strain heterogeneity and the role of micro- and macro-structural surfaces in taking up strain.

If only the first three zones are used, wall rock shortening accounts for only 30% of the volume of the pluton (Bateman 1985a; in the same range as that predicted around other plutons with better strain data; Paterson & Fowler 1993), but even this is an overestimate. Assuming volume loss in shortening estimates, as opposed to some component of constant volume strain, causes shortening estimates to be higher than they likely are (almost double the value for constant volume strain).

Although a few instances of volume losses of up to 50% have been described (Wright & Platt 1982, Beutner & Charles 1985), higher estimates are rare. The role of distal shortening may accommodate further room, but there is no evidence that it could accommodate the >70% needed.

*Room problem*

However space was made, it does not appear to have been made entirely or even largely by shortening of the wall rock and the pluton. Re-examination of the data and assumptions indicates that a reasonable estimate of space made by such a mechanism is approximately 30% of the pluton volume, and even that estimate involves not the creation of space, but the transfer of material from around the pluton to some other location. Transported material must move towards a free surface, either a structural void (fault bend), or the earth's surface, or down into the source area of the magma.

Potential models for making room (for a full discussion of each model and its problems, see Paterson *et al.* 1991a,b) include stoping, assimilation of wall rock, fault-related opening (local dilation) during regional deformation, dilation in fold hinge regions during deformation, ballooning as discussed above, diapiric backflow, and regional or roof uplift during diapirism. The latter possibility, raised as an alternative by Bateman (1985a), has renewed importance. Diapiric experiments involving a free surface were conducted by Cruden (1988, 1990) which suggest that diapirs may not form rim synclines. For diapirism then, either the near-field rise of wall rock during pluton ascent is offset by even more far-field descent of wall rock, or all of the room must eventually be made at the free surface (the Earth's surface) by uplift.

Most probably, a combination of the above processes is responsible for making room for any given pluton, dependent on parameters such as depth of emplacement, temperature of magma, heterogeneity of the crust and the nature of ongoing crustal deformation. Evidence from this study will be used to address the question of emplacement in terms of the end-members listed above.

Evidence for widespread stoping and assimilation is lacking, although detailed geochemical work has not been done (Bateman 1985b). Stoped wall rock blocks are generally only seen within 10–20 m of the pluton contact, and are of small sizes. Microdioritic enclaves are not uncommon, but may be of magmatic origin (Vernon 1984, Vernon *et al.* 1988). If large stope blocks are present, they must be located in the subsurface.

Although some faults have been mapped in the area with uncertainty (Amos & de Keyser 1964, Bateman 1983), the geometry of the faults does not appear to be consistent with fault-related dilation that might have made room for incoming magma. Equally uncertain is whether or not there may have been an initial dilation within a large $D_2$ fold hinge by décollement, permitting the accumulation of some melt in the early stages of ascent and/or emplacement. If such a large fold was present in the proper geometry, however, it is not easily defined now, mainly because of the poor stratigraphic control within the Hodgkinson Province near the pluton (Amos & de Keyser 1964).

As noted above, ballooning is unlikely to have accounted for more than 30% of the volume of the pluton by wall rock shortening, probably an overestimate, although as noted above, there is some question as to the reliability of wall rock strain estimates. Regional deformation during and/or following emplacement could account for the same wall rock shortening without making any room for the pluton at all. Diapiric emplacement might also lead to significant wall rock shortening (Dixon 1975, Cruden 1988, 1990, Schmeling *et al.* 1988), although theoretical studies using temperature-dependent wall rock viscosities (Marsh 1982, Mahon *et al.* 1988) suggest that strain patterns should show (1) a narrow deformation zone of high shortening strains close to the contact, with (2) abruptly lower strains beyond the deformation zone.

The amount of room created by possible diapiric backflow is unquantifiable at this point. No obvious rim syncline (Dixon 1975) is observed around the Cannibal Creek granite, although reversals in dip direction of $S_a$ are seen to the northeast of the pluton contact (Fig. 4). Exposure levels in the upper half of the pluton may not reveal the presence of rim synclines, in any case, so the possibility of backflow as a space-making mechanism cannot be discarded at this point.

Absence of major steep contact-parallel faults precludes local uplift of a roof plug, but the possibility of regional doming of the free surface needs to be considered, especially if diapirism is involved in emplacement but no rim syncline is formed (Cruden 1990). Such a mechanism involves far field and near field strain redistribution (Paterson *et al.* 1991a,b, Paterson & Fowler 1993), both to replace lost magmatic volume in the source region, and to compensate for the emplaced volume higher in the crust. One possible model involves near field strain around the pluton to accommodate the excess volume, in part by gentle doming above the pluton (see Fig. 7). Farther away from the pluton, meanwhile, material is moving radially from all sides into the source region at depth to compensate for ascent of the magmatic volume. Relative to a reference surface parallel to the geoid, the surface area above the pluton (even well beyond the radius of the pluton) domes gently upward above the equilibrium level by several cms to several metres, while the area farther away may even subside somewhat, so that doming is offset partially or wholly by distal subsidence. Material is simply redistributed, with large displacements of a small volume of wall rock in the near field strain regime of the pluton, and much smaller displacements of a larger volume on a regional scale (Fig. 7). While far-field redistribution proceeds slowly, much of the excess near field volume may be accommodated (buffered) by the doming of the free surface. Known uplift rates suggest that this is a plausible mechanism.

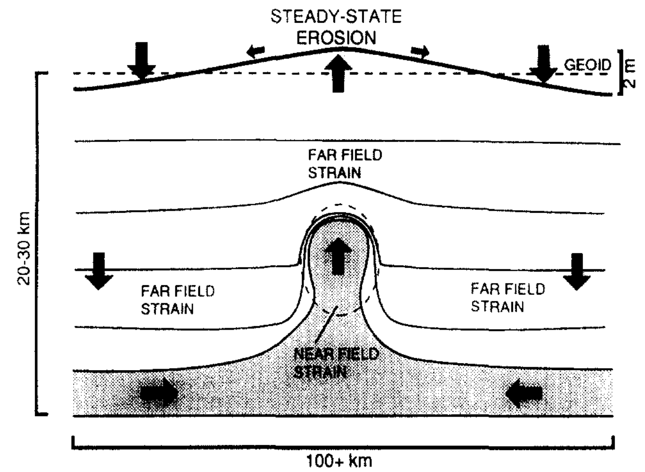


Fig. 7. Regional doming as a possible far-field mechanism for accommodating pluton emplacement. See text for discussion. The scales shown on the left and bottom are regional (in km), while the scale on the right (m or even cm) refers only to the uplift of the Earth's surface relative to an arbitrary geoid-parallel plane (dashed). Regional doming of a few tens of cm might occur over a diameter up to 10 times the diameter of the pluton itself (Reilinger *et al.* 1980), although there may be more localized, unusually high uplift (to 3.5 m) of the actual roof area (e.g. Campi Flegrei, Italy; Bianchi *et al.* 1987). Near field mechanisms are concentrated in wall rock and possibly pluton outer shell.

Uplift rates in areas of active plutonic activity are on the order of 5 mm year$^{-1}$ (Rio Grande, U.S.A., Reilinger *et al.* 1980) to 53 cm year$^{-1}$ (Campi Flegrei, Italy—70+ km$^2$, Berrino *et al.* 1984, Bianchi *et al.* 1987) and may be developed over areas of up to 7000 km$^2$ (Reilinger *et al.* 1980). Doming at these rates would require just over 40,000 years or less to accommodate the volume of the Cannibal Creek granite (assuming initial volume of 1500 km$^3$). This time period is fully consistent with known emplacement and crystallization rates suggesting that plutons require from 20,000 to 2 million years for emplacement (Barton *et al.* 1988, Mahon *et al.* 1988). One problem with a model of continued uplift is that the uplift forces are related to relative densities of the magma and the wall rock (buoyancy forces), and these forces are of limited strength (several hundred bars; Marsh 1982).

One way of continuing uplift even with a fixed small buoyancy force is to set up a steady-state uplift–erosion cycle. Reliable regional erosion rates for mountainous areas (England & Molnar 1990) are on the order of 0.7 to several mm y$^{-1}$, which is the same order of magnitude as uplift rates. Material from the domed area is eroded, moving off to the sides, thereby allowing continuous steady-state doming with only limited buoyancy uplift forces. Thus, it is possible that much, though probably not all, of the room needed for the pluton could be made by steady-state doming–erosion of the free surface above the pluton as shown in Fig. 7.

Unfortunately, there is no clear evidence supporting regional uplift at the Cannibal Creek site except that such a theory is not inconsistent with the data observed and it is the most likely alternative. Detailed work on geothermometry–geobarometry and geophysics would be required, but such supporting data sets are unavailable for the Cannibal Creek area as yet; the region itself has been only lightly surveyed.

Having reviewed the many possible ways of making room for the Cannibal Creek granite, it is obvious that there are numerous ways to account for portions of the emplacement space needed, but no firm evidence that any one process dominated. A combination of several mechanisms is favoured, specifically near-field processes such as wall rock shortening and backflow during diapiric emplacement, initial fold hinge dilation, plus or minus stoping, assimilation, and fault-related dilation, and far-field mechanisms such as regional doming plus or minus possible fault-related dilation. Near-field mechanisms must be compensated by far-field material redistribution at some point, and it seems reasonable that they operate in tandem, although far-field strain rates may be slower than near-field strain rates in the strain-softened aureole.

## SYN-TECTONIC BALLOONING OR SYN-TECTONIC DIAPIRISM

Having gone through the field evidence, microstructures and strain data, it is time to review the criteria in favour of ballooning and determine if there are alternative emplacement mechanisms.

### *Timing*

*Criterion* 1: *Syn-*$S_a$ *contact metamorphic porphyroblast growth*. This observation has been supported, although overgrowth of an early stage of $S_a$ ($S_3$) crenulation (similar to that seen in the matrix at greater distances from the pluton) by porphyroblasts close to the contact suggests that deformation began before porphyroblast growth. Again, this timing is equally or better suited to deformation during diapiric rise, or to early syn-emplacement regional deformation around the incoming pluton than to ballooning.

### *Mechanism*

*Criterion* 2: *Overprint of solid-state deformation on magmatic foliation*. The intensity of solid-state deformation in the pluton is not sufficient to create much room for emplacement. There is no strong evidence of sub-magmatic deformation which would be expected during ballooning (Paterson *et al.* 1991a,b), but there was moderate to high temperature strain (>550°C). As pointed out by Paterson (1988), the solid-state strain could also have resulted from regional deformation following a diapiric emplacement. Evidence for such a deformation has been documented ($D_4$ this study; Bateman's (1985a) $D_2$, $D_3$).

*Criterion* 3: *Closed elliptical contours for* $S_a$ *that are more circular than the pluton boundary*. As noted above, the $S_a$ contours actually appear to be sub-parallel to the pluton contact, both regionally and where the contact is exposed. It has been demonstrated experimentally and theoretically that intrusion of a diapir will create a contact parallel fabric (Cruden 1988, 1990, Schmeling *et al.* 1988). Even if that fabric is later deformed, it will retain closed elliptical contours. It is also possible to create closed elliptical patterns of $S_a$ by diapirism during a regional deformation (the tectonic squeeze model, Fig. 8).

*Criterion* 5: *Steeper dips for* $S_1$ *and bedding than for* $S_a$. Experimental models of diapiric ascent have shown that oblate fabrics will be formed during diapiric ascent ($S_a$?) without pluton expansion (Cruden 1988), and these fabrics will have dips less steep than initially vertical markers (Bateman's $S_1$; 1985a). Even in the diapiric models of Dixon (1975), vertical markers are often seen to be steeper than $S_a$, generally highly folded.

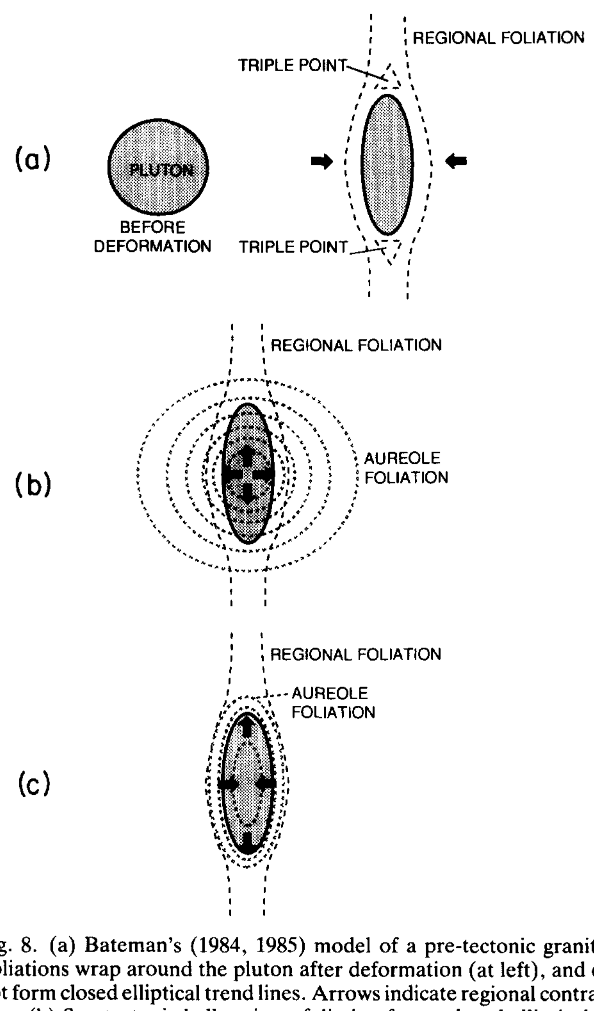


Fig. 8. (a) Bateman's (1984, 1985) model of a pre-tectonic granite. Foliations wrap around the pluton after deformation (at left), and do not form closed elliptical trend lines. Arrows indicate regional contraction. (b) Syn-tectonic ballooning—foliation forms closed elliptical to circular trend lines and will overprint or be overprinted by a regional foliation. From Bateman (1984). (c) Syn-tectonic emplacement (constant volume, no ballooning—the tectonic squeeze model). The pluton is emplaced during regional deformation and the ends push outward in the plane of the foliation in response to contraction normal to it, leading to the formation of an overall foliation pattern similar to that in (b) although subparallel to the pluton contact. The aureole foliation will likely overprint a regional foliation in the long axis ends of the pluton aureole, and may be overprinted itself, after the pluton cools, by ongoing regional deformation. Diapiric intrusion of an ellipsoidal pluton alone may produce similar patterns, without tectonic squeezing (as in Cruden 1988 but with an elliptical body ascending). Arrows indicate principal strains.

The two-dimensional Dixon model has experimental boundary problems not experienced in the later three-dimensional Cruden (1988) experiments.

*Criterion* 6: *Strain is highest at the pluton contact, dying away outward in the wall rock*. The contact is a natural high strain zone in many structural scenarios, including diapirism (Dixon 1975, Marsh 1982, Cruden 1988, 1990, Schmeling *et al.* 1988, Mahon *et al.* 1988) and syn- to post-emplacement regional deformation (Paterson *et al.* 1991a, b). The concentration of high heat flow, magmatic fluids and/or metamorphic fluids from dehydration reactions, and circulating meteoric fluids against a potentially strong competence contrast make the contact an ideal site for extreme strain softening (Etheridge *et al.* 1983, Page & Bell 1986). Both ballooning and diapiric strains will drop off away from the contact (Dixon 1975, Cruden 1988, Guglielmo in press), and regional strains influenced by pluton-centered strain softening will decrease in intensity away from the contact as well, so the observed strain gradient is not diagnostic at all.

*Criterion* 7: $S_a$ *is characterized by oblate strain rather than by plane strain*. Recent work by Cruden (1988, 1990) and Schmeling *et al.* (1988) indicates that diapiric ascent will produce oblate strains rather than plane strain, with no expansion of the diapir required. Regional deformation around a pluton is also capable of producing flattening strains.

## CONCLUSIONS

Bateman's (1985a) 'definitive' criteria for a ballooning pluton break down when applied to the Cannibal Creek granite. Porphyroblast timing (post-dating initial $S_a$ formation) actually favours diapiric intrusion ± syn- to post-emplacement regional deformation as the cause of aureole deformation ($D_a$) since if ballooning were the main cause of $S_a$ development, porphyroblasts should form before $S_a$. Other evidence for diapirism includes the presence of crudely radial magmatic flow lineations in the pluton (Schmeling *et al.* 1988, Cruden 1990), a strong magmatic foliation, and discontinuities between that magmatic pluton foliation and $S_a$ aureole foliations. In addition, there is no evidence for a transition from high temperature magmatic flow through to high temperature sub-solidus solid-state deformation to lower temperature solid-state deformation. Strain estimates show that ballooning is not likely to have made room for the entire pluton volume, whereas diapiric ascent with backflow in the aureole or regional uplift might have done so. The presence of contact-parallel $S_a$ within a 2–5 km aureole, with highest intensities near the pluton contact, is as consistent with experimental and physical models of diapiric emplacement (Marsh 1982, Cruden 1988, Mahon *et al.* 1988, Schmeling *et al.* 1988) as it is with ballooning. This pattern of $S_a$ development could also be due in part to regional contraction during emplacement, concentrating strain in the softened aureole.

Other evidence consistent with tectonic squeezing of an ascending diapir includes: (1) a pre- to syn-emplacement regional foliation that wraps around the pluton ($S_2$—Fig. 1), although this may also result from the later $D_4$ deformation or intrusion along the $S_2$ foliation; (2) observed folding of $S_a$ in the southern region within a hundred meters of contact (see Figs. 2 and 5); (3) moderate to high temperature deformation (>550°C) of the sheath dykes which is *incompatible* with ballooning deformation, but is to be expected during syn- to post-emplacement regional deformation.

Thin section transects and mapping north of the pluton suggest that a discontinuity in dominant foliation orientations (see Fig. 1), considered by Bateman (1985a) as a fault, could actually be the boundary of a strain shadow related to late-syn-emplacement or post-emplacement NNW-striking regional deformation around the competent pluton, with $S_1$ preserved in the pluton's strain shadow and $S_2$ wrapping around the pluton. The latter hypothesis would explain curious structural orientations in the northern zone of the aureole, the local presence of two pre-$S_a$ fabrics in the more protected zones, as well as the microstructural data. $S_2$, then, might be pre- to early syn-emplacement in timing, overprinted in the aureole by contact-sub-parallel $S_a$ as strain softening progressed. In order to fully evaluate this latter hypothesis, however, more detailed thin section work is required.

While data are still ambiguous enough that some component of ballooning could have occurred in the Cannibal Creek pluton, it seems that diapiric emplacement plus or minus syn- to post-emplacement regional deformation could account for the structural patterns, strains, and wall rock–pluton textures with fewer inconsistencies (Paterson 1988). With this model, no ballooning of the pluton is required at all.

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