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Pluton emplacement within an extensional transfer zone during dextral strike-slip faulting: an example from the late Archaean Abitibi Greenstone Belt

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Abstract—The Lake Abitibi area within the late Archaean Abitibi Greenstone Belt exhibits an interlinked plutonic, structural and metamorphic evolution that may characterize segmented strike-slip faults at upper-to-mid-crustal levels. Along the major, southeastward propagating Macamic D_2 dextral strike-slip fault, rheological and preexisting D_1 structural heterogeneities induced the development of NNW-trending dextral-oblique splays which evolved into an extensional trailing fan and created an extensional, NNW-dipping stepover. Magma flowing upwards from deeper parts of the Macamic Fault spread towards the southeast at upper crustal levels along both the oblique-slip and extensional D_2 splays, and built several plutons in a pull-apart domain between 2696 and 2690 Ma. Different emplacement and material transfer mechanisms operated simultaneously in different parts of the system, including fault dilation and wedging, lateral expansion, wall-rock ductile flow and stoping. Transfer of movement between D_2 splays occurred under ductile conditions during syn-emplacement, amphibolite-grade metamorphism (500–700°C). During cooling (<2690 Ma), narrower brittle–ductile zones of greenschist-grade shearing were concentrated along the pluton-wall rock contacts, but the extensional stepover locked since both normal and reverse movements occurred along NNW-dipping faults. Pluton emplacement, contact metamorphism and propagation of D_2 faults appear to have been closely linked during the Superior Province-wide late transpressional event. © 1998 Elsevier Science Ltd.

INTRODUCTION

A connection in space and time between plutonism and major transcurrent faults has been increasingly documented from Phanerozoic orogenic belts. Strike-slip faults appear to be well-suited for facilitating magma ascent from the mid- to the upper-crust and to provide space for pluton emplacement along transtensional fractures (Tobisch and Cruden, 1995), pull-apart domains (Hutton, 1982; Guineberteau *et al.*, 1987; Morand, 1990), shear-zone terminations (Hutton, 1988; Ferré *et al.*, 1995) or P-shear bridges (Tikoff and Teyssier, 1992). In the upper crust, the deflection or segmentation of strike-slip faults can lead to the formation of releasing bends or stepovers (Woodcock and Fischer, 1986), where pull-apart sedimentary basins are located (Crowell, 1974). Since ductile mid-crustal faults have more curvilinear trajectories compared to upper crustal ones (Davison, 1994), one might expect there to be numerous releasing bends or stepovers favourable for pluton emplacement along such strike-slip faults.

The 3D geometry and development of mid-crustal level segmentations remains less known than their upper crustal counterparts, in particular where plutons are involved (Archanjo *et al.*, 1994; Miller, 1994). Paterson and Tobisch (1992) stress that fault-related extensional models may require an incremental development with compatible duration and rates of wall-rock displacement and magma emplacement. Also, Paterson and Fowler (1993) point out that the roof, floor and sides of such plutons should show synchronous and compatible amounts of extension, or else have variable emplacement and material transfer mechanisms. Finally, the injection of voluminous, hot granitoid magma along active faults might cause thermal softening and strain localization (Hollister and Crawford, 1986; Sandiford *et al.*, 1992). Unfortunately, few extensional stepovers provide the opportunity to observe such pluton/wall-rock interactions.

This paper documents several plutons located within, and around, an extensional stepover adjacent to a major dextral strike-slip shear zone, the Macamic Fault, in the south-central Abitibi Greenstone Belt (AGB) of the Superior Province (Fig. 1). To investigate the relationship between the emplacement and the cooling of these plutons and the structural evolution of the region, we undertook a structural mapping and microstructural study of a key area where strike-slip and extensional faults are linked around many of the plutons. Estimates of the P–T conditions from the plutons and their wall-rocks place constraints on their thermo-mechanical evolution. This study highlights a coupling of strike-slip fault propagation and granitoid plutonism during Superior Province-wide late transpression.

REGIONAL TECTONIC SETTING

The southern Superior Province is composed of alternating E-striking low-grade granite–greenstone belts with higher-grade plutonic gneiss and metasedi-

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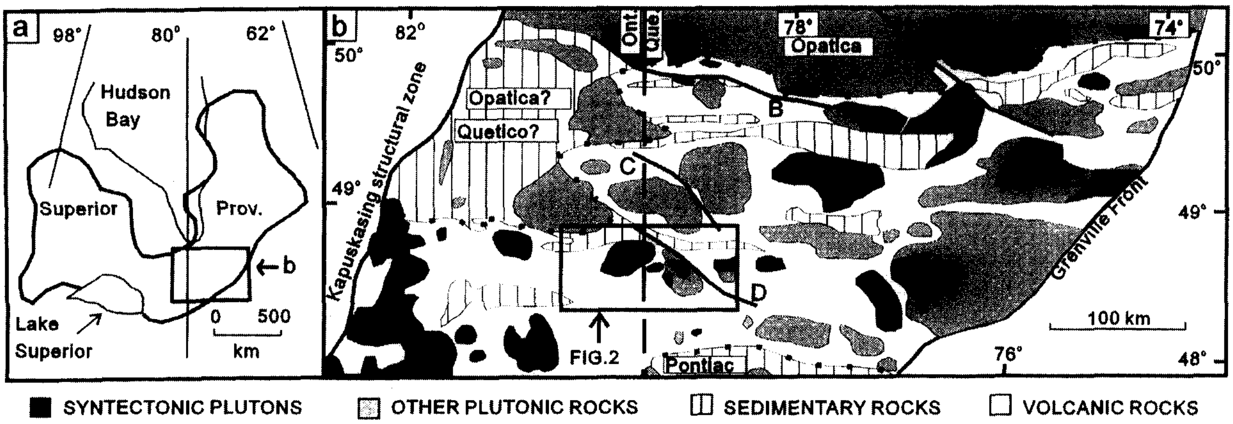

Fig. 1. Location of the study area in (a) the Superior Province and (b) the Abitibi Greenstone Belt (AGB) and neighbouring subprovinces (modified from MERQ-OGS, 1983;Hocq, 1990 and Chown *et al.*, 1992). Limits of the AGB indicated by dotted pattern. Major dextral strike-slip D_2 faults identified from A to D: A—Nottaway River, B—Grasset, C—Laberge, D Macamic.

mentary subprovinces, interpreted as having developed in a southward-younging, north-dipping, subduction-driven accretionary setting similar to some oblique convergent margins of the present western Pacific (Langford and Morin, 1976; Card, 1990). The AGB is located in the SE part of the Superior Province (Fig. 1a) and is one of its younger granite–greenstone belts (2750–2670 Ma, Mortensen, 1993). It is composed of alternating E-trending belts of basalt and basalt–komatiite sequences, lozenge-shaped basalt–rhyolite volcanic arc domains and elongate sedimentary belts (Ludden *et al.*, 1986; Chown *et al.*, 1992; Jackson *et al.*, 1994). Most domains are bordered by steep E- to ESE-trending D_1 brittle–ductile faults and have been internally deformed by similarly oriented folds during a major N–S horizontal shortening (Dimroth *et al.*, 1983; Daigneault and Archambault, 1990). Recent models based on structural field work and Lithoprobe seismic profiles (Sawyer and Benn, 1993; Lacroix and Sawyer, 1995) propose that most D_1 faults are listric to the north, as suggested by Hocq (1990), and interpret the structure of the AGB as that of an upper crustal foreland thrust belt that developed during a crustal-scale SSW-vergent thrust stacking D_1 event further north in the Opatica gneiss belt. After subprovince accretion, NNW-trending shortening was mostly accommodated by E- to SE-trending dextral strike-slip D_2 faults (Fig. 1b) in the Abitibi (Daigneault and Archambault, 1990) and the Opatica belts (Sawyer and Benn, 1993). Such a D_1–D_2 transition from dominantly compressive to transpressive deformation occurred throughout the southern Superior Province (e.g. Hudleston *et al.*, 1988; Williams *et al.*, 1992).

THE PLUTONS AND THEIR GEOLOGICAL CONTEXT

In the south-central AGB (Fig. 2), several elongated to oval-shaped plutons belong to a trondhjemite–tonalite–granodiorite–quartz monzodiorite (TTGM) suite. Hornblende and/or biotite-bearing trondhjemite–tonalite phases dominate most of the Lake Abitibi and LaReine plutons, whereas a granodiorite (with rare quartz monzodiorite) phase is present along most of their eastern edges and comprises the whole of the Dupuy, DuReine and Palmarolle plutons (Fig. 3). This granodiorite contains large phenocrysts (1–2 cm) of microcline, rounded aggregates of quartz and locally up to 20% biotite + hornblende. The Colombourg pluton is composed of quartz monzodiorite with an outer zone of tonalite and a central core of granodiorite (Chown and Daigneault, 1994). More mafic phases, e.g. hornblende or quartz diorite and gabbronorite, have only been observed in the Lake Abitibi pluton. Geochemically, these calc-alkaline plutons resemble subduction-related Phanerozoic volcanic arc batholiths in the Cordillera of Western North America (Rive *et al.*, 1990; Sutcliffe *et al.*, 1990; Feng and Kerrich, 1992).

Recent U–Pb dating of zircon fractions (Mortensen, 1993; Davis *et al.*, 1992) indicates that the LaReine (tonalite: 2694 ± 1 Ma), Colombourg (tonalite: 2696.9 ± 2 Ma) and Lake Abitibi (tonalite: 2694.8 ± 1.7 Ma, granodiorite: 2690 ± 1 Ma) plutons crystallized within a 4–10 m.y. interval. The Colombourg, Palmarolle and Dupuy plutons occur in close spatial association with the older Poularies pluton, which is thought to be comagmatic with the Hunter Mine Group (Chown and Daigneault, 1994), a 2729.6 Ma-old (± 1.4) calc-alkaline volcanic arc sequence. The Lake Abitibi and LaReine plutons are hosted by the 2717–2713 Ma-old Stoughton–Roquemaure Group, a komatiite–basalt sequence with rare rhyolite layers (Mortensen, 1993; Corfu, 1993). The ages of crystallization of all plutons, except Poularies, are much younger than their hosting rocks, and confirms that these plutons are syntectonic with respect to the Kenoran orogeny (Rive *et al.*, 1990; Chown *et al.*, 1992) althought their precise

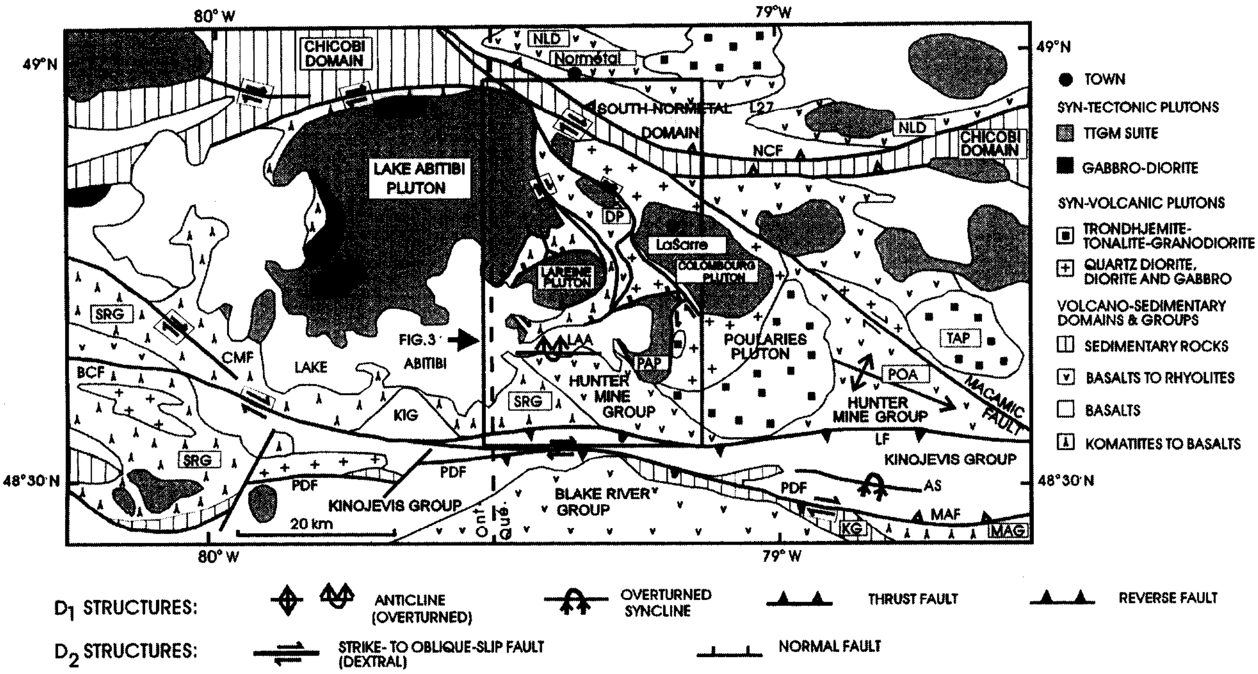

Fig. 2. Regional geology of the central-western AGB (modified from MERQ-OGS, 1983;Smith and Sutcliffe, 1988;Jackson and Fyon, 1992 and Lacroix, 1995). Labelled supracrustal units as follows: MAG—Malartic Group, NLD—Normetal–Ligneris Domain, SRG—Stoughton–Roquemaure Group. Named plutons: DP—Dupuy, PAP—Palmarolle, TAP—Taschereau. Named D_1 faults: MAF—Manneville, NCF—North-Chicobi, PDF—Porcupine–Destor. Named D_1 folds: LAA—Lac Abitibi Anticline, POA—Poularies Anticline, AS—Abijevis Syncline. Named D_2 faults: BCF—Bradburn–Coulson, CMF—Cochrane–Milligan, LF—Lyndhurst. (TTGM: Trondhjemite–tonalite–granodiorite–quartz monzodiorite.)

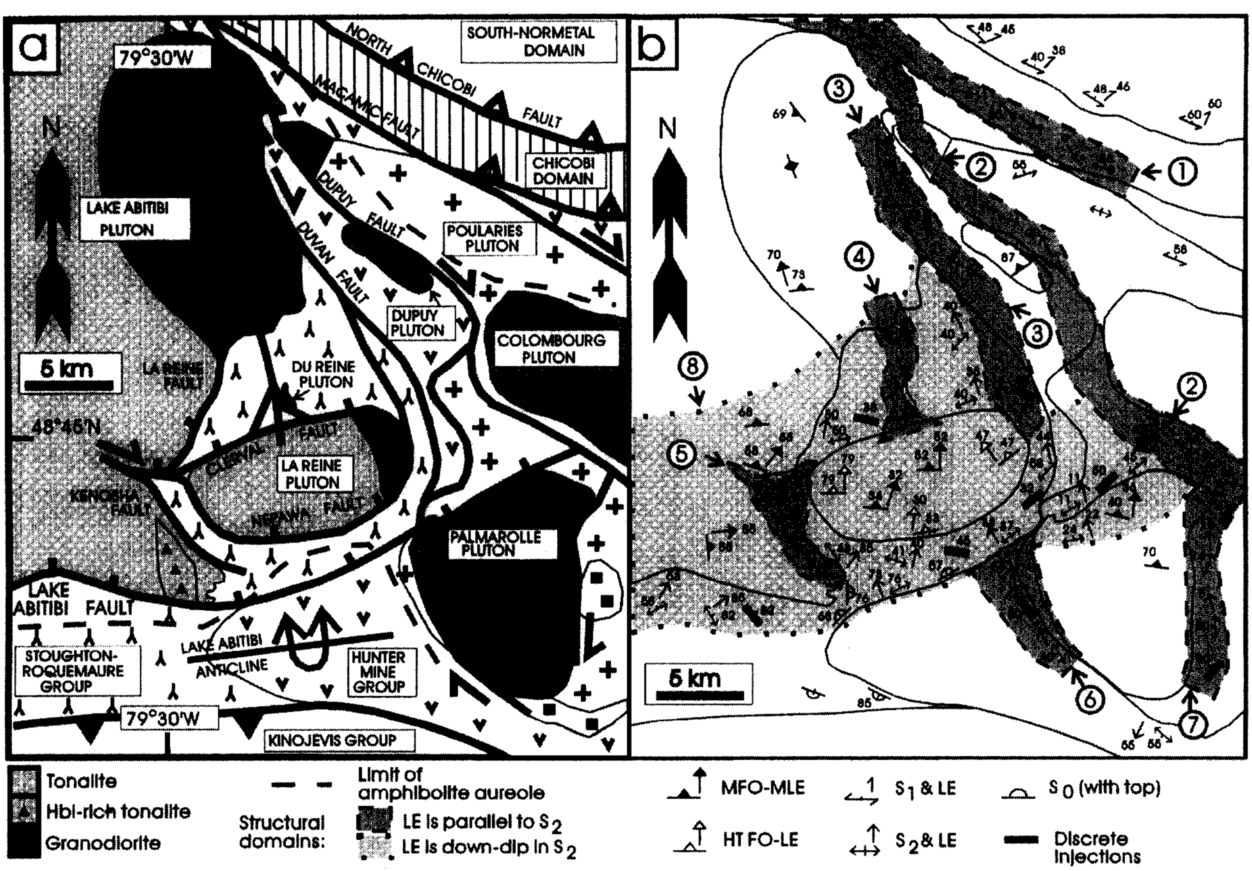

Fig. 3. Structural geology of the study area (modified from Lacroix, 1995): (a) Lithological, structural and metamorphic units. (b) Structural elements and domains. Structural domains are numbered from 1 to 8. Abbreviations as follows: HT—High-temperature, FO—Solid-state foliation (S_2), LE—Elongation lineation, MFO—Magmatic foliation, ML—Magmatic lineation. All unspecified patterns and labels as on Fig. 2.

relationship to the deformational sequence has been poorly documented.

STRUCTURAL ANALYSIS

First-generation structures (D_l)

East- to ESE-trending structures, referred to here as D_l, correspond to the first and more pervasive structures throughout most of the AGB; however, in some places where other workers (Dimroth *et al.*, 1983; Hubert *et al.*, 1984; Daigneault *et al.*, 1990) have documented an earlier north-trending phase of folds such structures are considered as D_2 structures. Low- to moderate-angle, south-vergent D_l thrusts, such as the North-Chicobi and Manneville faults occur along the boundaries of sedimentary belts. Recent mapping (Lacroix, 1995) indicates that the D_l Lake Abitibi Anticline is markedly asymmetric to the south, since both the Hunter Mine and Stoughton–Roquemaure groups are moderately north-dipping and north-facing on its northern flank, but subvertical and south-facing on its southern flank. Other D_l regional folds include the upright Poularies Anticline (Verpaelst and Hocq, 1991) and the Abijevis Syncline, also overturned to the south (Goutier, 1995). Steeply south-dipping reverse movements have been described along the Lyndhurst (Labbé, 1994) and Porcupine–Destor faults (Goutier and Lacroix, 1992), which probably represent D_l backthrusting with respect to the generally south-vergent D_l thrusting event. Such a scenario is consistent with their listric deep geometries to the south interpreted from Lithoprobe seismic profiles (Jackson *et al.*, 1995).

Second-generation structures (D_2)

Three major dextral strike-slip D_2 faults occur in the south-central AGB (Fig. 2). The Macamic Fault has been traced over at least 150 km in the AGB (Fig. 1b) as a 5 km-wide brittle–ductile shear zone that occurs along the northeast side of the Hunter Mine Group and the Poularies pluton (Labbé, 1994). Dextral D_2 shearing has also been described along the Cochrane–Milligan and Bradburn–Coulson faults (Jackson and Fyon, 1992), and has reactivated the eastern part of the D_l Porcupine–Destor Fault (Goutier and Lacroix, 1992). On Fig. 3, many structural domains have been distinguished by the attitude of D_2 lineations and foliations (see Turner and Weiss, 1963). The Macamic Fault is characterized by shallow-plunging lineations and steep WNW-trending foliations with NNW-trending shear bands (Figs 3 & 4—Domain 1). Within the Chicobi domain, D_l structures are steepened and overprinted by D_2 structures near the Macamic Fault (Lacroix and Sawyer, 1995). Dextral offset of the Poularies diorite and drag of the Chicobi sediments suggest a horizontal displacement of about 20 km along this fault (Labbé, 1994).

Southwest of the Macamic Fault, a large area is characterized by shallowly NNW-plunging elongation lineations but some NNW- to WNW-trending structural domains have variably dipping foliations (Figs 3 & 4 Domains 2–7). These domains contain clear evidence of non-coaxial deformation (see next section for microstructural and kinematic descriptions) and they correspond to the Dupuy, Duvan, Little Duvan, Kenosha, Duparquet River and Palmarolle fault zones. Given that NNW-trending faults are parallel to, or make an acute angle with, the Macamic Fault, exhibit similar stretching lineation orientations and dextral transcurrent shear sense and that the Dupuy and Duvan faults splay from it, they are interpreted to be second-order D_2 faults with respect to the major Macamic Fault.

North of the Lake Abitibi Anticline a 15 km-wide, ENE-trending structural domain exhibits low- to moderate-angle NNW-dipping foliations with down-dip lineations (Domain 8). The LaReine, Clerval, Nepawa and Lake Abitibi faults correspond to the most highly sheared zones in domain 8, and are mainly located along the pluton contacts. Given that NNW-trending and NNW-dipping domains display similar LS tectonites with NNW-plunging stretching lineations, and a mutually cross-cutting relationship, both likely developed during the D_2 event.

The S_2 foliation locally depicts outcrop-scale, centimetric to decimetric, open to isoclinal (rootless) intrafolial folds. Since no cleavage is associated with these folds and their axial planes vary greatly in attitude, but their axes are colinear with the lineations, these likely represent sheath folds (Cobbold and Quinquis, 1979) that developed at different D_2 stages. On stereograms 3, 4 and 8a, the poles to S_2 foliations plot along a great circle with a π-pole that is colinear with this lineation (Fig. 4—Stereogram 10), which reflects the influence of such local D_2 folds. A similar distribution of S_2 foliations on stereograms 9 and 11 reflects the preponderance of the elongation lineation during the development of S_2 fabrics in domains 2–8.

METAMORPHIC AND KINEMATIC EVOLUTION OF D_2 STRUCTURES

The syntectonic plutons are surrounded by amphibolite facies assemblages, which grade southward and northward into the characteristic greenschist facies regional metamorphism of the AGB (Fig. 3a). Amphibolite- and greenschist-grade basaltic rocks contain hornblende + plagioclase + quartz ± garnet ± Fe–Ti oxides ± epidote and actinolite + biotite + chlorite + epidote + quartz + albite + carbonate assemblages, respectively. Garnet-bearing amphibolites occur only in rocks of the Hunter Mine Group, east of the Lake Abitibi granodiorite, where garnet locally forms elongated aggregates of 1–4 mm subhedral grains scattered throughout the matrix. Other assemblages are dominated

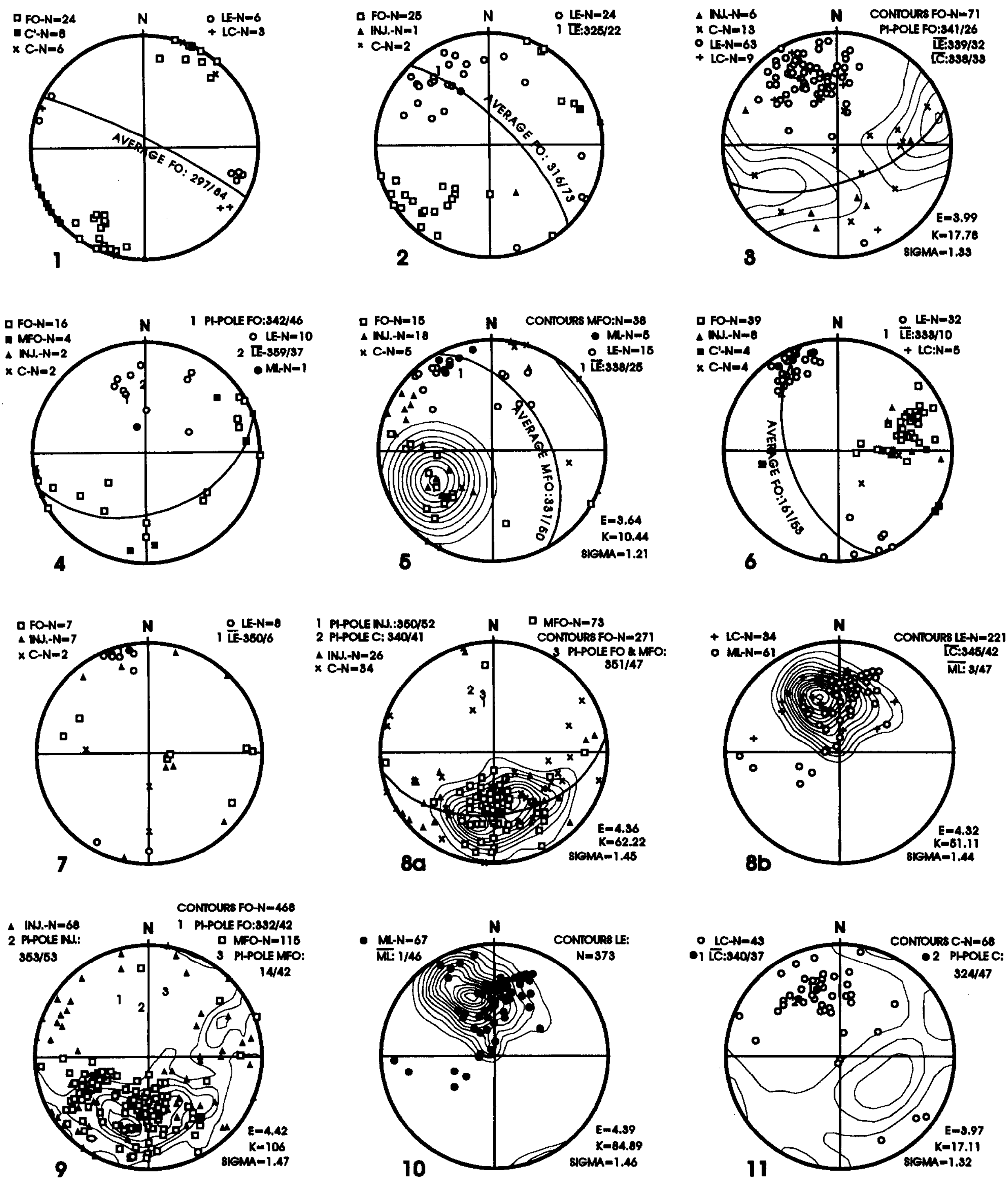

Fig. 4. Lower hemisphere projection, equal area stereograms of D_2 structures. Stereograms 1–7 refer to the numbered structural domains of Fig. 3b. Stereograms 8a and 8b present planar and linear fabrics, respectively, from domain 8. Stereograms 9–11 correspond to a synthesis of domains 2–8: (9) Planar and (10) linear magmatic to solid-state fabrics, (11) brittle–ductile planar and linear fabrics. Abbreviations as follows: C—Brittle shear, INJ.—Marginal injections, LC—Lineation in brittle shear (smears and slicksensides), C'—Shear band. All unspecified labels as on Fig. 3. The contours on some stereograms have been produced with Spheristat 1.0, which uses the weighting functions of Robin and Jowett (1986). The counting function (K for kurtesis), expected value (E) and dispersion (S for sigma) correspond to the parameters of this weighting function.

by hornblende (50–80%), while quartz appears as strain-free, elongate or polygonal grains (0.2–0.5 mm) and plagioclase grains have highly serrate boundaries. Amphibolite-grade assemblages are well-developed over wide zones in rocks which structurally overlie the plutons, i.e. north of the LaReine and Palmarolle plutons and northeast of the southeast part of the Lake Abitibi pluton (Fig. 5a). South of the LaReine pluton, only a relatively thin (0.5 km-wide) amphibolite facies aureole grades southwards into a 1 km-wide actinolite–chlorite schist, and finally into well-preserved lavas of the Stoughton–Roquemaure Group. This distribution of mineral assemblages is well explained by thermal models in which amphibolite facies assemblages developed as a contact metamorphic aureole with respect to plutonic heat sources.

However, amphibolite-grade assemblages have been variably retrograded to greenschist facies assemblages within numerous anastomosing systems of centimetre- to metre-scale schist bands, which developed preferentially along rheological discontinuities, such as pluton-wall rocks contacts. In highly strained areas, hornblende and garnet grains form isolated porphyroclasts (0.5–1 mm) within a greenschist facies mylonitic assemblage. Extensive proto-, ortho- and ultramylonitic textures and numerous shear bands (Fig. 5b) developed through the activity of crystal-plastic (i.e. dislocation) processes. Numerous asymmetric fabrics provide considerable evidence of semi-brittle deformation (Fig. 5c), such as microdominos like those described by Babaie and LaTour (1994). Since all amphibolite- and greenschist-grade assemblages display similarly oriented D_2 planar and linear fabrics in both NNW-trending and NNW-dipping domains, the amphibolite-facies contact metamorphic aureole is by definition synkinematic in respect to D_2, and D_2 structures likely developed under decreasing temperature conditions during the emplacement and subsequent cooling of the plutons.

Many observations indicate a significant component of non-coaxial deformation throughout the D_2 event, with dextral oblique movements along NNW-trending faults and normal dip-slip movements along NNW-dipping faults (Fig. 5b–e). Small hornblende laths (0.5 mm) in the asymmetric pressure shadows of some porphyroclasts confirm that non-coaxial shearing began under amphibolite-grade conditions. This is also supported by S/C fabrics in millimetre-scale ribbons of euhedral muscovite/biotite folia and polygonal mosaics of strain-free quartz grains (0.5 mm) indicative of High Temperature (HT) recovery and recrystallization within a mica schist east of the Dupuy pluton. However, wide areas of amphibolite-grade D_2 domains display mostly LS tectonites indicative of either coaxial flattening and elongation within a strongly partitioned deformation or high strain during shear development. Also, minor greenschist-grade shear zones with reverse movements within the NNW-dipping domain reflect a late structural complication. Abundant millimetre- to centimetre-scale, quartz- and carbonate-bearing veins are roughly concordant to the S_2, or shear (Fig. 5f) planes, within the country rocks and the plutons, and these contain mineral fibres that are oriented parallel to the stretching lineations in the hosting rocks (Fig. 4—Stereogram 11), but some veins have been asymmetrically boudinaged by shear bands, an increment of D_2 deformation that occurred under greenschist facies conditions.

THE RELATIONSHIP BETWEEN PLUTONISM AND D_2 STRUCTURES

Internal structure of the plutons

The internal structures of syntectonic intrusions are best exhibited by the LaReine pluton, which shows an outward progression from magmatic to solid-state mylonitic fabrics (Fig. 6). In its core, magmatic foliations and lineations are well-defined by an alignment of tabular, euhedral plagioclase crystals (30–50%, 1–4 mm) and by individual laths (0.5–1 mm) or aggregates of biotite and/or muscovite. The interstitial blebs, or enclosing interconnected network of coarse-grained aggregates of equant quartz grains (1 mm), show little evidence of deformation or recrystallization (Fig. 5g). Many albite-law twin planes are parallel to zoned plagioclase crystal faces, suggesting a magmatic to submagmatic flow of a plagioclase-bearing mush (Paterson *et al.*, 1989). The ENE-trending foliation apparently cross-cuts the contact between the two intrusive phases, which suggests the foliation was created, at least partly, during submagmatic flow following magma emplacement (Paterson and Vernon, 1995). Rare quartz-filled microfractures and serrate boundaries of plagioclase grains are likely to reflect fracturing and abrasion between grains, respectively, at the submagmatic stage (Bouchez *et al.*, 1992). In the granodiorite phase, cross-hatched twinned microcline, or perthitic orthoclase, occur as small interstitial crystals, or more rarely as large grains containing similarly oriented plagioclase grains. Local graphic and micropegmatitic textures are likely to reflect the crystallization of water-saturated melt.

High temperature (HT) solid-state fabrics become dominant in a 0.5–1 km-wide outer ring of the LaReine pluton. Rounded quartz blebs become progressively more flattened and elongated closer to the pluton margins until they form centimetre-wide quartz bands. Coarse, strain-free quartz grains (1 mm) exhibiting polygonal or elongated shapes (Fig. 5h) indicate recovery and recrystallization above epidote-amphibolite facies conditions (Simpson, 1985). Isolated biotite grains begin to form more continuous folia (1–2 cm long). These fabrics developed parallel to an earlier magmatic alignment of plagioclase grains which subsequently developed serrate boundaries, probably indicative of dynamic recrystallization through grain-boundary migration.

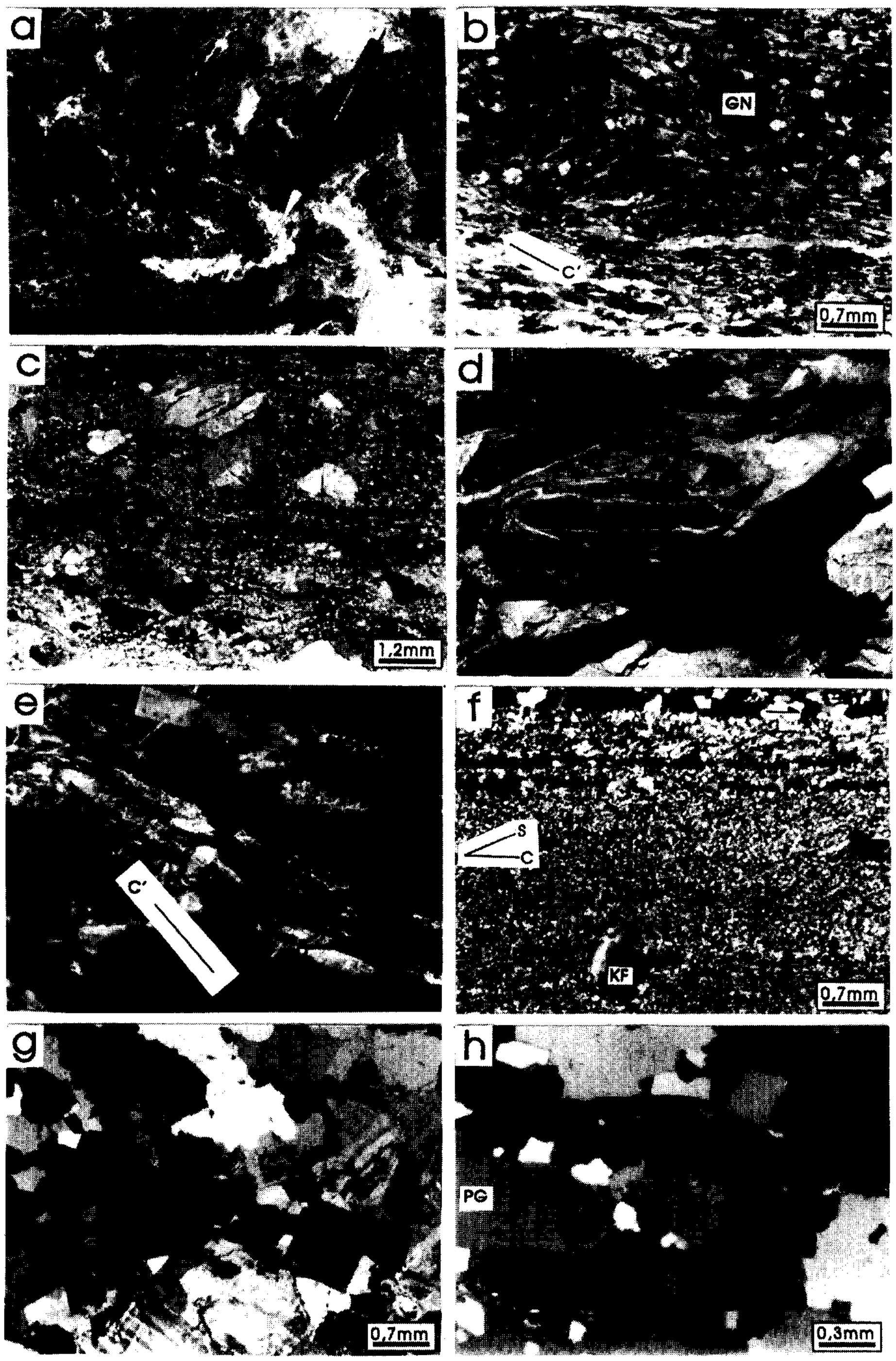

Fig. 5. Magmatic to solid-state D_2 structures in the plutons and their country-rocks. (a) Migmatite from the Kenosha Fault near the northeastern contact of the southeast part of Lake Abitibi pluton. Note that tonalitic melt is parallel to S_2 and infills discrete extensional structures. (b) Photomicrograph of garnet–hornblende HT wall-rock assemblage containing dextral LT shear bands (C') with a greenschist facies mineral assemblage (actinolite–chlorite), from the Duvan Fault. (c) Photomicrograph of LT orthomylonite with hornblende porphyroclasts (Duvan Fault). Note hornblende grains with bookshelf structure indicative of dextral shearing. (d) Reorientation of small intrusive veinlets parallel to amphibolite-facies S_2 which suggests syn-emplacement normal shearing along the roof contact of a NNW-dipping injection; photograph from the intersection of domains 2 and 8. (e) Asymmetric boudinage of marginal injections parallel to NNW-dipping S_2 foliations from the northeastern contact of the LaReine pluton, indicating a normal shear sense. (f) Photomicrograph from the eastern margin of the LaReine pluton exhibiting dextral LT ultramylonite defined by asymmetric pressure shadows (stair step) around a microcline porphyroclast in the lower part. In the upper part, a dextral movement is also indicated by S–C structures where muscovite-bearing S planes are oblique to small quartz veins parallel to C planes. (g) Photomicrograph from the core of the LaReine tonalite displaying a magmatic fabric defined by alignment of euhedral twinned plagioclase crystals, surrounded by interstitial or equidimensional aggregates of anhedral quartz. (h) Photomicrograph from the northern inner rim of the LaReine pluton showing HT solid-state mylonitic foliation defined by biotite folia surrounded by well-recrystallized polygonal quartz aggregates forming centimetre-scale bands. This HT foliation developed parallel to the euhedral plagioclase crystal orientation. Also note thin LT shears with smaller quartz and chlorite grains along the biotite margins.

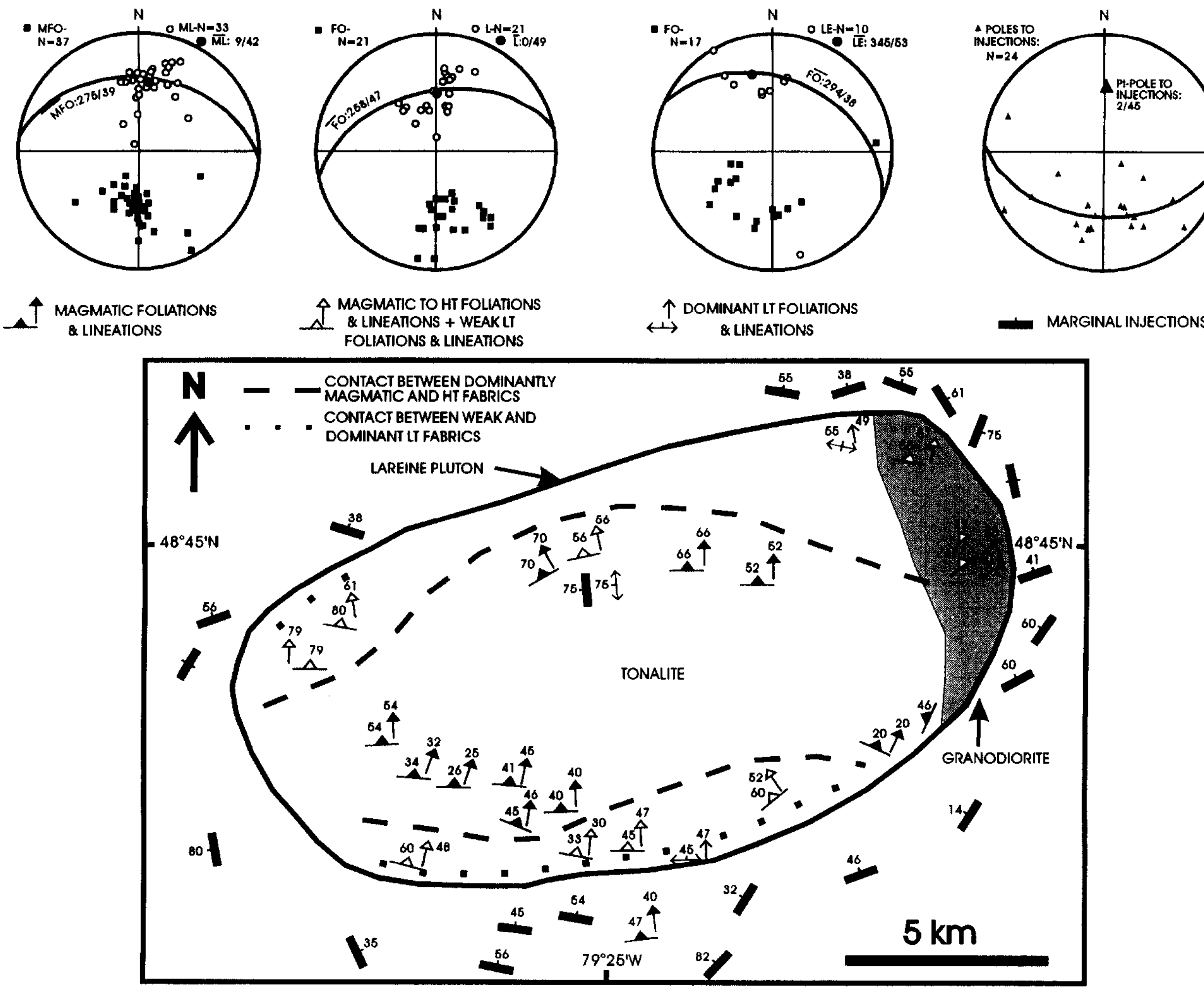

Fig. 6. Distribution of magmatic, HT and LT solid-state mylonitic D_2 structures within the LaReine pluton. All lower hemisphere projection, equal area stereograms. Unspecified labels as on Figs 3 & 4.

Such fabrics form a very homogeneous orthogneissic foliation at outcrop scale (Eakins, 1972). Myrmekitic textures in the LaReine pluton close to the Duvan Fault are likely to represent recrystallization during subsolidus cooling or amphibolite-facies deformation of the granitoids (Vernon, 1991), given the presence of solid-state HT recrystallization in neighbouring polymineralic aggregates.

The pluton margins are dominated by low-temperature (LT) deformation, which occurs as localized millimetre- to centimetre-wide bands that overprint more widespread HT fabrics. The LT fabrics range in intensity from protomylonitic to orthomylonitic (rarely ultramylonitic) with variable development of plagioclase porphyroclasts and more common asymmetric microstructures (Fig. 5f). These shear zones exhibit grain size reduction of plagioclase and dynamic recrystallization of quartz subgrains (0.1 mm) that form thin (0.4 mm) ribbons of fine-grained quartz–feldspar or mortar textured rims to larger grains. Folia of biotite $\pm$ muscovite (5–10 cm long) are variably replaced by chlorite, epidote and quartz. The fine-grained mortar-textured quartz, as well as strain localization and recrystallization of the biotite (300 ± 25°C), suggest that this deformation developed under greenschist-facies conditions (Simpson, 1985).

All planar and linear fabrics reflect an evolution as temperature progressively decreased (Gapais, 1989) but remain parallel to one another (Fig. 6), which suggests a synkinematic emplacement and cooling (Paterson *et al.*, 1989) of the LaReine pluton relative to NNW-dipping D_2 faults. Given that similar relationships are observed from all the other plutons with respect to adjacent second-order D_2 fault zones, their emplacement is interpreted to be synkinematic relative to the D_2 event. For example, the southern and northern parts of the Lake Abitibi and Palmarolle plutons also contain magmatic foliations, whose attitudes are parallel to pluton contacts and solid-state D_2 fabrics in the NNW-dipping D_2 domain (Fig. 3). In comparison, the Dupuy, DuReine and Colombourg plutons and LaReine and Lake Abitibi granodiorites have elongate map patterns, parallel to adjacent NNW- to WNW-trending D_2 faults. In the Colombourg pluton, Chown and Daigneault (1994) describe magmatic foliations that wrap along its southeastern edge and depict a synform plunging shallowly to the NW, parallel to the attitude of magmatic lineations. Although not as well exposed, the Dupuy pluton and Lake Abitibi granodiorite have similar internal structures since most magmatic foliations trend NNW but have NNW-dipping attitudes closer to their southern contacts (Fig. 3). A small granodiorite body located in the Kenosha fault zone, but too small to show at the scale of Fig. 3, also contains WNW-trending magmatic fabrics (Lacroix, 1995).

Marginal injections along pluton contacts

Syntectonic plutons are surrounded by numerous discrete injections, which are here referred to as marginal since most occur less than 1 km from the plutons (Figs 3 & 6). Undeformed injections contain from 20 to 40% plagioclase grains (1 mm), which occur as oriented tabular laths, or rectangular grains, with preserved zoning and twinning, thus each injection has been emplaced as a crystal-bearing suspension, much like the plutons. Other injections contain small hornblende or biotite grains (0.5 mm) which locally define well-developed magmatic fabrics. Whole rock geochemical compositions are similar to those of neighbouring plutons, i.e. most marginal tonalite and granodiorite injections occur in NNW-dipping and NW-trending D_2 fault zones, respectively (Lacroix, 1995).

Most injections are centimetre- to metre-wide, one to several metres long sheet-like bodies parallel to S_2 (e.g. sills) in all structural domains (Figs 3b & 4), although many locally cross-cut S_2 (Fig. 7a). Other injections intrude along planes of lithological weakness, such as the rims of slightly flattened pillows in lavas (Fig. 7b) and the primary compositional layering of the synvolcanic Poularies diorite. The parallel attitude of most marginal intrusions and S_2 foliations is well illustrated around the LaReine pluton (Fig. 6), where they define a north-plunging cylindrical geometry roughly parallel to the pluton contacts. The contact of the Colombourg pluton is notably marked by a 300 m wide zone of parallel tonalite sheet injections each charged with tabular wall-rock xenoliths, all cut by undeformed, late aplite dykes (Chown and Daigneault, 1994). The eastern contact of the Dupuy pluton also has steeply-dipping injections parallel to S_2, with small intrusive veinlets cross-cutting it.

These injections show variable relationships with D_2 deformation. Metre-wide spindle-shaped injections within the Rivière Duparquet Fault suggest that the magma passively filled a rhomb-shaped dilational site during dextral D_2 shearing (Fig. 7c). Within the Dupuy Fault, the reorientation of small intrusive veinlets parallel to S_2 above a tabular injection (Fig. 5d) indicates emplacement during extensional shearing along NNW-dipping planes that correspond to the easternmost extent of structural domain 8 (Fig. 3). Some injections parallel to S_2 underwent boudinage during HT coaxial deformation and have a pinch and swell geometry. Finally, other injections have been separated into isolated boudins during localized LT shearing (Fig. 7d).

The southeast part of the Lake Abitibi pluton exhibits an unusual 1 km-wide, 2 km-long zone of highly discordant contacts with the overlying ESE-dipping and ESE-facing variably metamorphosed and deformed volcanic rocks. There, tonalitic magmas intruded an irregular network of fractures that developed in coarse-grained, hornfelsed country-rocks (Fig. 7e & f). Centimetre- to metre-wide enclaves of massive and highly foliated wall-rock are separated by veins of massive tonalite, that are mostly oriented parallel to the foliation planes but also fill fractures in the enclaves. No enclaves exhibit evidence of internal straining after their incorporation in the magma, but some have undergone small amounts of rigid rotation and translation which are suggestive of stoping along the southeast part of the Lake Abitibi pluton. Centimetre-wide, local dykes appear for several hundred metres east of this pluton contact.

Most of domain 8 is cross-cut by, and reoriented in a clockwise rotation near, the Kenosha strike-slip Fault, whereas the planar and linear fabrics in the LaReine pluton become NNW- and NNE-trending, respectively, towards this fault. Along this fault, migmatitic structures and several generations of tonalite intrusions occur along a 20 m-wide, 10 km-long horizon in the wall-rocks directly above the southeast part of the Lake Abitibi pluton. There, tonalitic melts have been concentrated into local extensional structures (Fig. 5a), such as boudin necks and conjugate shear bands. Furthermore, several pulses of magma intruded into a network of sills parallel to S_2 and dykes orthogonal to the elongation direction (Fig. 7g & h). Early sills and dykes have been boudinaged and folded, respectively, while still partially molten, whereas younger dykes are rectilinear and cross-cut S_2 foliation, indicating periodic emplacement and incremental coaxial D_2 deformation during subhorizontal extension.

In summary, mutually cross-cutting relationships are observed between emplacement-related and amphibolite-grade D_2 structures, which have been together superimposed by greenschist-grade D_2 structures. Only locally have pluton contacts been severely affected by LT shear zones, such as the DuReine pluton where an iron carbonate-talc–chlorite alteration zone is well developed. At the northeastern contact of the LaReine pluton, numerous sill-like injections have also been extensively boudinaged by two conjugate LT shear zones, respectively, high-angle north-dipping shears showing normal movements and subhorizontal shears with reverse movements that developed during a down-dip elongation within the bisector S_2 foliation.

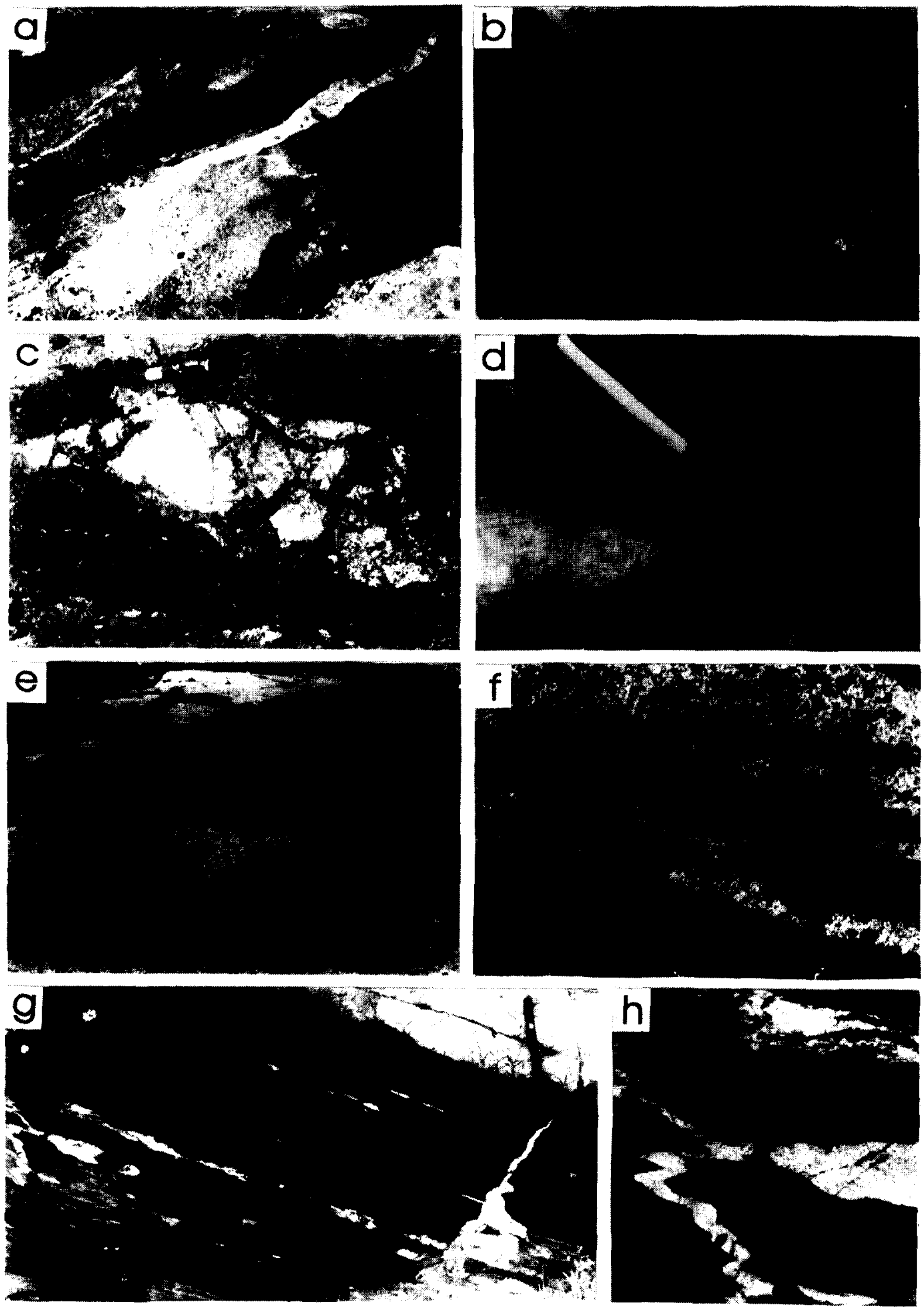

Fig. 7. Field observations from pluton contacts and their marginal injections. (a) Shallowly-dipping granodioritic injection cutting S_2 at a low-angle along the northern contact of the Palmarolle pluton. (b) Basaltic pillow rims filled by centimetre-wide granodioritic injections (Duvan Fault, northeastern contact of LaReine pluton). (c) Spindle-shaped granodioritic injection showing no internal deformation, suggestive of a passive filling of a small-scale releasing bend within the dextral strike-slip Rivière Duparquet Fault. (d) Dextral NNW-trending shear bands in the Macamic Fault that outline asymmetric boudinage of a granitoid injection parallel to S_2. (e) Tonalitic magma filling an irregular network of fractures in coarse-grained hornfelsed basalts, from the east contact in the southeastern part of the Lake Abitibi pluton. In the lower part, metre-scale enclaves floating in the tonalite are evidence for stoping. Note slight body rotation and translation of enclaves. (f) Close-up from (e) showing highly foliated amphibolite enclaves, without any evidence of younger internal straining. (g) Incremental emplacement of marginal injections during D_2 event, that occur parallel to S_2 (e.g. sills) and in fractures orthogonal to S_2 (e.g. dykes). Early dyke- and sill-like injections are folded and boudinaged, respectively, whereas younger ones are rectilinear and cross-cut S_2 foliation. (h) Close-up from (g) showing that the early dyke, which cross-cuts the S_2 foliation, and the injection parallel to S_2 have been, respectively, folded and boudinaged, both in molten state.

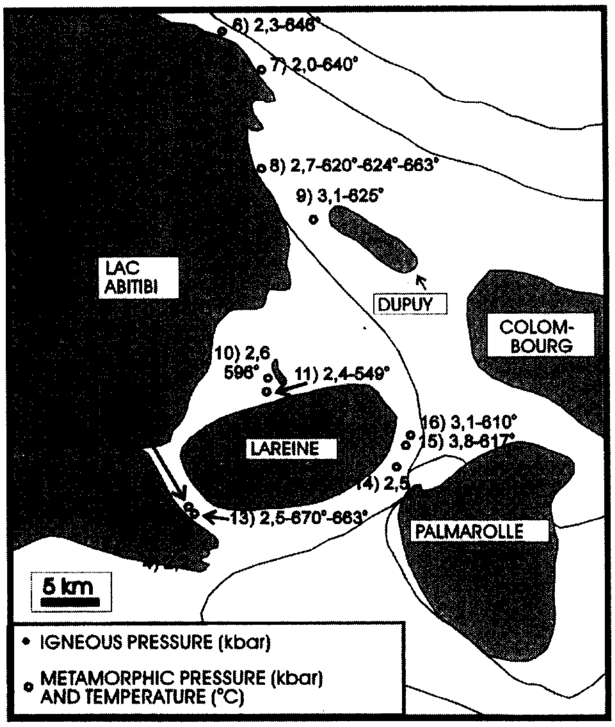

Fig. 8. Estimated average temperatures and pressures for the study area. Igneous crystallization pressures were obtained from thin sections of the Lake Abitibi and Palmarolle plutons, respectively, which have the required full mineral assemblages for the Al-in-hornblende geobarometer of Schmidt (1992). Pressure estimates were determined from micropobe analysis of the rims of amphibole grains showing textural equilibrium (i.e. polygonal grains) and very little compositional zonation. Country rock pressures are based on the Na content on the M4 site of these calcic–amphiboles (Brown, 1977). Metamorphic temperatures were estimated from the Ti content of amphiboles using the experimental calibration of Spear (1981) at 1 and 3 kbar reported by Schumacher *et al.* (1990) fig. 10.9. Pressure and temperature were determined on several sites numbered from 1 to 16, for which only the average of several estimated value has been indicated on the figure. The following list gives, for each site, the average and standard deviation (as well as the number of determinations) (P_I: Igneous pressure, P_M: Metamorphic pressure).1) P_I: 3,5–0,5 (14); 2) P_I: 1,8–0,2 (9); 3) P_I: 2,4–0,4 (24); 4) P_I: 2,2–0,3 (9); 5) P_I: 2,4–0,8 (23); 6) P_M: 2,3–0,3 (9), T: 646–9 (9); 7) P_M: 2,0–0,2 (3), T: 640–5 (5); 8) P_M: 2,7–0,2 (8), T: 624–20 (5), T: 620–17 (8), T: 663–6 (3); 9) P_M: 3,1–0,4 (6), T: 625–22 (8); 10) P_M: 2,6–0,5 (9), T: 596–15 (7); 11) P_M: 2,4–0,1 (4), T: 549–6–(5); 12) P_M: 2,6–0,1 (6), T: 696–27 (7), 649–9 (7); 13) P_M: 2,4–0,6 (6), T: 670–15 (10), T: 663–18 (13); 14) P_M: 2,5–0,2 (4), T: $<$540–0 (10); 15) P_M: 3,8–0,7 (6), T: 617–15 (11); 16) P_M: 3,1–0,4 (2), T: 610–15 (2).

ESTIMATES OF P–T CONDITIONS OF EMPLACEMENT AND METAMORPHISM

Figure 8 displays pressure and temperature determinations obtained in the study area. Igneous crystallization pressures based on the Al-in-hornblende geobarometer (Schmidt, 1992) vary from 1.8 to 3.5 kbar for the Lake Abitibi pluton. A pressure of 2.4 kbars was obtained from the core of the Palmarolle pluton. The narrow variation in whole rock geochemical composition of all granodiorites analysed (Lacroix, 1995) suggests that these pressures imply similar solidus temperatures (Anderson and Smith, 1995; Ague and Brandon, 1996). Wall-rock metamorphic amphiboles vary in composition from ferro-tschermakite to magnesio-hornblende in the classification of Leake (1978). Garnets are dominated by almandine (0.46–0.70 mole%), with grossular (0.17–0.27) and spessartine (0.04–0.21) as the other main components. Most plagioclases have been retrograded to albite during later greenschist facies deformation, but preserved examples range from An_{22} to An_{60}. Metamorphic pressures calculated from the Ca-amphiboles using the method of Brown (1977) range mostly between 2 and 3.1 kbar, in good agreement with the crystallization pressures obtained from the plutons. Similar pressures were obtained by Feng and Kerrich (1990) for the Lake Abitibi and Colombourg plutons (2.3–2.5 kbars) using the calibration of Hollister *et al.* (1987), and their wall-rocks (2–3 kbars).

Temperatures in the metamorphic aureole have been estimated from the Ti content of amphiboles (Schumaker *et al.*, 1990) and the plagioclase–amphibole geothermometer of Holland and Blundy (1994). Temperatures obtained from the former method vary from 540 to 696°C, whereas those from the latter gave higher results (between 662 and 823°C). Both methods indicate that the highest aureole temperatures were reached in the migmatite from the Kenosha domain (650–696°C and 757–823°C, respectively). The Ti-in-amphibole geothermometer gave more reasonable temperatures, close to those of a water-saturated tonalite solidus (e.g. 685°C) at 2–3 kbar taken from Hollister *et al.* (1987). The Ti content of amphiboles around the LaReine pluton suggests temperatures up to 617°C. East of the Lake Abitibi granodiorite (Duvan Fault), estimated temperatures with this method vary between 620° and 665°C, whereas slightly higher temperatures (651–748°C and 701°C) were obtained using the amphibole–garnet geothermometers of Graham and Powell (1984) and Perchuk *et al.* (1985), respectively. In summary, such results indicate that the synkinematic 2–3 kbar amphibolite-grade contact metamorphism produced temperatures of 650–700°C close to the plutons. However, the common presence of albitic plagioclase and low Ti amphibole ($<$0.038 p.f.u., i.e. T $<$540°C) indicates that a later greenschist-grade metamorphism has overprinted many high grade contact aureole rocks.

DISCUSSION

The development of an extensional D_2 transfer zone

West- to NW-trending dextral strike-slip faults, such as the Macamic D_2 Fault, occur throughout the southern Superior Province (Hudleston *et al.*, 1988; Borradaile *et al.*, 1988; Robert, 1989, 1991; Daigneault and Archambault, 1990; Williams *et al.*, 1992). The coexistence of steep NNW-trending and low-angle NNW-dipping second-order D_2 faults bearing identical LS tectonites, oblique stretching lineations and retrograde metamorphic histories, however, indicates a more complex structural evolution, west of the Macamic Fault.

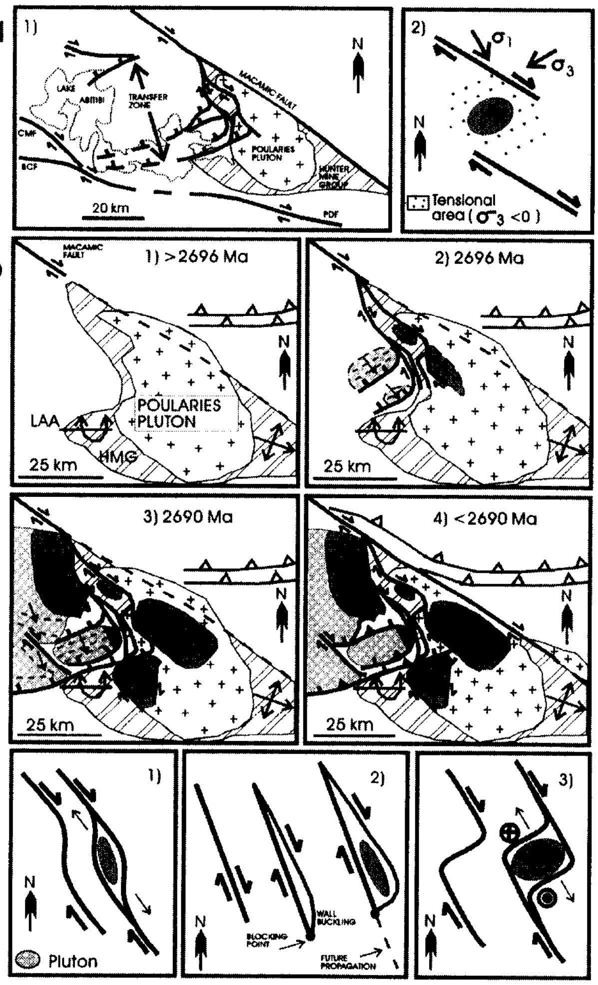

Fig. 9. Conceptual model of the D_2 structural and plutonic evolution in the Lake Abitibi area. (a) Structural geometry and evolution of D_2 structures in the Lake Abitibi area: 1) Structural geometry of the extensional transfer zone and adjacent strike-to oblique-slip D_2 faults; 2) schematic map view showing the creation of a local transtensional jog in respect to theoretical stress orientations when an isotropic medium is deformed along two right-stepping dextral faults in a transpressional situation (modified from Rodgers, 1980 and Segall and Pollard, 1980). (b) Possible sequence of faulting and plutonism in the easternmost part of the Lake Abitibi area: 1) Inferred pre-D_2 map pattern and structural geometry of the Poularies pluton, Hunter Mine Group and Lake Abitibi Anticline after the D_1 event; 2) structural development of NNW-trending D_2 faults and initial flow of magma during emplacement spreading toward the southeast around 2696 Ma; 3) continuous development of the linked D_2 fault system towards the southwest and final emplacement of many plutons around 2690 Ma; 4) after cooling of plutons, dextral-oblique movements still occurred along NNW-trending faults whereas NNW-dipping faults exhibit both normal and reverse movements. Further southeastwards propagation of the Macamic Fault produced a clockwise reorientation of low-angle D_1 thrusts along the Chicobi Domain and a dextral offset of the northeasternmost part of the Poularies pluton. Dashed lines and arrows in plutons correspond to magmatic foliations and magma flow direction, respectively. In stages 1–2–3, D_1 thrusts have not been traced up to the Macamic Fault to simplify drawing of the sketch. (c) Three possible models of pluton emplacement within favourable sites along the D_2 fault system: 1) Schematic NW-trending elongated map-pattern of plutons emplaced along a releasing bend of a dextral strike-slip fault; 2) schematic NW-trending elongated map-pattern of plutons emplaced along a fault termination of a dextral strike-slip fault after the model of Hutton (1988) and Ferré *et al.* (1995); 3) schematic ENE-trending elliptical map-pattern of plutons emplaced within an extensional transfer zone between dextral strike-slip faults. Note that a NNW-trending vertical section across the transfer zone will show the same structural geometry as the map view in model 1.

The distribution of rheologically competent units and preexisting structural heterogeneity might well explain the D_2 structural development in the study area (Fig. 9a-1). At the onset of the D_2 event, the northern part of the Hunter Mine Group and the Poularies pluton likely were NW-trending with moderate-angle dips toward the NE, whereas the southern part of the Poularies pluton would have been flanked by adjacent Lake Abitibi and Poularies D_1 anticlines (Fig. 9b—1). During D_2, it is proposed that NNW-trending faults (e.g. Dupuy and Duvan faults) splayed from the southeastward propagating Macamic Fault as they were deflected by these two competent units, and followed their western contacts (Fig. 9b—2). Such faults easily developed, since outcrop-scale NNW-trending dextral shear bands already existed in the Macamic Fault (Figs 3 & 4, Domain 1). As the splay faults propagated and approached the north-dipping contacts of the Poularies pluton and northern flank of the overturned D_1 Lake Abitibi Anticline, their NNW strikes underwent a clockwise reorientation and their dips flattened to develop as a trailing extensional imbricate fan (Woodcock and Fischer, 1986) with dextral-oblique movements along most fault segments, and eventually formed an extensional transfer zone (Figs 9b—2 & 3). Such a development is consistent with theoretical and experimental work (Davison, 1994), which indicates that highly oblique transfer faults do not form in a homogeneous material but are rather likely to form along favourably oriented basement weaknesses. A southward fault-propagation is also suggested from the map-pattern of NNW-trending faults (e.g. the Duvan, Little Duvan and Kenosha faults), which cross-cut the northern part of domain 8 but root into its southern part.

Reconnaissance mapping along the Lake Abitibi shoreline in Ontario indicates that the NNW-dipping domain continues at least 20 km west of the LaReine pluton. There, gravity data support a moderately north-dipping attitude for the southern contact of the Lake Abitibi pluton underlain by the Stoughton-Roquemaure Group (Antonuk and Mareschal, 1992). Moderately NNW-dipping foliations also occur within the westernmost Lake Abitibi pluton (Smith and Sutcliffe, 1988), as well as over a 2 km width around its NW corner (Lumbers and Cox, 1961). Thus, both LaReine and Lake Abitibi plutons likely correspond to tabular bodies enclosed within a 40 km-wide, >40 km-long NNW-dipping domain. The dimensions, oblique attitude and position of this domain showing normal movements relative to the Macamic, Cochrane–Milligan and Bradburn–Coulsen faults (Fig. 2) suggest that this whole zone could have acted as an extensional transfer zone between these dextral strike-slip D_2 faults under amphibolite facies conditions (Fig. 9a—1). The geometry and scale of this D_2 fault system would resemble extensional transfer zones described from Nevada (Oldow *et al.*, 1994) and California (Walker *et al.*, 1995).

Model of pluton emplacement

A synkinematic emplacement of plutons with respect to early D_2 deformation is well illustrated in the Lake Abitibi area by: (1) the similar attitude and continuity of evolution of magmatic to solid state fabrics; (2) the mutually cross-cutting relationship between pluton contacts with their marginal injections and amphibolite-grade D_2 structures. Fault-controlled dilation (i.e. the pull-apart model) is often invoked for similar plutons passively emplaced along, and during, the development of either strike-slip (Hutton, 1982; Guineberteau *et al.*, 1987; Morand, 1990; McCaffrey, 1992; Ferré *et al.*, 1995) or extensional (Hutton *et al.*, 1990; Koukoukevlas and Pe-Piper, 1991) faults. The elongate map-pattern and concordant attitude of NNW- to WNW-trending (e.g. Dupuy, Colombourg and DuReine plutons, LaReine and Lake Abitibi granodiorites) and NNW-dipping (e.g. LaReine and Lake Abitibi plutons) plutons, as well as the existence of marginal injections within outcrop-scale releasing bends and extensional structures (Figs 5a, d & 7c), is roughly consistent with their emplacement within dilatant positions along dextral oblique-slip and extensional D_2 faults, respectively (Fig. 9c).

However, other local observations suggest that rheological and structural (S_2) discontinuities likely acted as mechanical anisotropies for intrusive emplacement without necessitating an overall creation of space solely by fault displacement. Metre-scale injections intruded local rheological discontinuities where there is no evidence for non-coaxial deformation (e.g. pillow rims, Fig. 7b). Other marginal injections parallel to S_2 show evidence of boudinage when in a partially molten state (Fig. 7g & h), which requires either that magma should have overcome the normal stress across S_2 planes, or an incremental sequence of extension and compression orthogonal to S_2. Such a mechanism could also explain why the LaReine and Lake Abitibi plutons have magmatic fabrics and tabular geometries concordant to the enclosing transfer zone, which indicate relatively weak intrusive effects interfering with fault development. In comparison, the magmatic foliation within the Colombourg and Dupuy plutons, as well as in the Lake Abitibi granodiorite, are parallel to NNW-trending D_2 faults except along their southeastern edge where they depict a synform (Fig. 9b—2 & 3). Thus, the internal structure and map-pattern of NNW- to WNW-trending plutons with their rounded edges, differs from spindle- to rhomb-shaped pull-apart geometries of passively emplaced plutons (Hutton, 1982; Guineberteau *et al.*, 1987; Morand, 1990), and rather reflects an interaction between prominent lateral expansion and regional strain field (Brun *et al.*, 1990; Lagarde *et al.*, 1990; Cruden and Launeau, 1994). These plutons mostly resemble those emplaced along strike-slip fault termination (Fig. 9c—2) such as the Strontian (Hutton, 1988) and Solli Hills (Ferré *et al.*, 1995) granites. The internal structure and geometry of the Palmarolle pluton reflects both the influence of the NNW-dipping Lake Abitibi Fault and the southward converging NNW- and N-trending Rivière Duparquet and Palmarolle faults.

Thus, the emplacement of marginal injections and plutons along second-order D_2 faults also partly reflects a mechanism of magmatic wedging (Hutton, 1992) along D_2 structural discontinuities. Such emplacement mechanics overcome the problem of rate compatibility between fault displacement and pluton ascent/emplacement, the former being generally the slower and rate-controlling process in passive emplacement models (Paterson and Tobisch, 1992). Other mechanisms also likely contributed to 'space creation'. Given that the deformation around syntectonic plutons shows evidence of non-coaxial shearing and belongs to a kinematically compatible D_2 fault system, buoyant forces did not significantly modify the overall geometry and kinematic evolution of second-order D_2 faults west of the Macamic Fault. However, pluton expansion might have contributed to the development of wall-rock plane strain fabrics (LS tectonites), and ductile flow in the aureole could have represented a significant material transfer process. Local space made by wall-rock ductile flow around elliptical plutons may approximate 25% of the amount required for pluton expansion, and lateral expansion of tabular intrusions requires notably less bulk shortening than radial expansion of spherical plutons (Paterson and Fowler, 1993). The evidence of fracture filling and stoping along the southeast edge of the Lake Abitibi pluton, which would correspond to a frontal tip, confirm that rarely preserved stoping at the top of plutons might also have contributed to downward transfer of material. Hence, this study supports that several emplacement and material transfer processes (e.g. fault dilation and wedging, lateral expansion, wall-rock ductile flow, stoping) contribute simultaneously but in different parts of the system, to pluton building at mid- to upper-crustal levels, as suggested by other recent studies (Paterson and Fowler, 1993; McNulty *et al.*, 1995).

Although such multiple emplacement mechanisms operated rather than a simple passive filling of dilational jogs created by non-coaxial deformation, the emplacement of plutons should have been structurally-induced since they are not randomly distributed within the D_2 fault system. The presence of rare discrete injections along the Macamic Fault (Fig. 7d), in comparison to several major plutons and marginal injections southwest of this major fault, implies the development of favourable stress fields for pluton emplacement in this latter area.

Theoretical computation of principal stresses in an homogeneous elastic medium along two right stepping interacting dextral relay faults indicates the development of an extensive tensional area between these two faults (see Fig. 9a—2). If the Macamic and Cochrane–Milligan D_2 faults also developed in such a releasing overstep pattern, a transtensional stress field could have permitted the emplacement of voluminous plutons in the

Lake Abitibi area (Figs 2 & 9a—1). Transtensional bridges could also favour the development of a linking extensional fault between offset strike-slip faults (Segall and Pollard, 1980). Even if the Macamic Fault does not appear as a preferential pluton emplacement site, it may have played a role for magma ascent. Many observations indicate that all plutons were formed by southeastward magma spreading: (1) the constant attitude of magmatic lineations plunging about 40° toward the NNW (e.g. toward the Macamic Fault) and parallel to the regional stretching lineation; (2) the NNW-dipping attitude of tabular plutons with parallel magmatic fabrics; (3) the NW-dipping attitude and synform-like shape of magmatic fabrics near the southeast margin of NNW- to WNW-trending plutons and; (4) the interpretation of a frontal tip along the southeast edge of the Lake Abitibi pluton. Since all plutons occur southwest of the Macamic Fault (Fig. 3), we speculate that the magma tapped by this more deeply penetrating fault might then have risen obliquely toward the southeast and laterally infilled favourable sites created in the stress field (Fig. 9c). Other studies (D'Lemos *et al.*, 1992; Hutton and Reavy, 1992) also conclude that major strike-slip faults provide plausible deep channels for the migration of magmas.

Thermal role of plutons in the D_2 structural evolution

From a purely geometric perspective, it is surprising that both 5 km-wide, 10–20 km-long NNW-trending and 40 km-wide, >40 km-long NNW-dipping second-order D_2 fault zones developed to such an extent, rather than just leading to an aborted bend which was then bypassed by the rectilinear first-order Macamic Fault. Aydin and Nur (1985) emphasized that the development of straight strike-slip faults between offsets is energetically more efficient. Strike-slip faults may die out at geometrical barriers producing jogs and steps (Scholz, 1990), and an appropriate way could be to diffuse into a trailing extensional imbricate fan where part of the deformation is being taken up by rotation of curved fault segments (Peacock, 1991).

Since further propagation along this bend leads to the formation of a huge transfer zone with amphibolite-grade assemblages, pluton emplacement is thought to have modified the expected geometry of D_2 fault propagation. Crustal rheology is temperature-related, and the heat provided by high-level plutons can soften their wall-rocks and accelerate deformation in these localized areas (Sandiford *et al.*, 1992; Barton and Hanson, 1989). Early plutons intruded at the terminations of southward propagating NNW-trending D_2 faults likely raised the temperature in their wall-rocks to over 500°C. This eventually allowed further propagation, transfer and more magma emplacement until the formation of amphibolite-facies D_2 faults with temperatures up to 650–700°C. Amphibolite-grade shear zones tend to link together more naturally than more brittle upper-crustal faults, given their greater width, ductile behaviour and smoothly curved patterns (Davison, 1994). Although initially induced by pre-D_2 heterogeneities, pluton emplacement then permitted full-scale development of, and efficient transfer between, second-order D_2 faults.

This symbiotic relationship between pluton emplacement and amphibolite-grade D_2 deformation allows an accommodation of D_2 strain in the Lake Abitibi area during some million years. Taking into account absolute errors, all syntectonic plutons crystallized within a period of 4–10 Ma. For example, the granodiorite phase of the Lake Abitibi pluton crystallized at least 2 m.y. (2691 vs 2693.1 Ma) after the tonalite phase. Synkinematic emplacement of plutons with respect to the second-order D_2 faults implies a similar duration for the amphibolite-facies contact aureole metamorphism and deformation. The preservation of various stages of igneous-structural relationships and submagmatic to high-temperature fabrics also suggests similar rates of regional deformation, magma emplacement and crystallization (Paterson and Tobisch, 1992; Miller and Paterson, 1994). Finally, such a duration compares to both average emplacement and crystallization rates of 10 km-wide plutons and the preservation of temperatures over 500°C in their surrounding metamorphic aureoles at mid- to upper-crustal levels (Barton and Hanson, 1989; Tommasi *et al.*, 1994; Hanson and Glazner, 1995). Such contact metamorphism is identical to the pluton-enhanced, high-T, low-pressure 'regional aureole' metamorphism of den Tex (1963).

Perhaps the best evidence that the thermal state has a significant influence on the propagation of D_2 faults is provided by narrower greenschist-grade shear zones. During cooling (<2690 Ma), these shear zones were mostly localized along pluton-wall-rock contacts where fluids were probably also concentrated. At that stage, normal and reverse movements along the NNW-dipping domain might be explained by dominantly coaxial deformation. More likely, this zone was reactivated by reverse movements since it is orthogonal to the NNW-trending far-field maximum compressive stress, whereas part of the dextral movement along NNW-trending faults was still transferred into normal movement (Fig. 9b—4). In both cases, the transfer of movement within the linked system became less efficient, the transfer zone progressively locked during cooling of the plutons and D_2 shearing was then solely accommodated by major WNW-trending dextral faults. Similar examples of faults which locked during pluton cooling are given by Sandiford *et al.* (1988) and Miller and Paterson (1992).

CONCLUSION

Diapiric models of pluton emplacement and vertical tectonics in Archaean greenstone belts have been seriously questioned by both experimental (Marsh, 1982; Cruden, 1988) and field (Myers and Watkins, 1985; Schwerdtner, 1990) work. Recent studies of plutons in the AGB suggest that they may have utilized major faults for ascent and emplacement (Cruden and Launeau, 1994; Chown and Daigneault, 1994). This study supports such interpretations, and further emphasizes that pluton emplacement (at least of the TTGM suite) and propagation of strike-slip D_2 faults were intimately coupled during a late Archaean, Superior Province-wide transpressive event (D_2), that followed an earlier crustal-scale thrusting event (D_1) related to collision of arcs.

During D_2, rheological and D_1 structural heterogeneities facilitated the development of second-order, NNW-trending dextral-oblique faults which eventually transferred their movements into low-angle NNW-dipping extensional faults between two major WNW-trending, right-stepping dextral strike-slip D_2 faults. Many plutons were emplaced along both sets of second-order D_2 faults but several emplacement and material transfer mechanisms operated, including fault-dilation and wedging, lateral expansion, ductile flow and stoping. Thermal softening resulting from sequential pluton emplacement (between 2696–2690 Ma) permitted and enhanced an efficient linking and transfer between the second-order D_2 faults, which eventually locked as the crust cooled after intrusion ended at 2690 Ma. Thus, the inhomogeneous distribution of TTGM plutons likely had a significant influence on the pattern of D_2 fault propagation in the AGB. Since Jackson and Cruden (1995) proposed that the south-vergent D_1 thrusting event may also have been assisted by an older generation of sheet-like plutons in the mid-crust beneath the AGB, most of its structural and plutonic evolution should have been coupled which is typical of many low-P, high-T metamorphic belts in arc and back-arc settings (Barton and Hanson, 1989).

Voluminous pluton emplacement during a late Archaean transpressional tectonic regime invites a comparison with the emplacement of plutons and batholiths in favourable deformation fields during active shearing related to Phanerozoic oblique plate convergence (Glazner, 1991; D'Lemos *et al.*, 1992; Hutton and Reavy, 1992; Tikoff and Teyssier, 1992; Tobisch *et al.*, 1995; Ferré *et al.*, 1995). In particular, the decoupling of normal and strike-slip components of oblique convergence (Archanjo *et al.*, 1994; Miller, 1994; Karlstrom and Williams, 1995) may represent a major control of the ascent and emplacement of granitoid magmas during the late Archaean. Pull-apart sedimentary basins are typically developed within the uppercrust at releasing stepovers, where they are generally bounded by two vertical offset strike-slip faults that are linked by two parallel oblique- to normal-slip faults (Crowell, 1974; Aydin and Nur, 1985). In the Lake Abitibi area, the structural site of pluton emplacement also corresponds to a releasing bend between major WNW-trending strike-slip D_2 faults, where NNW-trending extension parallel to adjacent oblique-slip faults defines a pull-apart domain. Hence, at least some late Archaean strike-slip faults were apparently segmented down to at least mid-crustal levels where they provided a favourable stress field for pluton emplacement.

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