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Fracture control of late Archean pluton emplacement in the northern Slave Province, Canada

J. F. DEHLS* and A. R. CRUDEN

Department of Geology, Erindale College, University of Toronto, Mississauga, Ontario, Canada
E-mail; John.Dehls@ngu.no

and

J.-L. VIGNERESSE

CREGU and ENS Géologie Nancy, France, L5L 1C6

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Abstract—The structural and geophysical characteristics of 2590–2580 Ma leucogranites in the northern Slave Province have been studied to determine the role and conditions of late Archean regional deformation during their emplacement. The irregularly shaped, straight sided, *c.* 10 km long Ulu pluton is located in the southern part of the High Lake greenstone belt, northern Slave Province. Fabrics in the pluton and its wall rocks indicate that it was emplaced at mid- to upper crustal levels during regional E–W late Archean compression. A gravity survey and resulting three-dimensional gravity model of the pluton show that it has several linear, deep (>6 km) root zones, which feed a relatively thin (<2 km) tabular body. The orientations of the major root zone, along the pluton's western side, and three subsidiary roots correspond to those of the pluton contacts to within 5°.

Landsat TM data reveal several sets of lineaments, interpreted to represent fractures formed during the early assembly of the Slave Province, which cut both the greenstone belt and the younger plutons. Analysis of these lineaments defines several maxima whose orientations correspond with those of both the feeder zones and the contacts of the Ulu pluton. The pluton therefore appears to have been emplaced via an intersecting set of vertical fractures. Magma was arrested by and spread along an unknown horizontal structure. Subsequent inflation of the pluton was also facilitated by vertical translation on pre-existing fractures. © 1998 Elsevier Science Ltd. All rights reserved

INTRODUCTION

Over the last two decades, geologists have begun to question the importance of diapirism in the ascent of felsic magma through the crust, and the final emplacement of plutons. An increasing number of workers have suggested that the dominant mechanism of granitic magma ascent is through fractures, either pre-existing faults (Petford *et al.*, 1993, 1994) or fractures created by the magma itself (Emerman and Marrett, 1990; Clemens and Mawer, 1992). In either case if the initial dyke is wide enough, and the magma viscosity low enough to prevent freezing, magma transport is quite rapid. The rate-limiting factor is either the supply of magma, or the material transfer process necessary to make space. Weinberg (1996) has suggested that in some cases magma may ascend as diapirs part way through the crust, with dykes propagating from the top at shallow levels. Ultimately, the structural features of a high-level pluton may not be related to the ascent mechanism at all, but to the mode of emplacement, once the magma has arrived. That mode of emplacement will reflect the deformation behaviour of the wall rocks and the local stress field, which is itself a function of the regional conditions and stresses related to the presence of the magma. While in general we expect brittle wall rock behaviour at shallow crustal levels, and ductile behaviour at deeper levels, a complete continuum exists between these end-members (Paterson *et al.*, 1991). Complicated field relationships may result from a combination of the two styles of deformation.

During the emplacement of a pluton, sufficient space must be created locally for the influx of new magma. This space can be made in a number of ways. Ductile deformation of the surrounding rocks may allow downward flow towards the source region during diapiric emplacement; regional deformation may allow, or cause, lateral wall rock displacement by folding or faulting; the roof of the pluton may be lifted, if it is not too thick; the wall rocks may be fractured, allowing blocks to be stoped and sink into the pluton; or a single large block may sink into the underlying magma chamber, in a process referred to as 'cauldron subsidence'. These final two mechanisms may be influenced by the presence of pre-existing fractures in the wall rock.

We have studied the structural and geophysical characteristics of 2590–2580 Ma leucogranites in the

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*Current address: Geological Survey of Norway, Trondheim, Norway northern Slave Province to determine the role of late regional deformation in their emplacement. Modelling of gravity data from one of these plutons reveals a relatively thin tabular body fed by several linear, deep root zones, suggesting that it was fed by several dykes. These root zones are parallel to several of the pluton contacts, which are also linear. We have examined the pattern of fractures throughout the region and have found a correlation between these fractures and the shape of the plutons. Recent reviews have shown that the majority of plutons may be tabular bodies, with the bulk of their area and volume less than 3 km deep (Vigneresse, 1995b; McCaffrey and Petford, 1997; Cruden, 1998). We propose that the Ulu pluton is lopolithic, that it was fed by magma rising along a set of intersecting fractures and that most of the space was made for its emplacement by sinking of the floor between those fractures.

GEOLOGICAL SETTING

The High Lake greenstone belt is located in the northernmost Slave Province (Fig. 1). The supracrustal rocks range in age from 2705 to 2605 Ma. Granitoid batholiths, ranging in age between 2620 and 2600 Ma, surround the belt. Two young leucocratic granites intrude the belt. The Sneezy pluton, in the north, has been dated at 2580 ± 8 Ma (Villeneuve *et al.*, 1997). The Ulu pluton, in the south, was emplaced at 2588 ± 4 Ma (Villeneuve *et al.*, 1997).

The Ulu pluton is a homogeneous quartz, plagioclase, microcline, biotite leucogranite. The pluton has a very low mafic mineral content, and appears as an aeromagnetic low on regional aeromagnetic maps. Similar late- to post-deformational leucogranites have been described throughout the Slave Province. Their geochemistry is consistent with a partially melted metasedimentary source region (Davis *et al.*, 1994). It has been suggested (King *et al.*, 1992; Kusky, 1993; Davis *et al.*, 1994) that such late leucocratic granites in the Slave Province were emplaced during a period of crustal extension. Although earlier studies have concluded that compressional deformation in the Slave Province was over by *c.* 2600–2595 Ma (van Breemen *et al.*, 1992; Isachsen and Bowring, 1994), microstructural observations and magnetic fabric studies show that compressional deformation outlasted the emplacement and cooling of the Ulu pluton (see below and Dehls, 1997). This deformation produced variable magmatic and solid-state fabrics parallel to the main cleavage in the belt.

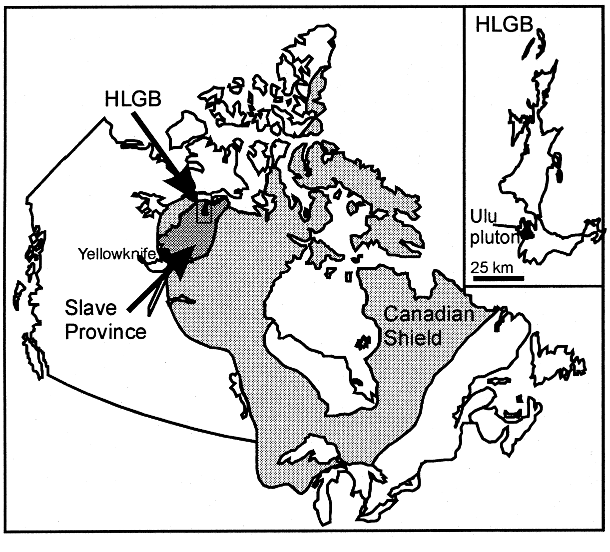

Fig. 1. Map of Canada showing the location of the Ulu pluton, within the High Lake greenstone belt (HLGB), in the northern Slave Province.

CONTACT RELATIONSHIPS

The contacts between the pluton and the surrounding supracrustal rocks are sharp and linear at both the map (Fig. 2) and outcrop scale (Fig. 3a). The granite is exposed in an area that is systematically 10 m or more lower than the surrounding supracrustal rocks (Fig. 3b). This, together with the observation that contacts dip outward at moderate (~50–60°) angles in a number of locations along the east, west and northern margins, suggest that the present level of exposure is close to the original roof of the pluton. However, in most places pluton–wall rock contacts are steep, and are remarkably straight for several kilometres with consistent trends of 035°, 077°, 145° and 178° (Fig. 2). There is no evidence, such as mappable offsets, that these linear contacts are faults which post-date emplacement. In several localities dykes of Ulu granite can be seen penetrating the wall rocks without disruption at the pluton contact.

There is no evidence of a contact-parallel foliation in the wall rock suggestive of forceful emplacement of

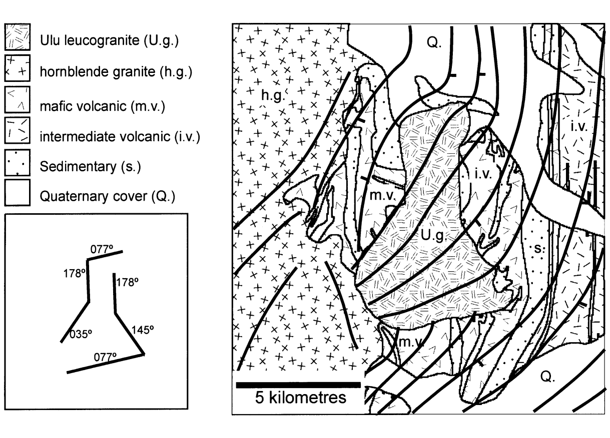

Fig. 2. Detailed map of the Ulu pluton. The contacts between the Ulu pluton and the surrounding supracrustal rocks are long and linear. The trends of the contacts (inset) are 035°, 077°, 145° and 178°. The regional S_3 foliation (thick lines) passes through, but is partly deflected by the Ulu pluton.

Fig. 3. (a) Sharp, intrusive contact between the Ulu pluton and the surrounding supracrustal rocks. (b) The surrounding supracrustal rocks rise 10 m more above the exposed surface of the pluton. The dashed white line indicates the pluton margin.

the pluton into ductile crust. However, bedding planes, as well as the regional S_3 foliation, which are both subvertical throughout the belt, become shallower within 2 km of the pluton's northeastern and northwestern margins (Fig. 2). Microstructural and anisotropy of magnetic susceptibility (AMS) studies of the Ulu granite show that the bulk of the internal foliation within the pluton is continuous with S_3 in the wall rocks, and that this fabric formed during cooling of the pluton from high *T* to ambient greenschist facies conditions (Dehls, 1997). Because of the syn- to post-intrusive nature of the S_3 foliation with respect to emplacement of the Ulu pluton, these relationships suggest that the local rotation of bedding and S_3 adjacent to the pluton occurred during regional D_3 deformation and is not related to emplacement (Dehls, 1997). Wall rocks were effectively forced to flow locally around a relatively rigid, tabular body in a similar manner to a pre-kinematic porphyroblast.

Regional metamorphic conditions during formation of the regional S_3 foliation were at greenschist facies. Near the Ulu pluton this cleavage overprints porphyroblasts of biotite and chiastolite, which may have formed at the initial stages of emplacement of the pluton or be related to an earlier event. This suggests that the pluton was emplaced at P–T conditions below the Al_2SiO_5 triple point (i.e. less than *c*. 10 km), but present data cannot be used to constrain a minimum intrusion depth.

GRAVITY MODELLING

A gravity survey of 130 stations was performed over the Ulu pluton to determine its three-dimensional shape. Data processing and three-dimensional modelling procedures are described by Dehls (1997).

The resulting three-dimensional model of the Ulu pluton is shown in Fig. 4, along with a depth contour map. The pluton has several linear, deep (>6 km) root zones, highlighted by the white lines in Fig. 4, which may have fed a relatively thin tabular body. More than 60% of the pluton is less than 2 km deep (Dehls, 1997). The individual roots along the main root zone are an artefact of the gridding of the gravity data (Dehls, 1997). The main root zone, along the pluton's western side, trends 030°. It is through this zone that the bulk of the magma is assumed to have ascended. Three subsidiary roots trending 077°, 140° and 170° intersect the main root.

The linear nature of the root zones suggests that the magma ascended along a set of intersecting fractures. There is no evidence, from the gravity modelling alone, as to whether these fractures were the result of some earlier event or were created by the magma itself.

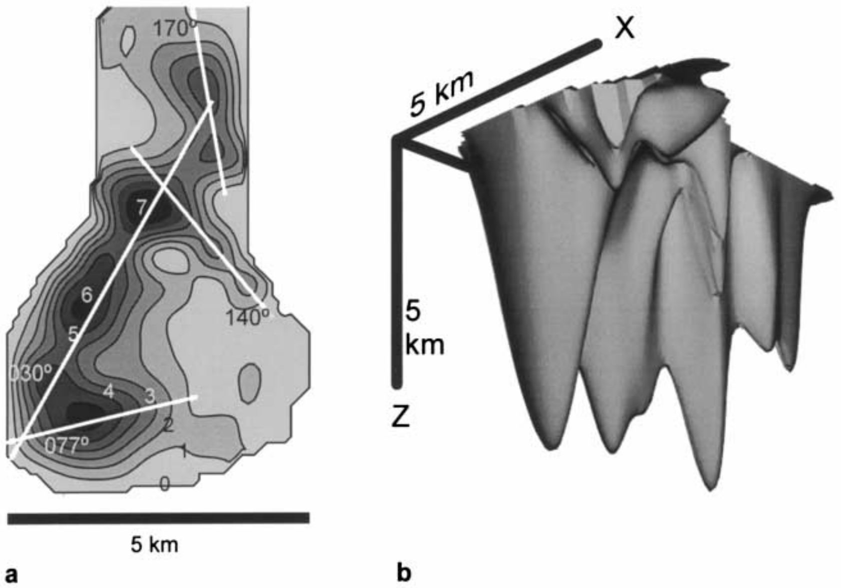

Fig. 4. (a) Depth contours (in km) of the floor of the Ulu pluton from gravity modelling. Several linear deep root zones are highlighted by the white lines. These root zones are parallel to the pluton contacts. More than 60% of the pluton is less than 2 km thick. The individual roots along the main root zone are an artefact of the gridding of the gravity data (Dehls, 1997). (b) Three-dimensional view of the bottom of the pluton model, showing the extent of the root zones.

LINEAMENT ANALYSIS

It is generally accepted that most lineaments are the expression of fractures, including joints, faults and dyke-filled fractures. In the Canadian Shield, lineaments have a strong topographic expression, and can readily be detected on aerial photographs and satellite images (Lowman *et al.*, 1992). In order to determine the regional extent of the fractures associated with the Ulu pluton, a 90 × 90 km LANDSAT TM scene centred on the High Lake belt was studied.

Lineament detection

Image analysis was performed on a PC using the software package ER-Mapper 5.2. Lineaments were visible in several band combinations, but a false-colour image using bands 5, 4 and 1 was found most suitable for the analysis. In order to enhance the visual detectability of lineaments, a linear contrast stretch was applied to the histogram of each band to enhance the colour differentiation in the image. The image was then converted to hue, saturation and intensity channels. By applying a Gaussian stretch to the histogram of the intensity layer, the contrast in the image was significantly enhanced, without changing the colour balance (e.g. Kowalczyk and Ehling, 1991). By applying an edge-preserving adaptive filter (Budkewitsch *et al.*, 1994) to the intensity layer, high-frequency noise was removed while linear features were preserved. The result of these enhancements is an image in which topographic features are highly visible. The intensity channel, which contains most of the information, is shown in Fig. 5.

Lineaments were drawn on a vector layer over the image. By varying the scale at which the image was displayed, linear or curvilinear features ranging in length from 3 km to greater than 50 km were traced. The lower limit of 3 km was chosen arbitrarily so that only fractures of regional significance, which could be expected to extend to some depth, were analysed. The resulting lineament map was then overlain upon a geological map of the area, and all lineaments corresponding to conformable contacts in the supracrustal rocks were discarded. The resulting lineament map is shown in Fig. 6. Statistical analysis of the lineaments was then performed to determine their peak directions.

Statistical analysis of lineament directions

In lineament studies, the distribution of lineament directions is usually displayed on a rose diagram (circular histogram), using a counting class of 5° or 10°. Ideally, the data should be weighted by a length factor. In order to analyse their directions, all lineaments are represented as straight-line segments, although they may be somewhat curvilinear in reality. In order to avoid this step, and to automate the process, a method based upon counting of intercepts on raster images was used (Launeau and Robin, 1996).

The intercept counting technique has been developed in order to determine the shape preferred orientation of mineral grains (Panozzo, 1983; Launeau *et al.*, 1990), but is equally useful for any object population. The technique is based on counting the number of times a set of parallel test lines intercepts a set of objects on the image along a number of directions. The number of intercepts is a periodic function of α,

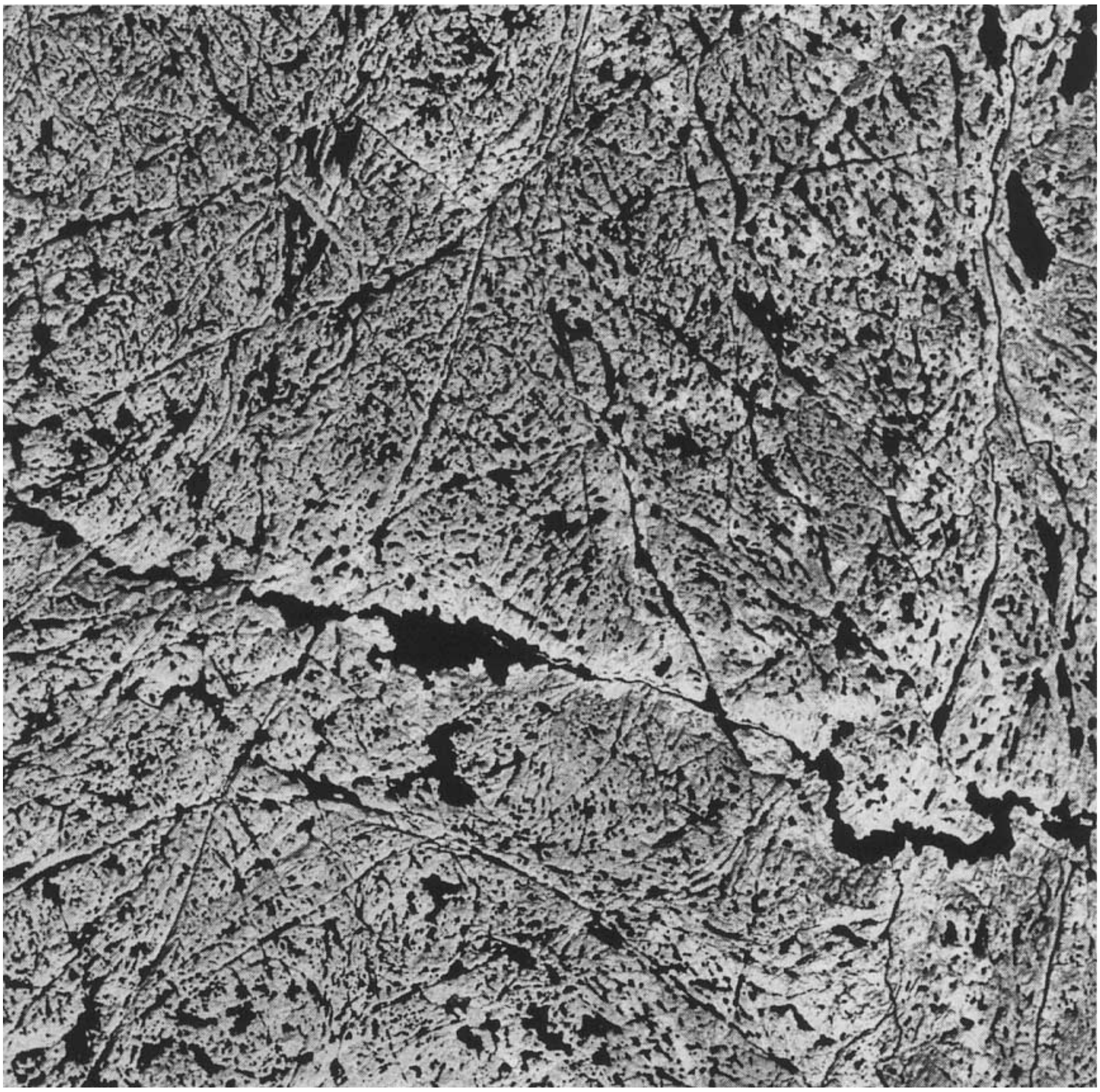

Fig. 5. A 50 × 50 km portion of the final enhanced LANDSAT TM image used to analyse lineaments in the study area. Bands 5, 4 and 1 were combined as red, green and blue channels, and then converted to hue, saturation and intensity channels. Shown is the intensity channel, which contains most of the information. See text for details on image processing techniques used. The Ulu pluton is situated to the southeast of this area.

the counting direction, and can be represented by a Fourier series (Launeau and Robin, 1996). From this Fourier series, a 'rose of directions' can be calculated. The Fourier series is usually truncated at a level such that the resulting curve matches the main features of the data curve. This truncation is the equivalent of smoothing the curve with a Gaussian filter, whose half-height width is related to the level of truncation (Launeau and Robin, 1996). This method of analysis for lineament directions thus provides a measure of directional density that is both weighted by lineament length, and smoothed to remove noise.

In theory, the intercept method can be applied to a vector dataset. However, in practice, it is convenient to convert the dataset to a raster image such that the lineaments have a thickness of 5 pixels. The lineament map of the High Lake belt and surroundings was converted to such a raster image. The intercept method was applied with a 2° counting step. The rose of directions (Fig. 6) shows seven directional maxima at 010°, 029°, 056°, 074°, 125°, 147°, and 171°.

In a study of fracture patterns in the Canadian Shield, Lowman *et al.* (1992) analysed three Landsat scenes in the Slave Province, southwest and west of the present study area (Fig. 7). Their circular histogram for the orientation of lineaments in the Slave Province shows several peaks with similar orientations to the High Lake area. The data are not smoothed, but peaks are located at 355–15°, 25–35°, 50–75°, 100–120° and 135–155°. Each of the peaks in the High Lake area falls within one of these intervals.

Origin of the lineaments

In both studies, the peak centred on approximately 140°/320° is very large. This orientation corresponds to that of the Mackenzie dykes. Indeed, when the lineament map is overlain on the aeromagnetic map of the

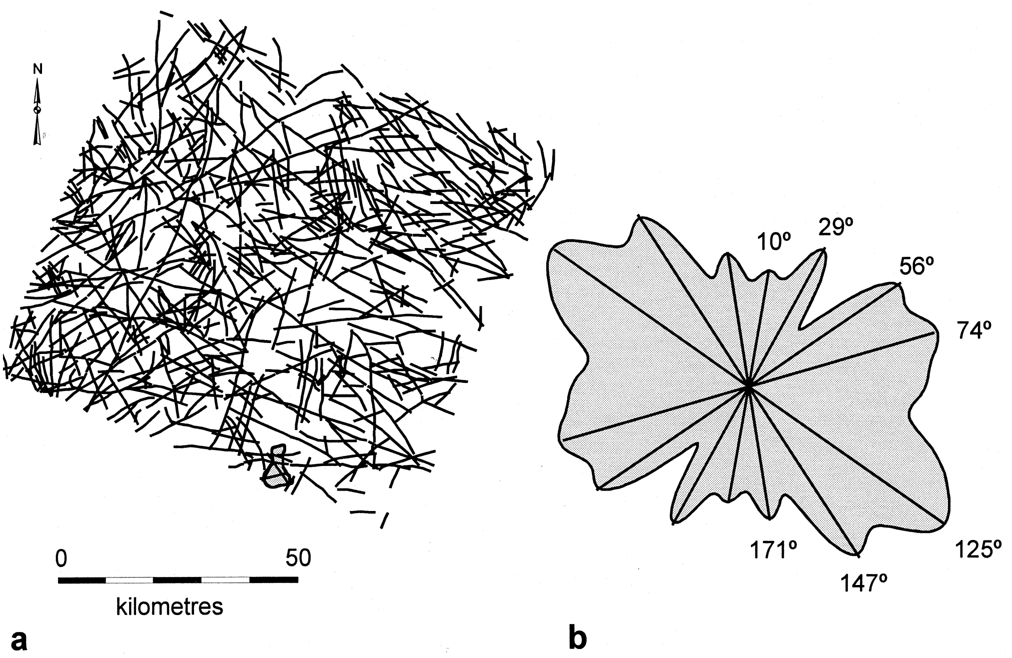

Fig. 6. (a) Topographic lineaments in the High Lake greenstone belt and surrounding area. These lineaments are the expression of fractures, including joints, faults and dyke-filled fractures. (b) The rose of directions for the topographic lineaments. Several directional maxima correspond with the orientations of the root zones of the Ulu pluton, as well as the contacts of the pluton with the surrounding rocks (see Fig. 2 inset).

High Lake area, it is clear that many lineaments correspond to mafic dykes (Fig. 8). This is not surprising, as mafic magmas, like granitic magmas, may ascend within self-propagating fractures or intrude along pre-existing fractures. These fractures may have any orientation in regions where the horizontal principal stress difference is much smaller than the magmatic driving pressure (Delaney *et al.*, 1986). Differential erosion between the diabase and the surrounding rocks (mostly granite in this case) makes these features clearly visible from space.

The other lineament orientations are related to faults and joints that may have formed either in the Archean or the Proterozoic. Within the High Lake belt, major faults show movement that post-dates the latest folding event. Exact timing for the movements cannot be determined from cross-cutting relationships. However, given that each of the fractures along which magma ascended to fill the Ulu pluton corresponds with one of the regional fracture sets, it is reasonable to suggest that they existed at 2588 Ma when the Ulu pluton was emplaced. Other evidence for the existence of these fractures in the Archean comes from within the adjoining Anialik River greenstone belt, where Relf (1996) has documented Archean movement along a number of large faults with various trends. All of these faults are found within the area of this study. Other faults in the Anialik belt have demonstrable Proterozoic move-

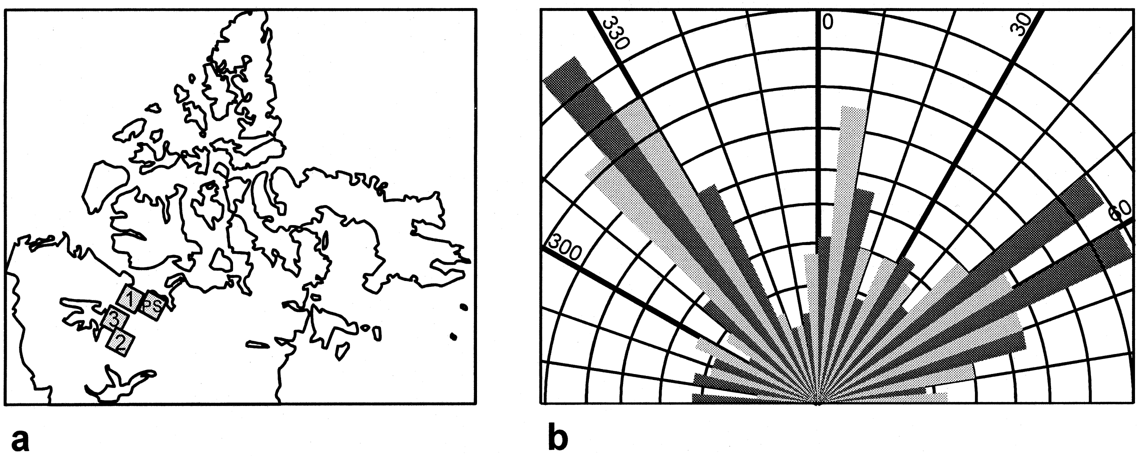

Fig. 7. (a) Location of images studied by Lowman *et al.* (1992) (boxes labelled 1–3) and the present study (box labelled PS). (b) Circular histogram of the orientation of lineaments in the Slave Province (modified from Lowman *et al.*, 1992). Note the similarity between the peak directions and those of the present study, shown in Fig. 6.

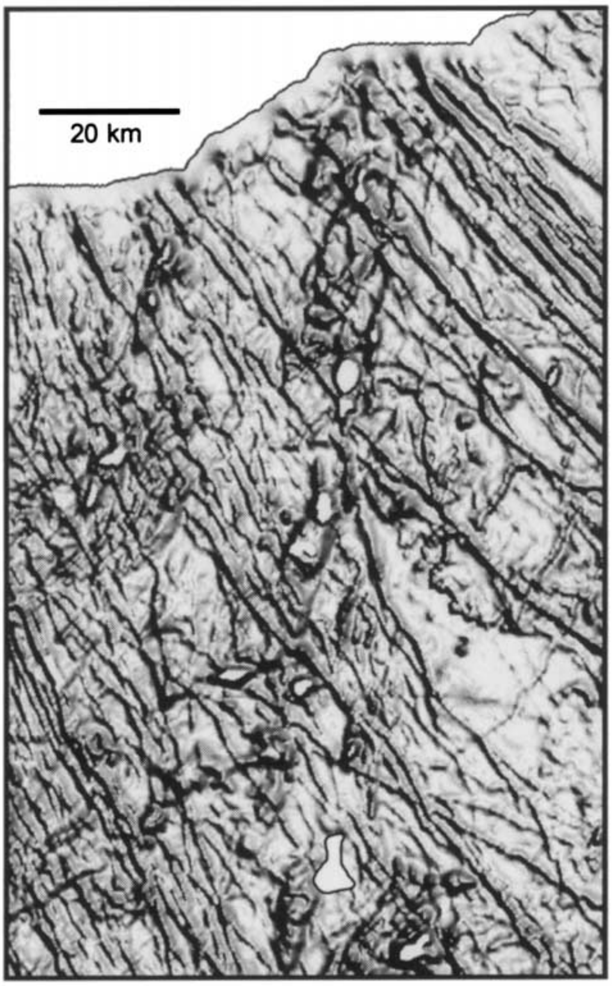

Fig. 8. Shaded total field aeromagnetic data for the High Lake area. The Mackenzie diabase dykes, which have a very strong magnetic expression, account for many, but not all, of the lineaments with ~140° trend. The location of the Ulu pluton is shown in white near the southern edge.

ment histories, however earlier movement cannot be ruled out.

EMPLACEMENT OF THE ULU PLUTON

Structural control of granite emplacement by fractures has been reported for the Rosses Centred pluton in Donegal (Pitcher and Berger, 1972) and plutons in the Coastal Batholith of Peru (Bussell, 1976; Pitcher and Bussell, 1977). In these cases individual plutons were emplaced by lifting and foundering of large crustal blocks between fractures, resulting in a rectilinear pattern of contacts. In the Sierra Nevada it has been proposed that in the Bald Mountain pluton magma coalesced through the use of pre-existing joints (Tobisch and Cruden, 1995). Although work by Clemens and Mawer (1992) has demonstrated the ability of granitic magma to ascend in self-propagating dykes, this does not seem to be the case for the Ulu pluton. The correlation between the orientations of the pluton feeder zones, the pluton contacts and the regional lineament pattern indicates that the mode of emplacement of the pluton was controlled by brittle fractures that were regional in extent.

The negative density contrast between the Ulu pluton and its wall rocks suggests that the magma did not stop rising because it had reached a level of neutral buoyancy. Instead, the magma had to have been stopped mechanically. Weertman (1980) has demonstrated that magma rising through a fracture in the crust may be stopped by a freely slipping horizontal joint. The freely slipping criteria can be relaxed under conditions of horizontal compressive stress (Weertman, 1980). Alternatively, the ascending magma may be stopped by a sub-horizontal strength anisotropy (Hogan and Gilbert, 1995). When the magma has been stopped it spreads laterally, forming a sill and then grows to form a tabular body. The final width and thickness of the pluton is dependent on the growth mechanism (i.e. roof-lifting, floor depression, stoping), the available magma driving pressure, the magma supply rate and volume, the emplacement depth, and the state of stress in the lithosphere laccolith (Pollard and Johnson 1973; Corry, 1988; Hogan *et al.*, 1998; Cruden, 1998).

In the case of the Ulu pluton, magma appears to have risen along multiple fractures before spreading laterally between them. Field relationships do not allow us to conclude what caused the magma to stop. The pluton is bound by pre-existing fractures which suggests that they may have arrested the laterally spreading magma and have played a role in the subsequent vertical growth of the pluton (Fig. 9). Growth of the pluton by stoping of angular blocks controlled by the fracture pattern in the wall rocks may have occurred. However, xenoliths are extremely rare in the pluton, so that if stoping did occur the blocks may have sunk below the current level of exposure, or the blocks may have disintegrated due to fracturing caused by thermal stresses (Clarke *et al.*, 1998).

The Ulu pluton may have grown by roof lifting to form a laccolith, in which case vertical fractures in the wall rocks would have acted as guides to lift the overburden. Lifting of the roof requires that the magma driving pressure be greater than the vertical stress at the emplacement level (Hogan *et al.*, 1998). Under most circumstances this restricts laccolith growth to the uppermost 3 km of the crust (Hogan *et al.*, 1998), explaining the observation that laccoliths are rarely reported for emplacement depths less than 2 km (Corry, 1988). The fact that ductile deformation was still occurring when the Ulu pluton was emplaced, as well as the lack of a contact metamorphic aureole, seems to rule out such a shallow level of emplacement. However, greater emplacement depths for laccoliths are possible if the source is very low density magma from very deep crustal levels, in which case magma driving pressures will be extremely high (J. Hogan,

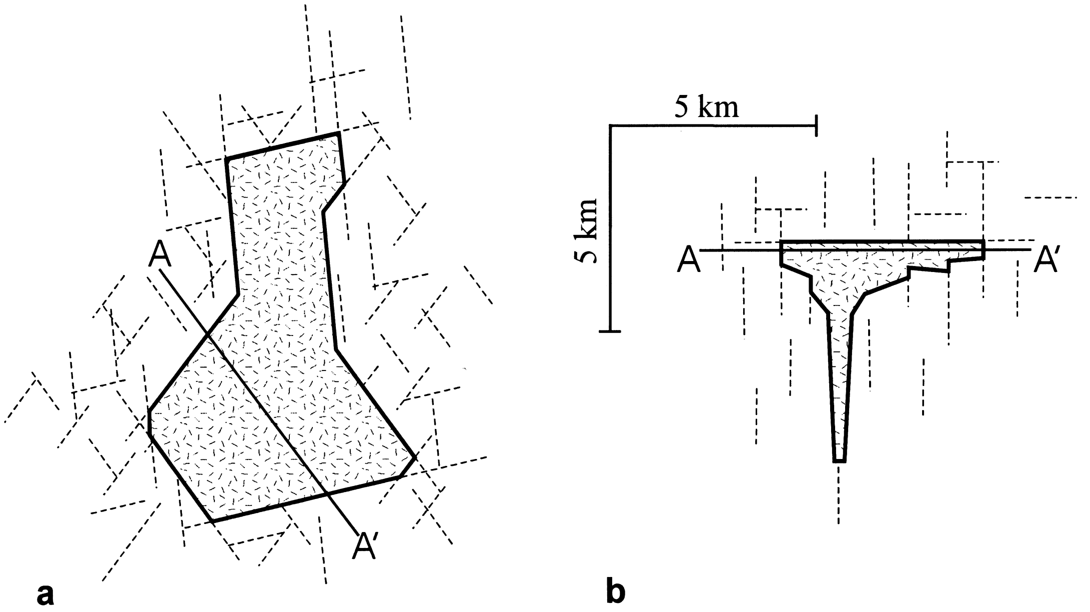

Fig. 9. Sketch of the Ulu pluton showing a hypothetical case of how regional fracture sets may have controlled the final geometry of the pluton. (a) Map showing current exposure level and location of cross-section A–A′. (b) Cross-section of the pluton showing present level of erosion A–A′. Orientations of contacts and fractures are based on field observation and lineament analysis and cross-sectional shape is based on gravity modelling. Precise location of fractures is conjectural.

personal communication, 1998). Laccoliths also have flat floors and rarely exceed thicknesses of 2 km (Corry 1988). Although the bulk of the Ulu pluton is < 2 km thick, its floor is inclined inwards at angles of < 20° in the southeastern part to > 80° adjacent to the feeder zones (Figs 4 & 9b), which is inconsistent with a laccolithic geometry.

Our preferred interpretation for the geometry and mode of emplacement of the Ulu pluton is that it is lopolithic in form (e.g. Corry, 1988), and that vertical growth occurred mostly by depression of its floor (e.g. Cruden, 1998). End-member kinematic models for floor depression are a cantilever model in which space is created by tilting the floor toward the magma feeder zone, and a piston model in which space is created by dropping the floor of the pluton between vertical faults (Cruden, 1998). In both cases space is ultimately accommodated by sinking of the crustal column beneath the pluton into a deflating, partially molten source region. The Ulu pluton appears to have growth by a combination of both mechanisms, with piston sinking occurring on pre-existing vertical fractures,

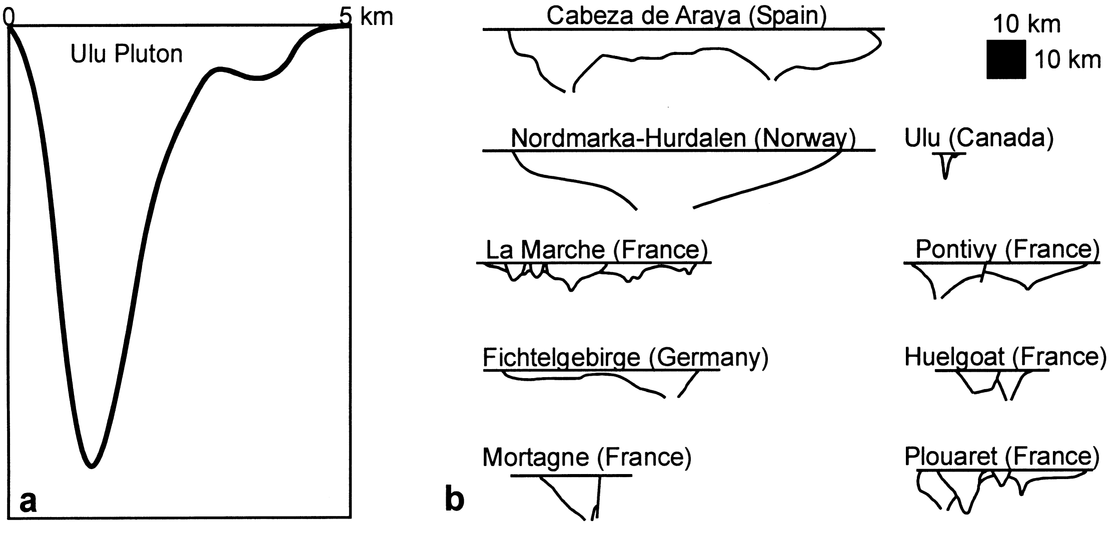

Fig. 10. (a) An E–W depth profile across the Ulu pluton, derived from the gravity model, shows the floor dipping towards the feeder dyke. (b) Shapes of pluton floors derived from gravity models (modified from Vigneresse, 1995a). The sloping floor of the Ulu pluton is typical of many plutons.

resulting in the angular outcrop pattern of the pluton, and tilting of the floor towards the root zones (Fig. 9). Note that contributions by stoping and roof lifting cannot be ruled out, but their role is less evident in the data.

The cross-sectional shape of the Ulu pluton is similar to a number of other plutons revealed by gravity modelling (Fig. 10) (Vigneresse, 1995a). This shape appears to support a hybrid model of floor depression, somewhere between the piston and cantilever models. However, the width of the root zones and the observed convex-up steepening of the floors toward them are not predicted by the cantilever or piston models (Cruden, 1998). This may be explained by differential subsidence of the floor due to a combination of hotter, more ductile rocks close to the conduits and variations in volume loss in the source region, which is likely to be greatest where conduits exit.

CONCLUSIONS

Seven fracture sets occur throughout a large portion of the Slave Province. Field mapping and geophysical modelling of the Ulu pluton show that its final emplacement was controlled by intersecting fractures that correspond to the regional sets. Magma is interpreted to have ascended along several of these vertical fractures, and then spread laterally between them along a horizontal crustal anisotropy. Space was made for vertical growth of the pluton by differential sinking of the underlying crust between fractures into the deflating magma source region. Stoping and roof lifting may have created additional room.

The fracture sets, which controlled pluton emplacement in the late Archean, were subsequently reactivated during brittle deformation of the Slave Province. They acted as preferred avenues of ascent for Proterozoic mafic magmas and developed into brittle structures now visible as lineaments throughout the region.

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