

THE RELATIONSHIPS BETWEEN THE ANNIEOPSQUOTCH OPHIOLITE BELT, THE DASHWOODS BLOCK AND THE NOTRE DAME ARC IN SOUTHWESTERN NEWFOUNDLAND

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ABSTRACT

The Lloyds River fault accommodates oblique sinistral underthrusting of the Annieopsquotch ophiolite complex beneath the Laurentian margin of the Dashwoods block at amphibolite-facies conditions. This is confirmed, on a regional scale, by relationships in the Buchans area, immediately to the north of the study area. Based on similar setting and field characteristics it is likely that the Star Lake shear zone is the extension of the Lloyds River fault. The Lloyds River fault is intruded syn-kinematically by sheets of the Notre Dame arc-magmas resulting in melt-weakening, and cutting by post-kinematic plutons. This implies an eastward migration of the magmatic axis of the Notre Dame arc, which could be the result of stepping-back or rapid roll-back of the west-dipping subduction zone.

INTRODUCTION

The Annieopsquotch ophiolite belt (AOB) (Dunning, 1981; Dunning and Chorlton, 1985) is considered to form part of the Notre Dame Subzone (Williams *et al.*, 1988) of the Dunnage Zone (Williams, 1979) of the Newfoundland Appalachians. The Notre Dame Subzone mainly comprises the remnants of obducted Middle Cambrian to Arenig oceanic lithosphere and a magmatic arc (Notre Dame arc (NDA)) of dominantly Ordovician age (van Staal *et al.*, 1998). The NDA is also prevalent in the Dashwoods Subzone that occurs immediately to the south and west of the Notre Dame Subzone. The Dashwoods Subzone is underlain by continental crust of Laurentian affinity (Whalen *et al.*, 1997) and its rocks are commonly intensely metamorphosed at amphibolite-facies conditions. Isotope and zircon studies have demonstrated that this basement is also widespread beneath the Notre Dame Subzone, although it is rarely exposed. Hence, the NDA was mostly constructed on a sliver of extended Laurentian crust, generally referred to as the Dashwoods block, after it had already interacted with some ophiolitic rocks near the Laurentian margin (Whalen *et al.*, 1997; Waldron and van Staal, 2001). It comprises several intrusive gabbro–diorite–tonalite–granite complexes where tonalite predominates (e.g., Hungry Mountain and South-west Brook complexes, Whalen *et al.*, 1987; Dunning *et al.*, 1989). The AOB comprises several ophiolitic fragments,

most notably the King George IV, Annieopsquotch, and Star Lake ophiolite complexes (Figure 1). Other ophiolitic fragments in this belt are the Skidder basalt (Pickett, 1987) and the Mansfield Cove complex (Dunning and Chorlton, 1985; Dunning *et al.*, 1987).

The Annieopsquotch ophiolite complex, like the Star Lake and Mansfield Cove ophiolitic fragments is early Arenig (481 to 478 Ma, Dunning and Krogh, 1985; Dunning *et al.*, 1987; Whalen *et al.*, 1997) and is the largest and most studied ophiolite complex of the AOB. It consists of olivine–plagioclase–clinopyroxene cumulates, gabbros, sheeted dykes and pillow basalts that appear to have dominantly N-MORB geochemical signatures (Dunning, 1987). The stratigraphic units trend northeast and generally have steep to vertical dips. The ophiolite and related rocks are structurally bounded to the southeast by the Red Indian Line (Figure 1), which separates it from volcanic rocks of the Exploits Subzone, whose rocks have Gondwanan affinities (Williams *et al.*, 1988).

The Annieopsquotch ophiolite complex is bounded to the northwest by the Lloyds River fault (Figure 1). The movement history and tectonic significance of the Lloyds River fault were previously poorly understood. Dunning (1987) interpreted the fault to separate the Annieopsquotch ophiolite complex from the NDA plutons and supracrustal

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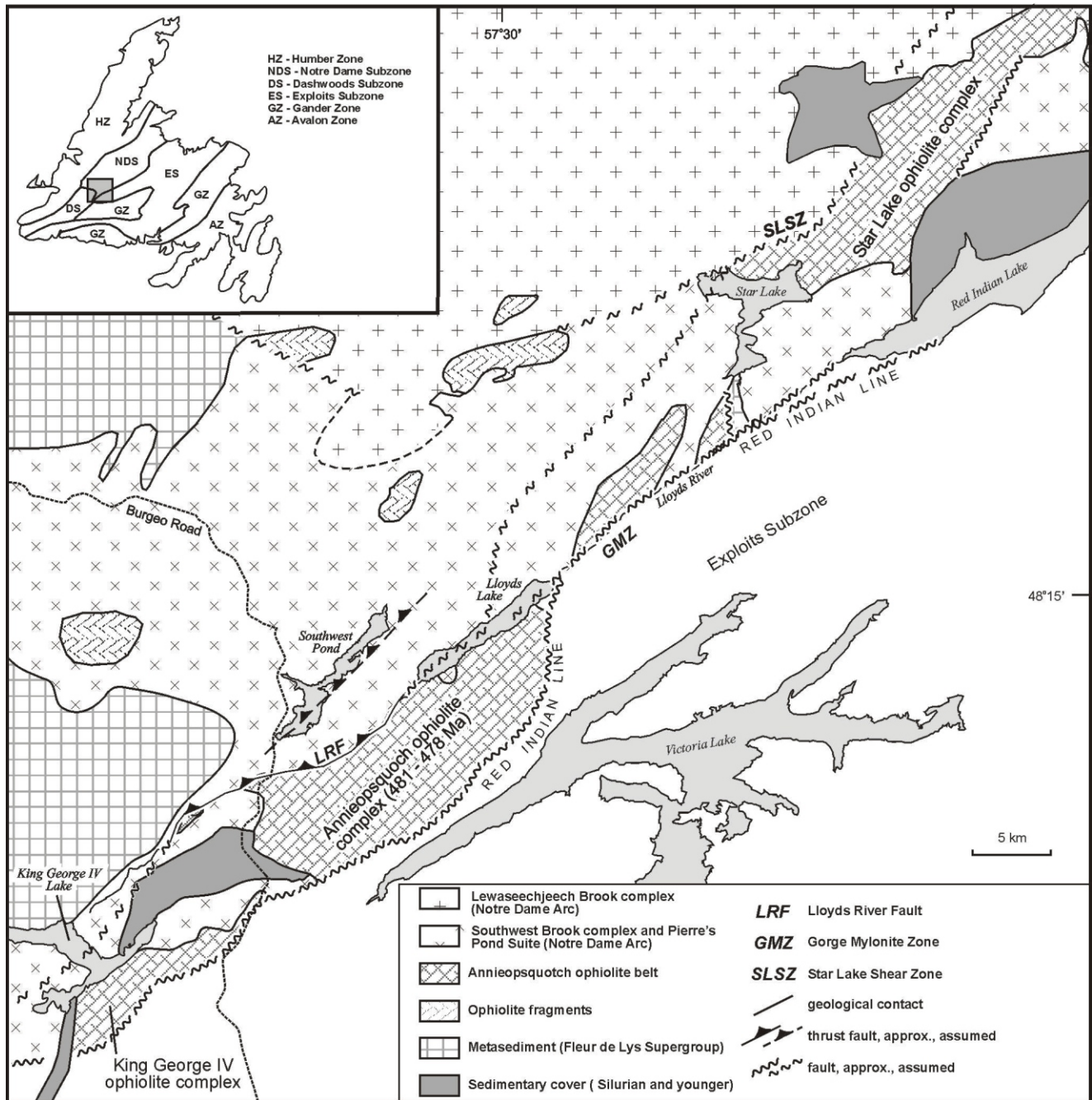


Figure 1. Simplified geological map showing the relationship between the Annieopsquotch ophiolite belt (AOB) and the adjacent rocks of the Dashwoods and Notre Dame subzones. The AOB continues to the northwest, and includes the Skidder basalt and the Mansfield Cove complex. The map is partly compiled from Whalen (1993a, b), Currie and Van Berkel (1992) and Dunning and Churlton (1985).

enclaves of possible Fleur de Lys Supergroup that define the Dashwoods Subzone to the west (van Berkel and Currie, 1988; Williams, 1995). The NDA plutons range between 488 and 456 Ma (Dubé *et al.*, 1996; Dunning *et al.*, 1989). The Ordovician and older rocks of the Dashwoods Subzone

and AOB are intruded by Early Silurian (ca. 440 to 430 Ma) mostly calc-alkaline plutons (e.g., Boogie Lake diorite) and unconformably overlain by Silurian red beds (Dunning *et al.*, 1990).

The Star Lake ophiolite complex is in tectonic contact to the northwest with Ordovician NDA plutons of the Lewaseechjeech Brook complex (Figure 1) and intruded by Silurian plutons of the Topsails igneous suite (Whalen, 1993a, 1997).

In this paper, the preliminary results of the investigations into the Lloyds River fault are presented. This paper discusses its (Lloyds River fault) proposed extension to Star Lake, its relationships with the adjacent rocks of the Dashwoods and Notre Dame subzones, and its implications for the geological history of this part of southwest Newfoundland.

THE LLOYDS RIVER FAULT

The Lloyds River fault (LRF, Figure 1) was previously interpreted to run through the entire Lloyds River valley, i.e., from King George IV Lake in the southwest to Red Indian Lake in the northeast (Dunning, 1981, Figure 2.2; Dunning and Chorlton, 1985, Figure 2). In part, this interpretation is correct, but a narrow mylonite zone, which is exposed in the Lloyds River valley (gorge) between Lloyds Lake and Red Indian Lake, herein termed the Gorge

mylonite zone (GMZ), is a late structure unrelated to the tectonites that define the LRF elsewhere (Figure 1). Mapping has revealed that the LRF exposed between King George IV Lake and Lloyds Lake (Figure 1), which is designated as its type locality, comprises a complex shear zone having a central high-strain zone, mainly characterized by mylonitic mafic and felsic tectonites. The central high-strain zone is bounded by less-strained, moderately foliated amphibolite and orthogneiss dissected by narrow shear zones. Parallel subsidiary shear zones having similar kinematic histories (*see below*) occur outside the fault zone and cut the Annieopsquotch ophiolite complex and plutons of the Southwest Brook complex of the NDA (e.g., on the southeast shore of Southwest Pond, Figure 1).

The central high-strain zone is, at least, 100 m wide, and comprises an intimate mixture of banded amphibolite and metapyroxenite that are probably of ophiolitic origin, and strongly foliated quartz–diorite and tonalite, interpreted to be smeared-out sheets of the Southwest Brook complex that intruded the mafic rocks of the AOB. The presence of moderately deformed, late-kinematic tonalitic to granodioritic veins that cut the sheared rocks indicate that the arc magmas intruded syn-kinematically (Plate 1).

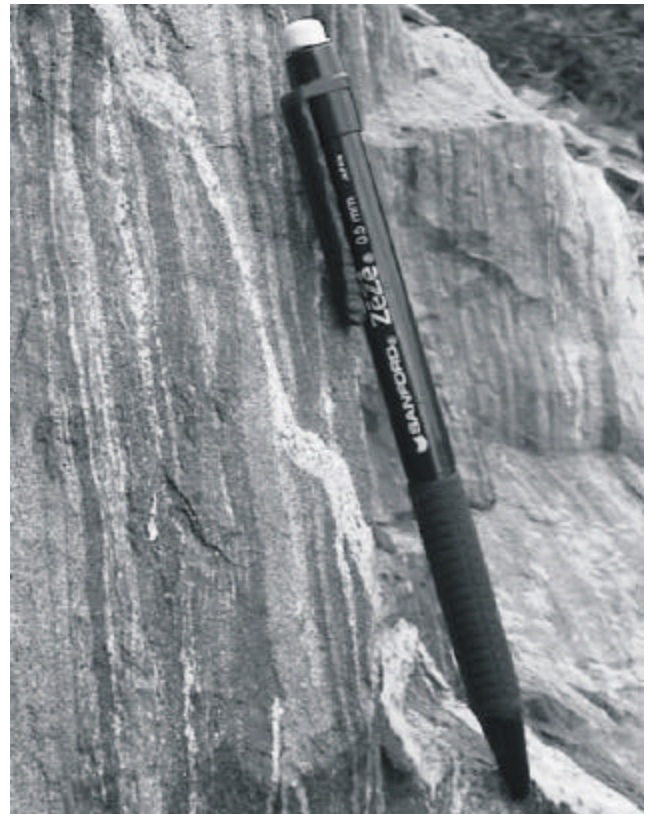
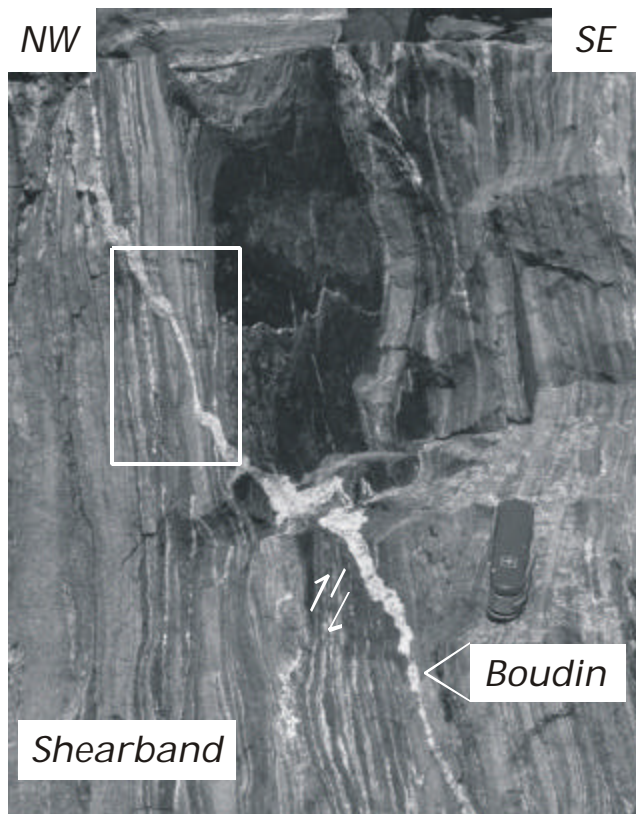


Plate 1. Left) Mylonite of the central high-strain zone of the Lloyds River fault, composed of alternating bands of amphibolite (dark grey) and tonalite (light grey), cut by a late-kinematic folded, boudinaged and stretched granodiorite vein. Shear bands and obliquity of stretched vein indicates NW side up. Right) Enlargement of stretched and folded part of the vein as indicated by the white box in left plate.

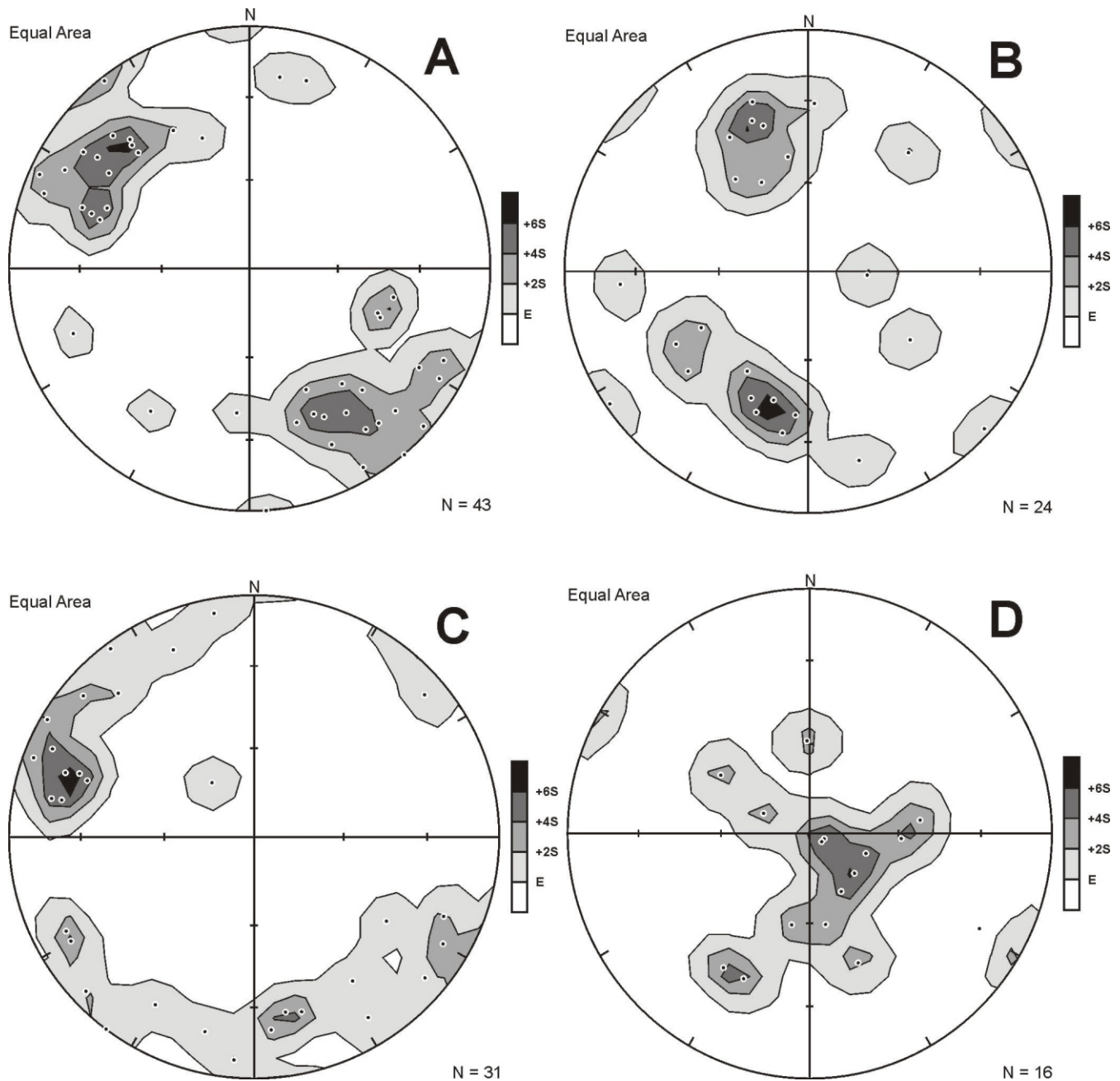


Figure 2. Equal area lower hemisphere projections of the foliations and lineations of the Lloyds River fault and the Star Lake shear zone. A) Poles to S_1 in the tectonites that mark the Lloyds River fault; B) L_1 in the tectonites that mark the Lloyds River fault. C) Poles to S_1 of the tectonites in shear zones in the Star Lake area; D) L_1 in the tectonites in shear zones in the Star Lake area.

The outer zone of the fault is exposed on the steep northern edge of the Annieopsquotch ophiolite complex, in the Lloyds River valley and the southwestern part of Lloyds Lake (Figure 1). It consists of gabbro and diabase cut by diorite and tonalite of the Southwest Brook complex. Weakly deformed and metamorphosed mafic rocks alternate with

strongly sheared amphibolite and orthogneiss, derived from intrusive metadiorite sheets. Preferential localization of the shear zones in the intrusive diorite sheets rather than the relatively undeformed gabbro host, suggests that the shear zones were localized and weakened due to the presence of melts.

The LRF is cut by post-kinematic tonalite and granite of the Southwest Brook complex, as is evidenced by foliated and amphibolitized gabbro and diabase enclaves in undeformed sheets and plutons cutting the Annieopsquotch ophiolite complex (e.g., on the shore of Lloyds Lake, Figure 1). Hence, NDA magmatism continued after ductile deformation in the LRF had ceased.

The widespread occurrence of metamorphic hornblende indicates that the LRF mainly formed at amphibolite-facies conditions. However, greenschist-facies and prehnite–pumpellyite facies mineral assemblages have locally developed that probably represent a retrograde overprint. Brittle faults, 2 to 3 m wide, have been observed in two locations indicating that movement along the fault continued in the brittle domain, or that the fault was reactivated at a later stage.

The main foliation (S_1) of the LRF dips steeply either to the northwest or southeast (Figure 2a). A mineral/stretching lineation (L_1) is generally present, defined by streaked-out quartz–plagioclase aggregates, boudinaged veins and amphibole minerals. On northwest-dipping foliation planes L_1 plunges ca. 40 to 50° north-northwest; on southeast-dipping foliation planes, lineations plunge ca. 30° southwest (Figure 2b).

Shear-sense indicators (boudinaged and shortened veins oblique to layering, shearbands and small-scale dragfolds) indicate that the fault accommodated oblique motion with a sinistral strike-slip component on the northwest-dipping foliation planes. The northwest-dipping planes have a top-to-the-southeast dip-slip reverse component, suggesting underthrusting of the Annieopsquotch ophiolite complex beneath the Dashwoods block. The southeast-dipping foliation planes in Lloyds River are restricted to a ca. 1-km-long section, which is devoid of syn- or post-kinematic NDA-related sheets. A few poorly developed shear-sense indicators in this section also suggest a sinistral strike-slip, which, if correct, suggests that the LRF accommodated, at least locally, two different movement histories. Alternatively, disregarding the poorly developed shear-sense indicators in the southeast-dipping planes, the orientation of the structures (Figures 2a, b) suggest that the LRF tectonites could be folded on a macroscopic scale by tight, upright folds having shallow- to moderately northeast-plunging hinge lines.

Underthrusting of the Annieopsquotch ophiolite complex is consistent on a regional scale with relationships observed in the Buchans area, immediately to the north of the area of investigation, where the ophiolitic Skidder basalt together with rocks of the Buchans Group were overthrust by a hot thrust sheet comprising Ordovician NDA plutons of the Hungry Mountain Complex (Thurlow, 1981; Thurlow *et al.*, 1992; Calon and Green, 1987; Whalen *et al.*, 1987).

STAR LAKE SHEAR ZONE

The boundary between the Star Lake ophiolite complex and the NDA plutonic rocks of the Lewaseechjeech Brook complex (Whalen *et al.*, 1997) has not been observed due to poor exposure, but is inferred to be a fault zone on the basis of numerous narrow mylonitic shear zones exposed on the islands and shore lines of Star Lake immediately to the south of this boundary as mapped by Whalen (1993a, Figure 1); this inferred fault zone is here informally named the Star Lake shear zone (SLSZ); the anastomosing narrow mylonite zones exposed on islands in Star Lake are considered to represent the southernmost extent of the SLSZ.

The steeply dipping shear zones (Figure 2c) exposed on the islands in Star Lake cut undisturbed to weakly foliated, coarse- to very coarse-grained, gabbro and pyroxenite cumulates of the Star Lake ophiolite complex and are composed of amphibolite and mylonitic tonalite, with boudins or low-strain pods of gabbro and pyroxenite (Plate 2). Tonalite veins in the shear zones are isoclinally folded and boudinaged (Plate 3). The hingelines of the folds are parallel to



Plate 2. Typical occurrence of shear zones in the Star Lake area; relatively undeformed igneously layered pyroxenite and gabbro cut by mylonitic amphibolite (grey) with boudins of relatively undeformed gabbro and stretched and isoclinally folded tonalite veins (white).



Plate 3. *Shear zone on an island in Star Lake, showing iso-clinally folded and boudinaged tonalite veins in sheared amphibolite.*

the commonly steeply plunging mineral and stretching lineations (Figure 2d), which suggests a dominantly dip-slip movement vector. Close inspection of weakly strained parts revealed that the protolith of the amphibolite is mainly quartz diorite to diorite. Both the diorite and tonalite probably form part of the Pierre's Pond plutonic suite of the NDA (Whalen *et al.*, 1997), which is the equivalent of the Southwest Brook complex of Dunning *et al.* (1989). Generally, the shear zones are localized in the intrusive sheets of the NDA where they cut the ophiolite complex, not the ophiolitic rocks themselves. The contact between the sheared diorite and tonalite on the one hand and the gabbro and pyroxenite cumulates on the other is generally very sharp, with little or no strain accumulated in the latter (Plate 4). Furthermore, these shear zones have been observed to cut and offset each other (Plate 5), suggesting that the SLSZ also experienced a complicated movement history. Overall, the present observations indicate a close spatial relationship between diorite and tonalite sheets and the shear zones, which is consistent with observations in the LRF that the arc magmas intruded syn-kinematically, and suggest that the deformation was preferentially localized in the weak, not yet completely solidified rocks (melt weakening). Furthermore, NDA magmatism continued after deformation ceased locally, evidenced by the presence of tonalite and granite sheets that crosscut the small shear zones (Plate 5).

The presence of highly deformed sheets of arc magmas in the SLSZ suggest a temporal and genetic link with the LRF immediately west of the Annieopsquotch ophiolite complex.



Plate 4. *High deformation contrast between gabbro of the Star Lake ophiolite complex and shear zone composed of diorite and tonalite, suggesting strain localization in the intrusive rocks.*



Plate 5. *Crosscutting relationship between two shear zones in diorite and tonalite on an island in Star Lake. Weakly deformed tonalite of the NDA crosscuts both the shear zones and gabbro of the Star Lake ophiolite complex.*

REGIONAL EXTENT OF THE LLOYDS RIVER FAULT

Based on of their similar setting and field characteristics, the SLSZ is interpreted as the extension of the LRF. How the two shear zones connect between Lloyds Lake and Star Lake is poorly constrained due to poor exposure and the presence of numerous plutons of the Southwest Brook complex and Pierre's Pond plutonic suite. However, based on preliminary field investigations the LRF curves are inter-

puted to curve slightly anticlockwise at Lloyds Lake (Figure 1). This interpretation places the fault northwest of two isolated ophiolitic fragments that lie between the Annieopsquotch and Star Lake ophiolite complexes (units Om and OESa of Whalen, 1993a; Figure 1). The present interpretation differs from that of Dunning (1981), who connects the LRF with the GMZ, which lies southeast of the ophiolite fragments and the Star Lake ophiolite complex. The GMZ (Figure 1) is not cut by syn-kinematic NDA intrusions and is characterized by greenschist-facies rather than amphibolite-facies tectonites, suggesting it is a late structure. Furthermore, this mylonite zone transects the AOB and abuts the Red Indian line where the latter curves anticlockwise to the north at the northeastern tip of Lloyds Lake, i.e., the GMZ postdates juxtaposition of the AOB and rocks of the Exploits subzone (*see* also Whalen, 1993a) to Laurentia, and hence must be a relatively late structure.

DISCUSSION

Field relationships observed last summer corroborate the conclusions of earlier workers (e.g., Dunning and Chorlton, 1985) and leave no doubt that the AOB was intruded by plutonic rocks characteristic of the NDA. This conclusion is important because it suggests that there must have been an eastward migration of the magmatic axis of the NDA before, during and/or after the Early to Middle Ordovician underthrusting of the AOB beneath the Dashwoods block (van Staal *et al.*, 1998). An eastward migration of the NDA is compatible with the available U–Pb ages of NDA plutonic complexes. Tonalite and granodiorite rocks immediately adjacent to the AOB yielded exclusively Middle Ordovician U–Pb zircon ages (467 to 456 Ma; Dunning *et al.*, 1989; Whalen *et al.*, 1997), which are younger than the oldest phases known in NDA represented by the ca. 488 to 469 Ma granodiorite and tonalite rocks (Dubé *et al.*, 1996) of the Table Mountain complex (Hall and van Staal, 1999).

As already observed by Dunning and Herd (1980), several isolated ophiolitic fragments occur within the NDA plutonic complexes, the largest of which is the Long Range ophiolite complex (Dunning and Chorlton, 1985; Hall and van Staal, 1999). Although some of these ophiolite complexes were structurally emplaced, on or incorporated, into a sedimentary host (e.g., Long Range ophiolite complex–Mischief mélange association, Hall and van Staal, 1999) prior to intrusion of the NDA plutons, others could conceivably represent large exotic enclaves incorporated in the arc plutonic complexes prior to any interaction with continental crust. The ophiolitic fragments range in size from a few centimetres to kilometres, and are mainly composed of harzburgite, pyroxenite, gabbro and amphibolite (Figure 1).

An important question is to what extent these ophiolitic fragments belong to the AOB. Dunning and Chorlton (1985) included all of them in the AOB, but subsequent dating by Dunning (1987) shows that at least some of these, like the Long Range ophiolite complex, are much older (> 488 Ma) than the AOB and predate the oldest known phase of the NDA. Work in progress (U–Pb dating and geochemistry) is testing the extent of AOB-related ophiolitic fragments in the plutonic complexes of the NDA. If these data confirm that the AOB had a larger width than is presently exposed, it must represent basement to part of the Notre Dame arc. The latter is consistent with the positive ϵ_{Nd} value of one tonalite sampled close to the AOB (Whalen *et al.*, 1997). However, most analyzed NDA plutons yielded negative ϵ_{Nd} values, which indicate that most of the NDA plutons were built on continental crust of the Dashwoods block (Whalen *et al.*, 1997). This suggests two possible tectonic settings for the origin of the AOB and generation of the Middle Ordovician phase of NDA magmatism: 1) the AOB belt was accreted prior to or during the Middle Ordovician to the Dashwoods block such that the NDA plutons interacted with a composite continental-oceanic crust when the magmatic axis migrated eastward, probably in response to stepping-back of the westward-dipping subduction zone (van Staal *et al.*, 1998), or 2) the NDA magmatic axis migrated significantly eastward in response to rapid slab-rollback such that the Middle Ordovician phase was constructed in part on oceanic lithosphere of the AOB. The latter model implies that the AOB was generated immediately to the east of the Dashwoods block and occupied a forearc setting during west-directed subduction in the Middle Ordovician. This model could explain the overall lack of regional deformation and metamorphism within the AOB itself away from the LRF and the Red Indian line (Zagorevski and van Staal, *this volume*). More isotopic analyses in conjunction with geochronology, geochemistry and metamorphic studies are needed to discriminate between these two models.

CONCLUSION

The LRF consists of a central high-strain zone surrounded by relatively less-strained zones of tectonites cut by subparallel narrow shear zones. The fault does not extend to Red Indian lake as was previously thought, but probably curves slightly anticlockwise and continues into the proposed SLSZ. The LRF zone mainly accommodated oblique sinistral underthrusting of the Annieopsquotch ophiolite complex beneath the Dashwoods block and developed syn-kinematically with intrusion of Early to Middle Ordovician plutonic rocks of the NDA. Strain associated with formation of the LRF was preferentially localized in NDA plutonic rocks during their intrusion in the AOB, which suggests that

the shear zones were significantly localized and weakened by the presence of partly molten rocks.

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