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KINEMATIC EVIDENCE FOR TERRANE DISPLACEMENTS IN THE GRENVILLE PROVINCE IN EASTERN LABRADOR

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ABSTRACT

Field investigations in 2003 and 2004, coupled with information extracted from field notes and photographs taken during earlier 1:100 000 regional geological mapping, and a previous published study provide sufficient data for an initial synthesis of shear-sense kinematic structural data for a part of the Grenville Province in eastern Labrador. Four types of movements are recognized. Outward-vergent thrusting / reverse faulting took place on the north, south and southwest flanks of the Hawke River terrane and is attributed to doubly vergent Labradorian orogenesis. Steep oblique-slip movements involving a component of dextral strike–slip occurred in the easternmost Mealy Mountains terrane (between the Long Harbour and Fox Harbour faults), but are of uncertain age. Dextral-sense transcurrent kinematic indicators are ubiquitous across the width of the southeast Lake Melville terrane (Gilbert River belt) and include both Labradorian and Grenvillian features. Extensional ductile to brittle faulting and concomitant emplacement of minor granitic intrusions occurred along the western flank of the Hawke River terrane, and are attributed to Grenvillian tectonism.

INTRODUCTION

During field investigations in the Grenville Province in eastern Labrador during 2003 and 2004, superb new exposures created during construction of the Red Bay to Cartwright highway (Route 510) and branch roads to St. Lewis (Route 513) and Charlottetown–Pensons Arm (Route 514) were examined. The objectives of the field work were to improve the geological cartographic database, to search for signs of mineralization and to obtain more information regarding the kinematic history of the region. It is the latter aspect that forms the focus of this article. The region addressed is shown in Figure 1.

Kinematic structural data for much of the region was (and to a large extent still is) extremely scarce. Previous geological mapping (at 1:00 000) was carried out during the mid-1980s, when collecting kinematic data was much less routine than is currently the case. Thanks to research popularized during the early 1980s, the value of kinematic information has become much more widely recognized. The subject matter has been concisely and lucidily summarized by Hanmer and Passchier (1991). In eastern Labrador, the excellent coastal exposures allow kinematic information to be easily obtained, but such is not the case in inland areas where the outcrops are extensively covered by moss and lichen and, commonly, can only be inadequately observed in the third dimension. The road-cuts and road-stone quarries have done much to alleviate this difficulty.

The above comments should not leave the impression that no kinematic information was previously available. Albeit scanty, some data were recorded during mapping and are indicated on 1:100 000 geological maps for the region (e.g., Gower *et al.*, 1988b, c). This information was sufficient to allow some rudimentary postulates to be made regarding major thrusting and strike–slip displacements (e.g., Gower *et al.*, 1987). Information was considerably augmented during a field investigation by Hanmer and Scott (1990). A complementary geochronological study based on samples collected during their field study provided information on the times of ductile deformation (Scott *et al*., 1993). The latter two studies focussed on a critical, well-exposed part of the region, namely the coastal area between Occasional Harbour and St. Lewis (Figures 1 and 2), and led to greatly improved understanding of the kinematic history in that district. The interpretation of offshore seismic results obtained during the Lithoprobe ECSOOT project (Gower *et al*., 1997) was considerably assisted by these data.

Kinematic structural data for the region is subdivided into four groups that indicate: i) thrust / reverse fault dip-slip movements; ii) steep oblique-slip, reverse-sense movements; iii) strike-slip / shallowly oblique-slip movements; and iv) extensional (detachment) displacements. Note that, because most of the data were collected during reconnaissance mapping, or from roadside outcrops, specific shear zones have not been mapped out on the ground, but, rather, inferred from regional geological, topographic and geophys-

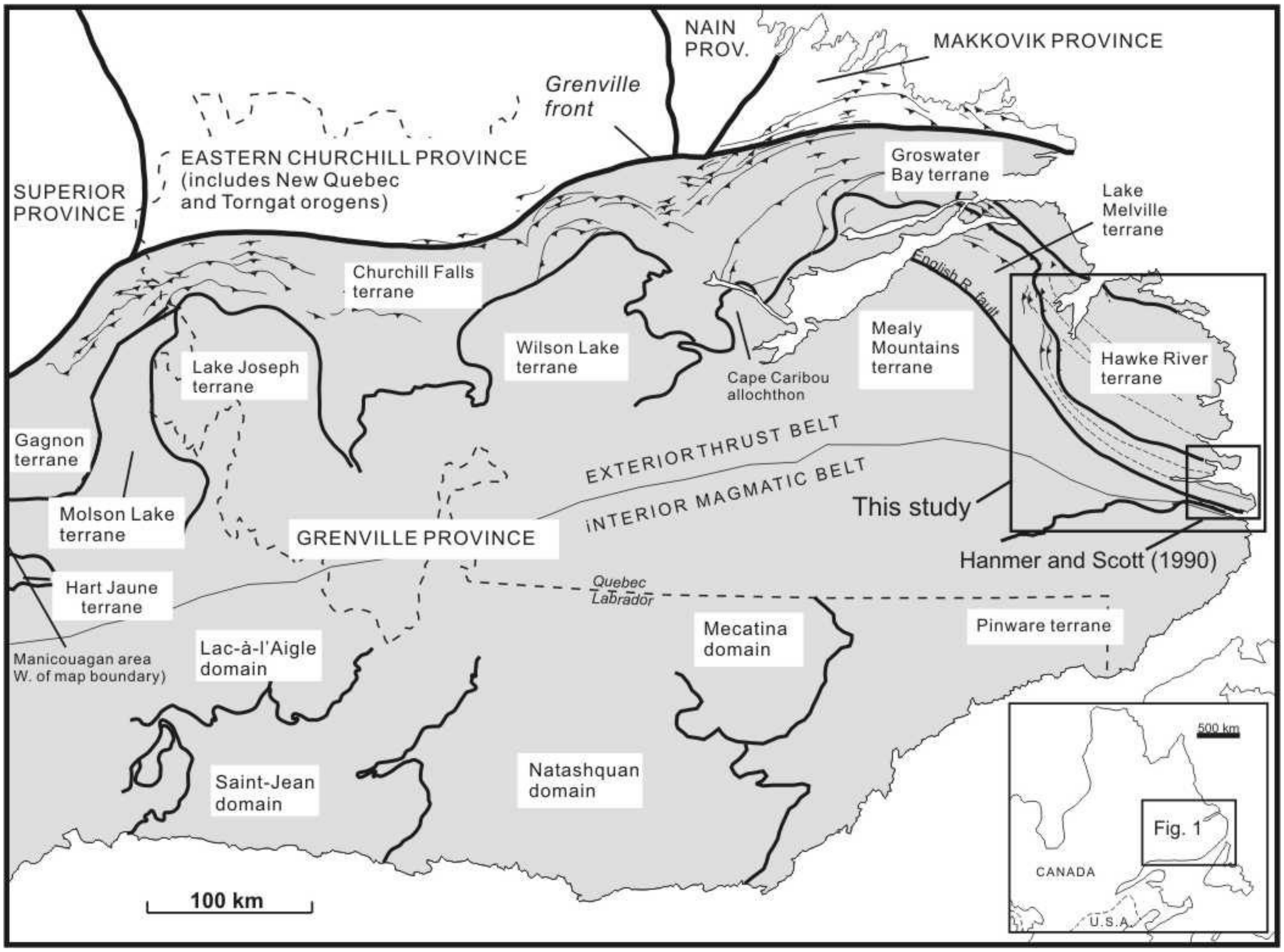


Figure 1. *Structural subdivision of the eastern Grenville Province. Location of the area addressed in this study and that of a structural study carried out by Hanmer and Scott (1990) are also shown.*

ical data. Information pertaining to these four types of faulting is reviewed below, following which interpretation of the kinematic history of the region is revisited.

THRUST / REVERSE-SENSE KINEMATIC INDICATORS

Grouped together here are ductile, dip-slip, hanging-wall-up displacements, of both low- to moderate-angle and steeply dipping character (including some structures interpreted to have been overturned). These features are recognized in three geographically separate areas; at, or near, the northern, southern and western boundaries of the Hawke River terrane, respectively (*see* Figure 2 and geographic locations detailed in the following subsections).

NORTHERN HAWKE RIVER TERRANE

In the northern Hawke River terrane, at its boundary with the Groswater Bay terrane, a segment of a thrust was mapped by Gower *et al.* (1986a, b, c) south and southwest of Black Tickle (Figure 2). The rocks were described as well-banded gneiss, mylonite and ultramylonite by Gower *et al*. (1986b) and occur within a zone approximately 0.5 km surface width (Plate 1a; all plate locations are indicated on Figures 2, 5 or 6, as appropriate). Stretching lineations (simply indicated as lineations by Gower *et al.*, 1986a) plunge south between 25 to 60° (but mostly about 40°). Rotated winged K-feldspar (Plate 1b) and stair-step porphyroclasts indicate northward transport of the hanging wall. Mylonite was recorded (Gower *et al*., 1982, 1983) at various coastal locations farther west in a west-northwest-trending zone between Black Tickle and Cartwright, but details of its extent, thickness and kinematic sense were not collected at the time. This zone (highlighted in grey tone) was taken as defining the boundary between the Groswater Bay and Hawke River terrane. The boundary, as indicated by mylonite localities on currently available maps, is not well defined and several separate shear zones (possibly linked in an anastomosing system) may be present.

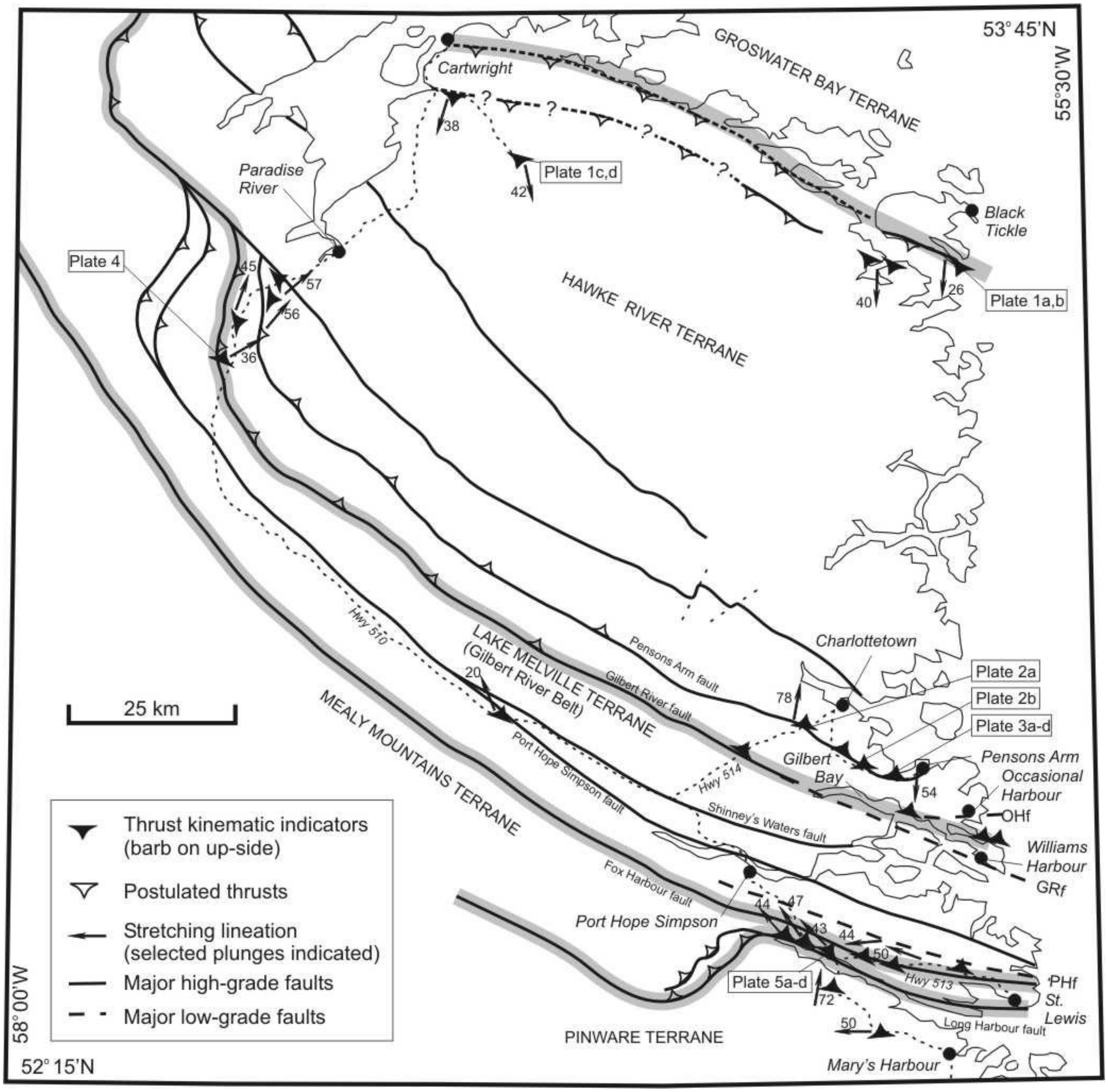


Figure 2. *Locations where reliable thrust-sense and steep oblique-slip shear indicators were observed. The barb is on the up-side; this is also the direction of dip except at the eastern end of the Pensons Arm fault, which dips to the south. OHf - Occasional Harbour fault, GRf - Gilbert River fault and PHf - Petty Harbour fault.*

During field investigations in 2004, mylonite, tens of metres thick, was found at outcrops adjacent to a road that branches off Highway 510 about 10 km south of Cartwright (heading southeast). This road did not exist during 1:100 000 geological mapping in the area in 1985. The mylonites have a 100° strike and show stretching lineations plunging south at 40°. Kinematic information collected from shear bands (asymmetrical extensional shears), strain-insensitive sigmoidal foliations, rotated winged K-feldspar porphyroclasts and tight asymmetric folds all indicate north-directed transportation of the hanging wall. Structures interpreted as sheath folds are also present. These features are spectacularly exposed at a locality 22 km southeast of Cartwright, and some are illustrated in Plates 1c, d. The overall distribution of the mylonite in the area has not been determined. It is possible that all the mafic bodies that underlie the higher

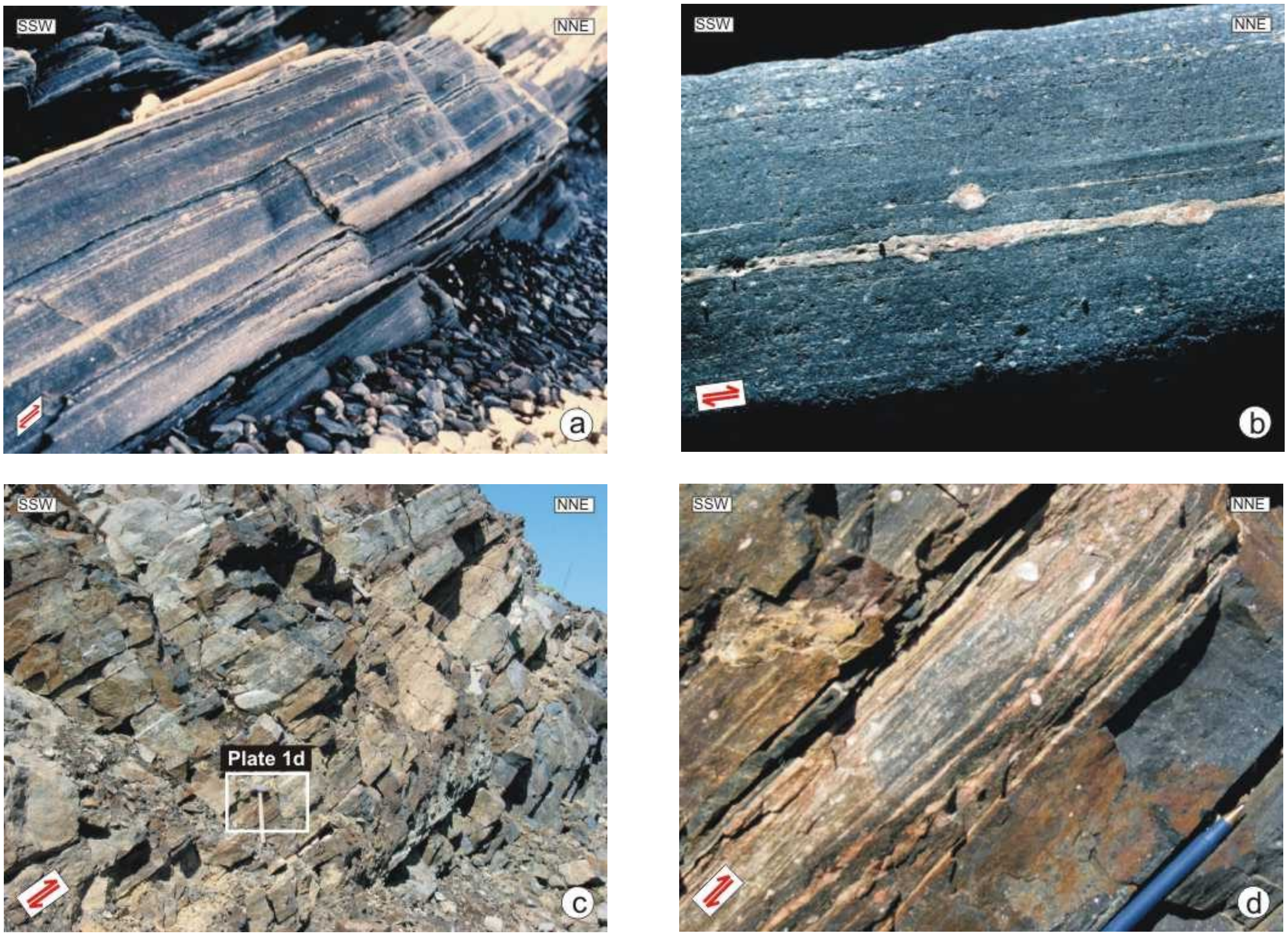


Plate 1. *Thrust-related features at the northern margin of the Hawke River terrane: a) mylonite south of Black Tickle (CG85-608); b) rotated, winged K-feldspar-rich aggregate porphyroclast south of Black Tickle (CG85-608); c) asymmetric structure indicating thrusting to the north (CG04-273); and d) detail of Plate 1c (boxed area) showing rotated winged porphyroclast and z-fold (CG04-273).*

ground in this area are floored by near-horizontal ductile shear zones and hence allochthonous. The attitude of the mylonitic zones and stretching directions are essentially identical with those seen south of Black Tickle, but whether thrusts in the two regions should be linked remains undetermined. A possible thrust is depicted conceptually in Figure 2 (indicated with question marks), and is drawn to follow chains of small lakes and other low-lying drainage features with which such a structure would likely spatially coincide. The eastern end of such a structure is known to exist from mapping carried out in 1981.

SOUTHERN HAWKE RIVER TERRANE

The southern Hawke River terrane, close to the Lake Melville terrane was interpreted by Gower *et al*. (1987) as having been isoclinally folded and then tectonically sliced during southwestward- or westward-directed thrusting. This interpretation relied on poor-quality kinematic observations as well as interpretative compatibility with shear-sense indicators on thrusts at the western margin of the Hawke River terrane (*see* next section).

More reliable kinematic information was collected during 2004 from road-cuts adjacent to the branch road to Charlottetown and Pensons Arm (Highway 514). A previously recognized shear zone in the area (Gower *et al*., 1987, 1988a) is here named the Pensons Arm fault from the superb exposures of mylonite along much of the Pensons Arm road. Although depicted as a single shear zone, there are some features that suggest it is a multiple, anastomosing structure. For example, the main shear zone may continue southeast through Occasional Harbour, rather than curving northeast through Pensons Arm. Detailed mapping is needed to improve delineation of the structure(s).

Several zones of mylonite and ultramylonite, up to several tens of metres thick, are well exposed where the Pensons Arm fault crosses the road southwest of Charlottetown. The mylonitized, lithologically heterogeneous rocks wrap around megaboudins of more homogeneous material. Rocks types include gabbronorite, K-feldspar megacrystic granitoid rocks, amphibolite, mafic granulite, granodiorite to tonalite gneiss and pink granite. The pink granite is highly tectonized (Plate 2a) and particularly striking visually, and is also present in outcrops adjacent to the Pensons Arm road farther east. Where the Charlottetown road crosses the mylonite zones, foliations dip north at 65 to 80°, but, farther east, dips are south between 50 and 90°. Lineations are not obvious in many of the mylonites, but plunge down dip, where seen. Regardless of whether the foliation dips north or south, shear-sense indicators demonstrate north-side-up sense of displacement. An example of sigmoidal structure is illustrated in Plate 2b. An interesting feature (possibly of controversial significance) can be seen in a road-cut (south side) 10 km east of Pensons Arm (Figure 3 and Plate 3). It is interpreted here as a rotated boudinage structure. The boudin (Plate 3a, the lower part of which is enlarged in Plate 3b) consists of a mafic dyke that discordantly intruded an already-foliated granite (Plate 3c) and both granite and mafic dyke were subsequently preserved within enveloping high-strain zones. The sense of rotation (north-side-up) is evident from tails of mafic material trailing off from the mafic dyke into mylonite (Plate 3d). An alternative explanation, that the tail results from magmatic injection, is rejected. The locality is a worthy candidate for geochronological study.

In the region between the Pensons Arm fault and the Gilbert River fault (the latter, a late-Grenvillian feature taken to mark the southern boundary of the Hawke River terrane – *see* subsection on low-grade mylonite), foliations are near vertical and lineations generally down-dip, in contrast to south of the Gilbert River fault where lineations generally have moderate west-northwesterly plunges. Of the numerous shear-sense criteria observed by Hanmer and Scott (1990), only three record dip-parallel transportation; all three indicate north-side-up movement and all are situated north of the eastward extrapolation of the Gilbert River fault. These locations are indicated on Figure 2; two are between Williams Harbour and Occasional Harbour, and one is west of Occasional Harbour. Stair-step K-feldspar porphyroclasts indicating north-side-up movement were also observed in 2004 at a road-side locality, 500 m north of the Gilbert River. Hanmer and Scott (1990) relate their dip-slip kinematic indicators to an F_2 folding event, which can perhaps be equated with the isoclinal folding and south-vergent reverse-sense fault movements in the southernmost Hawke River terrane proposed by Gower *et al.* (1987). Evidence seems convincing that the southern Hawke River ter-

Plate 2. *Kinematic indicators associated with the Pensons Arm fault; a) ultramylonitized pink granitoid intrusion and possible sigmoidal structure adjacent to it (CG04-012), and b) oblique internal asymmetric foliation in minor granitoid intrusion; photograph reversed to give west-viewing consistence (CG04-090).*

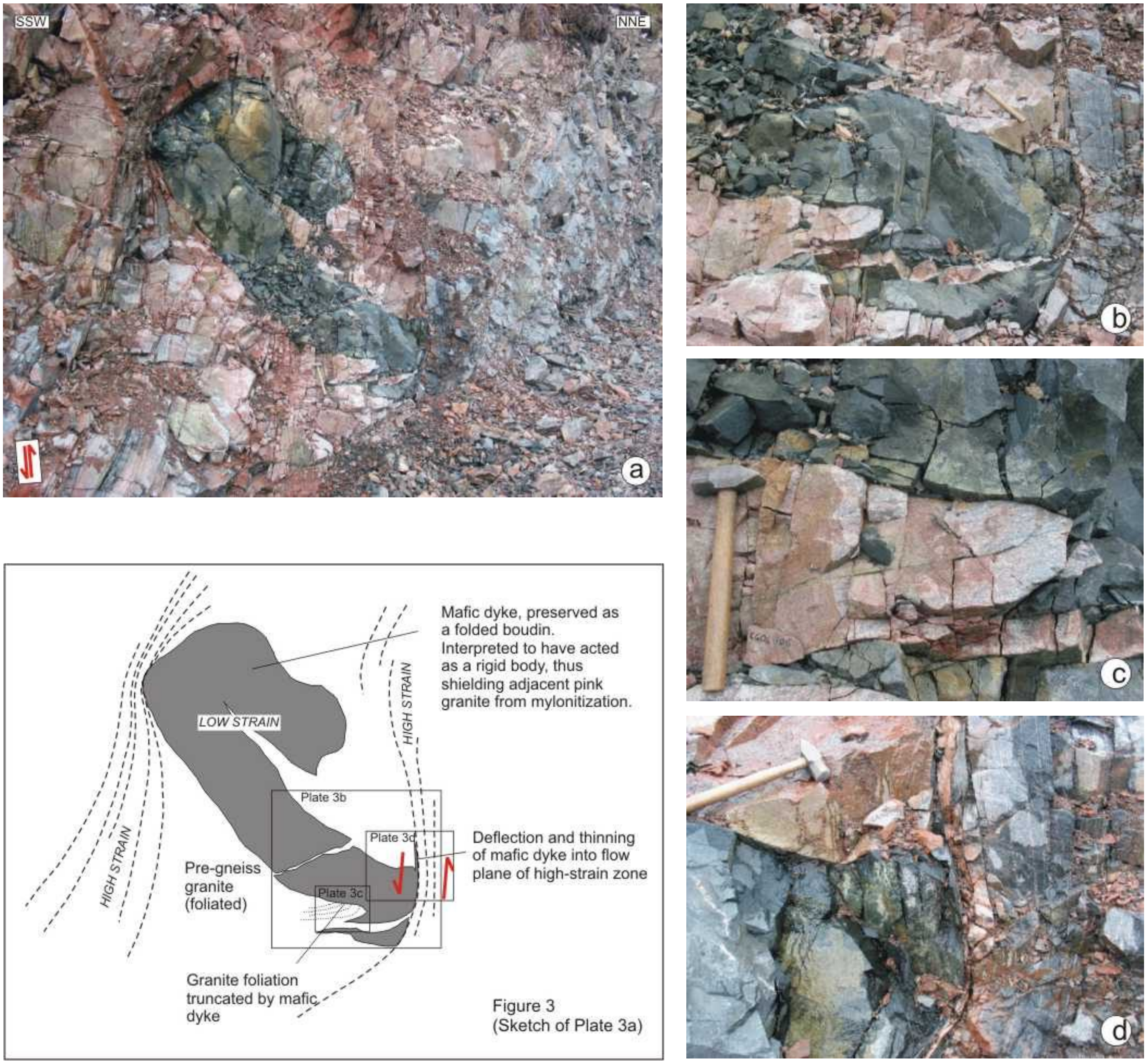


Figure 3. *Sketch of Plate 3a showing locations of Plates 3b-d, and highlighting points of structural interest.* **Plate 3.** *A possibly controversial kinematic indicator from composite mafic dyke–host granite boudin within high-strain envelop (CG04-106): a) segment of a folded mafic dyke intruding pink granite and trapped between steeply dipping mylonite zones; b) lower part of dyke enlarged; c) detail of contact between mafic dyke and host granite showing foliation in granite truncated by mafic dyke; and d) detail of contact between mafic dyke and high-strain envelop showing attenuated tail of mafic dyke deflected into parallelism with high-strain fabric.*

rane has been thrust upward against the Lake Melville terrane in a south to south-southwest direction.

WESTERN HAWKE RIVER TERRANE

West-vergent thrusts at the western end of the Hawke River terrane, southwest of Paradise River, were first identified by Gower *et al.* (1985). Multiple zones of mylonite are present, but their thickness and continuity remain undetermined. Only the major structures are illustrated in Figure 2. Gower *et al*. (1985) commented that there are probably many more than they indicated. The mylonite zones dip mostly between 40 and 60°E and carry northeast-plunging stretching lineations (Gower *et al*., 1986d). Rotated winged

K-feldspar porphyroclasts demonstrate southwestward oblique-slip transportation of the hanging wall, one example of which is illustrated in Plate 4. Dip in gneiss not immediately adjacent to the zones of mylonite is more variable and was interpreted, in conjunction with minor- and map-scale folds, to indicate west- or southwest-vergent, overturned isoclinal folding.

STEEP OBLIQUE-SLIP KINEMATIC INDICATORS

Steep oblique-slip movements are characteristic of the attenuated eastern part of the Mealy Mountains terrane (Figures 2 and 4). The oblique-slip movement also implies apparent-dextral horizontal displacement. Note that many of the kinematic indicators grouped as strike-slip in the next section (especially those in the easternmost part of the Gilbert River Belt), are also oblique-slip, embodying a north-side-up movement component. They are generally much more shallowly plunging structures, but the distinction between the two groups is not as great as might be assumed from their separate classification.

The rocks in the easternmost Mealy Mountains terrane were described by Gower *et al.* (1988b) as fine-grained, finely laminated, dark-weathering mylonite grading into lower strain rocks recognizably derived from monzonite, K-feldspar megacrystic granodiorite, granite, quartz diorite and amphibolite. Shear sense was determined at several localities along Highways 510 and 513. The most common features observed were local sigmoidal structures (Plates 5a-d), but rotated winged K-feldspar porphyroclasts and stair-step fabrics were also recorded; all consistently indicate northwest-side-up.

The boundary between the Mealy Mountains and Lake Melville terrane (herein named the Fox Harbour fault) is sharp and, without having addressed its precise location during field work in 2003, it was, on the basis of field notes and structural data, later narrowed down to a 500-m strike-normal interval on both highways 510 and 513. Structural measurements across the boundary, along Highway 510, are tabulated in Table 1. The data stations progress northwest along the road.

The contrast in orientation of lineations north and south of station CG03-204 is persuasive that a significant structural feature is present. The total distance along the road between stations CG03-203 and CG03-205 is 0.8 km. The Fox Harbour fault is interpreted to lie between the two. On Highway 513, lineation data only constrains the Fox Harbour fault to within a 3.5 km length of road, but, as the road crosses strike in a narrowly oblique way, this distance reduces to roughly 0.5 km across strike. A thin unit of laminated psammitic gneiss and possible calc-silicate gneiss was noted at the two localities where the Fox Harbour fault intersects Highways 510 and 513.

Plate 4. *Rotated winged K-feldspar porphyroclast on Beaver Brook, southwest of Paradise River (VN84-439).*

Attention is drawn to two features possibly relevant to understanding of the Fox Harbour fault. The first is a change in orientation of lineations across a roughly 4-km-wide zone south of the fault (Figure 4). On the south side of this zone (close to St. Lewis Inlet) lineations plunge north-northeast between 50 and 60°. Progressing north and approaching the fault, the plunge and azimuth change to northwest between 40 and 50°, asymptotically approaching the Fox Harbour fault in an anticlockwise manner. The second feature is a contrast in garnet abundance in rocks of comparable composition. For any given composition, south of the fault, garnet is only sparsely sporadically present; north of the boundary it is ubiquitous and abundant. Both of these features require consideration in any kinematic synthesis of the region (*see* Discussion section).

Farther west, southwest of where the northeasterly draining St. Lewis River enters St. Lewis Inlet, a series of southeast-vergent thrusts (Figure 4) were mapped by Gower *et al*. (1988a, c). Although neither the exact position nor the number of thrusts depicted should be given complete credence, the general concept conveyed is considered to be valid. The basal thrust is taken to mark the surface along which the Mealy Mountains terrane overthrust the Pinware terrane in a southeasterly manner. The change in lineation azimuth from north or north-northeast at the base of the 'thrust stack' to west-northwest above the uppermost thrust is similar to that seen farther east, so it is not unreasonable to invoke a common cause. That this might be so is also indicated by the implied commonality of southeast-directed thrusting along St. Lewis River having a similar direction of

Plate 5a-d. *Asymmetric structures interpreted to indicate oblique-slip (north-side-up and dextral) shear sense. In various mafic and granitoid host rocks between Fox Harbour and Long Harbour faults (CG03-185, CG03-186, CG03-189, CG03-190). Note: photographs are east-viewing.*

Table 1. Structural measurements across the boundary between the Mealy Mountains and Lake Melville terranes (Fox Harbour fault)

Data station	Strike/ Dip of planar fabric	Azimuth/ Plunge of lineation
CG03-201	290/52	342/47
CG03-202	280/60	320/50
CG03-203	276/51	345/42
CG03-204	285/72	No lineation measured.
CG03-205	290/74	105/12
CG03-206	292/65	107/23
CG03-207	290/66	107/08

transport in the mylonites between the Long Harbour and Fox Harbour faults. If this is so, then the Mealy Mountains terrane would have been transported southeast (i.e., sinistrally) relative to the Lake Melville terrane and also have been upthrust against part of the northern Pinware terrane.

STRIKE–SLIP KINEMATIC INDICATORS

Dextral transcurrent movements, along shallow to moderately west–northwest-plunging extension lineations that imply a north-side-up, dip-slip component, characterize much of the Lake Melville terrane (Figure 5). These features are mostly found southward from the Gilbert River fault, which marks the boundary between the Lake Melville and Hawke River terranes, to the Fox Harbour fault, which defines the boundary between the Lake Melville and Mealy Mountains terranes. The zone was first identified by Gower *et al*. (1987) and termed the Gilbert River shear belt. Gower *et al.* (1987) reported that kinematic indicators, particularly rotated K-feldspar porphyroclasts, consistently show dextral shear-sense within the belt. Hanmer and Scott (1990) concluded that the mylonitic zones were confined to discontinuous corridors (100 to 1000 m wide), within which discrete, narrow (10 m wide), individual mylonite zones were arranged either *en-echelon* or *en-relais*. The proportion of

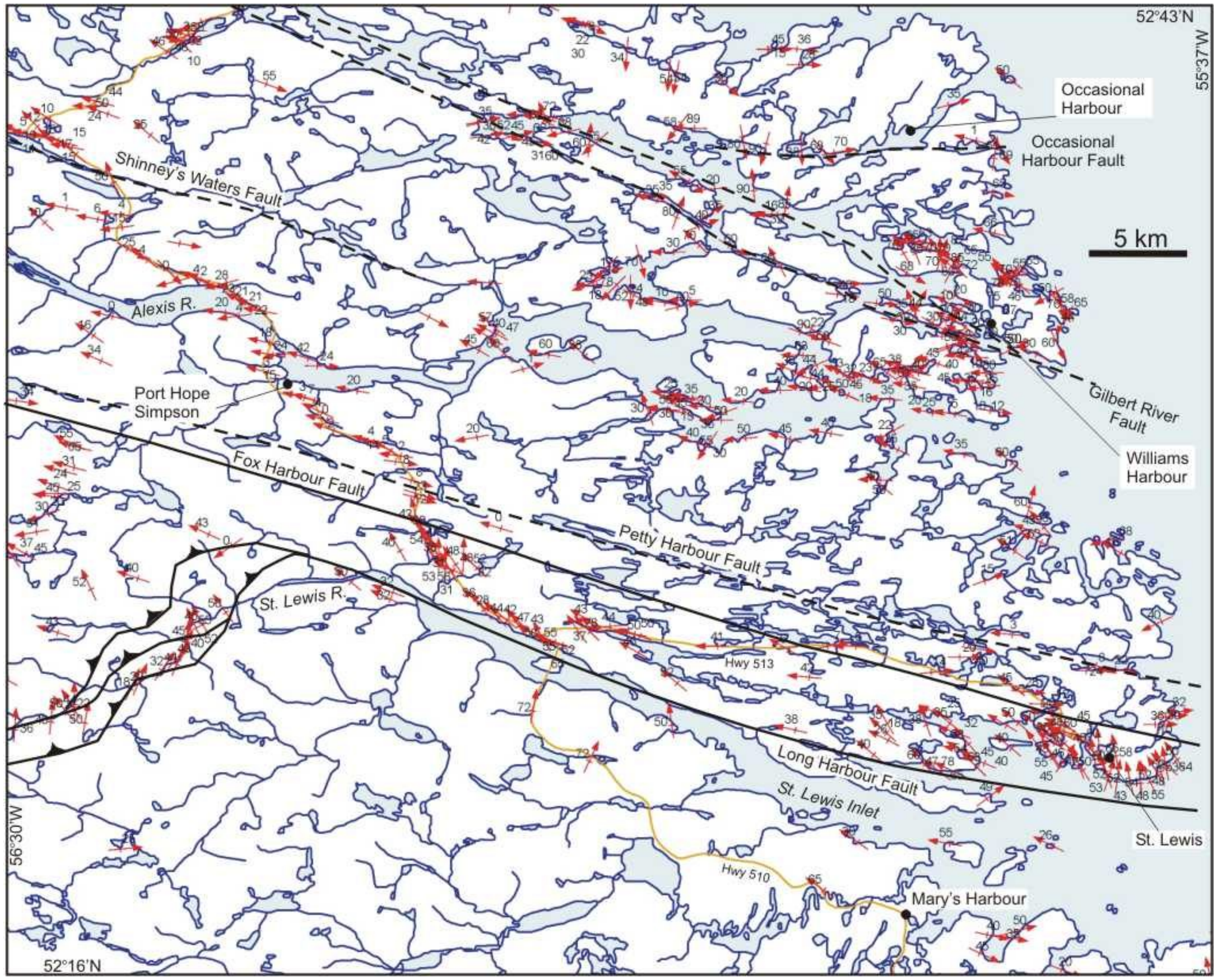


Figure 4. *Lineation directions and major faults in the St. Lewis Inlet–Alexis River district.*

intensely strained rocks within the belt was deemed by Hanmer and Scott (1990) to be minor. They revised the name to Gilbert River belt, at the same time interpreting it as a fold belt and corridor for emplacement of syntectonic granitoid intrusions.

Given the possibility of horizontal offset during Iapetan faulting (which mostly trends north-northeast), the mylonite zones may have greater along-strike continuity than inferred by Hanmer and Scott (1990). Whether or not the belt should be termed a shear zone is a decision left here to the collective wisdom of structural specialists. In the interim, the name revision of Hanmer and Scott (1990) is accepted. Regardless of the nomenclature issue, the Gilbert River belt is a major crustal feature, evident for 300 km across eastern Labrador from, i) very obvious, linear aeromagnetic patterns, ii) spatial coincidence of the northern margin of the belt with the base of a steep southwest-facing slope in the regional Bouguer anomaly field, iii) an extraordinarily marked elongation in mapped lithological units in the belt, and iv) by marking the northeast flank of significant Grenvillian tectonothermal effects (Gower, 2003).

Hanmer and Scott (1990) divided the mylonites into two groups; high-grade mylonites, which formed at amphibolite facies, and low-grade mylonites, which formed at greenschist facies. This subdivision is endorsed and expanded here.

HIGH-GRADE MYLONITE

During field investigations in 2003 and 2004, additional shear-sense evidence from high-grade mylonites was recorded and confirms dextral strike–slip transposition. Field notes and photographs taken in the course of 1:100 000 mapping of the region between 1984 and 1987 were

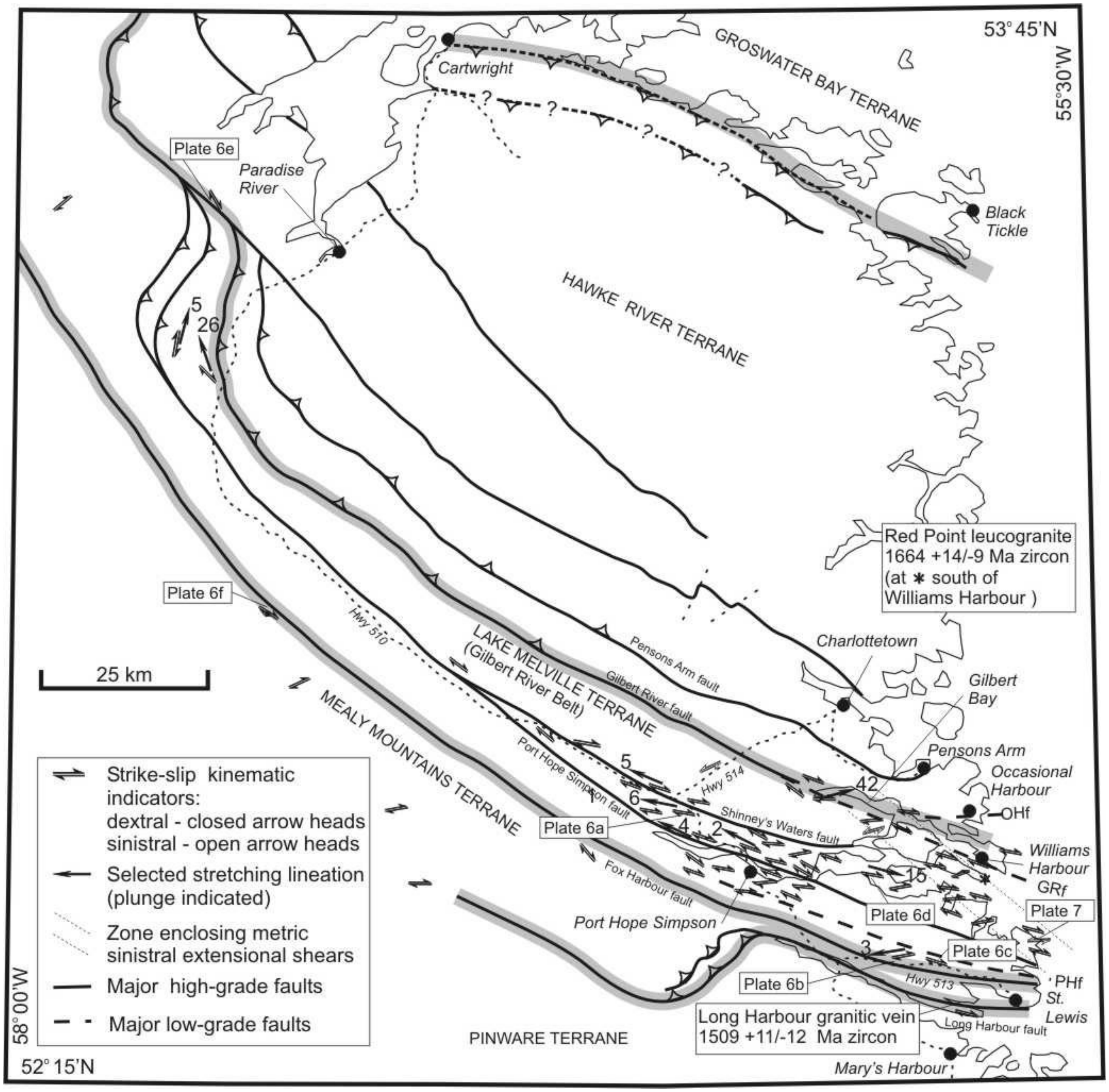


Figure 5. *Locations where reliable strike–slip shear sense indicators were observed. OHf - Occasional Harbour fault, GRf - Gilbert River fault and PHf - Petty Harbour fault. Additional information is provided by Hanmer and Scott (1990) for the southeast end of the Gilbert River belt.*

also re-examined. Much of the evidence reported is provided by rotated winged K-feldspar porphyroclasts, but is augmented by stair-step K-feldspar porphyroclasts, rotated garnet porphyroclasts, shear bands, fabric deflection adjacent to discrete shears, back-rotated layer segments, Z-folded gneissosity and locally sigmoidal strain-insensitive foliations. A selection of these criteria is depicted in Plates 6a-f. Additional data were reported by Hanmer and Scott (1990), who obtained evidence from C and S fabrics, shear bands, metric extensional shears and rotated winged porphyroblasts.

Some sinistral shear-sense indicators are also present, almost all of which were recorded by Hanmer and Scott (1990). Most of the features are metric extensional shears, but include some shear bands. Of interest is that almost all

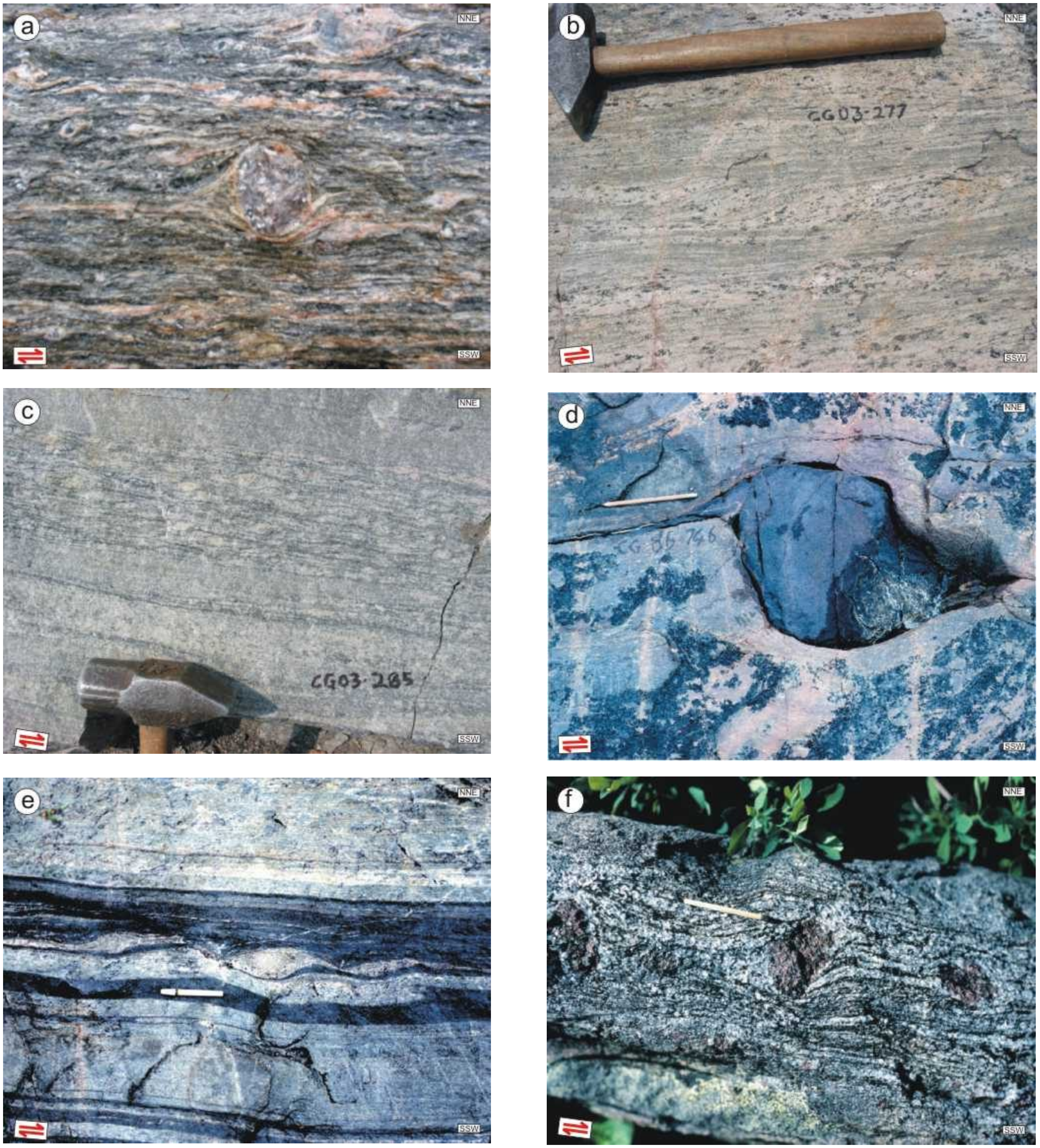


Plate 6. *Rotational and asymmetric structures indicating dextral strike–slip shear sense: a) rotated, winged K-feldspar porphyroclast comprising stiff, unrecrystallized grey K-feldspar cores enveloped in pink, polycrystalline aggregate (CG04-141); b) asymmetric structure developed in leucosome in quartzofeldspathic gneiss (CG03-277); c) asymmetric extensional shear bands in granodiorite (CG03-285); d) dextrally rotated swell in amphibolite dyke or part of dextral* en-relais *fracture array filled with mafic dyke within mylonitic granodioritic host (CG86-746); e) back-rotated granitoid veins in amphibolite (CG84-442); and f) rotated garnet in quartz diorite gneiss (VN91-264).*

of these structures (including a few recorded during 1:100 000 scale geological mapping, e.g., Plate 7) fall within a 5-km-wide, northwest-trending domain extending from the head of Gilbert Bay to north of St. Lewis, perhaps representing a conjugate shear package. At a few localities, earlier dextrally transcurrent mylonite (as exemplified by rotated K-feldspar porphyroblasts) is cut by sinistral metric extensional shears, oriented anticlockwise to the mylonitic foliation (Hanmer and Scott, 1990).

LOW-GRADE MYLONITE

Hanmer and Scott (1990) identified two low-grade mylonite zones. One is aligned parallel to regional strike through Rexon's Cove (a part of the Gilbert Bay fault) and the other has an easterly trend through Occasional Harbour (Occasional Harbour fault). Both faults were identified during 1:100 000 scale mapping, although they are not specifically indicated on existing maps as low-grade mylonite zones. Apart from mylonite and greenschist-facies mineral assemblages, the faults are also characterized by pseudotachylite veins, brittle fractures and narrow zones of cataclasis.

The existence of the Gilbert River fault structure is long established; it is shown on the map of Eade (1962), for example. A parallel fault, 2 km farther north, through Gilbert Bay, was inferred by Gower *et al.* (1987) to explain an apparent 2.5-km dextral offset of the Grenvillian Gilbert Bay pluton on either side of Gilbert Bay. This branch coincides with low-grade mylonite mapped by Hanmer and Scott (1990) west of Williams Harbour, and it probably links up with the Gilbert River fault about 2 km southeast offshore of Williams Harbour. Gower *et al*. (1987) pointed out that the Gilbert River fault, its branch(es) and the Occasional Harbour fault correlate spatially with, and probably acted as a control on, the emplacement of the Gilbert Bay alkalic mafic dykes. The Gilbert Bay alkalic mafic dykes are unmetamorphosed, high-level intrusions (some are amygdaloidal) and represent the final igneous activity at the northern boundary of the Gilbert River belt. The dykes were emplaced at 974 ± 6 Ma (Wasteneys *et al*., 1997), and so demonstrate that the fault was still active until this time. The composite Gilbert River fault also controlled the location of the Gilbert River pebbly arkose (situated on the fault 1 km northwest of Highway 514; cf. Gower *et al.*, 1988a), which is either similar in age to the Gilbert Bay dykes or younger (it is generally assumed to be latest Neoproterozoic).

As noted by Hanmer and Scott (1990), coarse white mica occurs immediately adjacent to the mylonite associated with the Gilbert River fault, suggesting that the fault may have initiated at higher temperatures and narrowed with cooling. White mica, retrograded from sillimanite, is common in pelitic gneisses in a 2-km-wide zone north of the Gilbert River fault, and there seems little doubt that the northern border of the Gilbert River belt persisted as a high- to low-temperature, long-term zone of weakness.

Plate 7. *Sinistral metric extensional shear (CG87-333).*

Two other low-grade, strike–slip mylonite zones are now recognized (Figure 4). These are the Shinney’s Waters fault (Plate 8a) and Petty Harbour fault (Plate 8b). They are characterized by non-penetrative, shallow-plunging lineations on discrete shear surfaces, although the Shinney’s Waters fault is also a reactivated high-grade mylonite zone. As is evident from Plate 8a, lineation directions vary considerably in attitude from one surface to the next, indicating adjacent slices of rock moved in somewhat different directions. A visual analogy might be a school of dolphins, each surfacing and diving independently of its neighbours. Low-grade mylonites are also present between the Mealy Mountains and Pinware terranes, in the thrust zone along the St. Lewis River, west of St. Lewis Inlet.

EXTENSIONAL MOVEMENTS

The extensional faults addressed in this section were newly recognized in 2004 and are a key element in the enhanced understanding of the kinematic history of the region. At the outset, it should be emphasized that these are distinct from rift-related faulting linked to the formation of the Iapetus Ocean, which started around 615 Ma. Faults formed during Iapetan rifting have a shallow-level, brittle character, trend north-northeast and are characterized by fault breccia and low-grade alteration (producing quartz, chlorite, albite, epidote and hematite fillings).

The extensional movements addressed here were only found in one area, situated southwest of Paradise River (Figure 6), and are associated with east-dipping high-grade mylonite showing good evidence of earlier southwest-directed thrusting (Plate 4). In most examples seen, the fault

Plate 8. *a). Variably plunging linear fabrics developed on low-grade shear surfaces forming part of the Shinney's Waters fault; host rock is ultramylonitized mafic granulite derived from the White Bear Arm complex (CG04-095); and b) horizontal linear fabrics developed on discrete low-grade surfaces forming part of the Petty Harbour fault; rock type is garnetiferous amphibolite belonging to Alexis River anorthosite unit (CG03-208).*

surfaces are occupied by pegmatite. Sense of movement is readily apparent from the deflection of host-rock fabrics (gneissosity, earlier granitic veins and other heterogeneities) into parallelism with the wall of the pegmatite (Plates 9a-c, Figure 7). It would seem that extension commenced in a ductile manner until the rock ruptured, thus allowing the ingress of granitic fluids, crystallizing as microgranite, aplite and pegmatite. There are clear indications that the minor granitoid intrusions are late syntectonic. Earlier, more-deformed dykes, showing pinch-and-swell shape and/or having penetrative fabrics, are crosscut by later intrusions, for example.

While remaining cognizant of the concerns raised by Gower (1993) regarding determining the age of deformation using minor intrusions, there can be little doubt, in this instance, that the emplacement of minor intrusions is both spatially and genetically related to the extensional faults (but note that genetic/temporal linkage is not extended to embrace the earlier southwest-directed thrusting). Four minor intrusions, all discordant, have been dated in the surrounding district, and have ages of 1079 ± 6 Ma, 1047 ± 2 Ma, 1029 ± 2 Ma (all U–Pb zircon dates) and 1003 ± 6 (U–Pb, titanite). The minor intrusion dated to be 1047 ± 2 Ma, discordantly intruded pelitic gneiss containing rotated garnet (Plate 6f) indicating strike–slip dextral shearing, and is itself deformed, in part. The 1029 ± 2 Ma minor intrusion is a planar dyke that truncates granulite-facies mylonite, but is not, itself, significantly deformed. The originally interpreted emplacement age for the 1003 ± 6 Ma intrusion may be younger than its actual time of intrusion, given that i) most activity elsewhere in the Lake Melville terrane occurred before 1030 Ma, ii) metamorphism in the host rock is dated to be 1030 ± 2 Ma, and iii) the 1003 ± 6 Ma date is based on titanite rather than zircon.

Making the assumption that the undated extensional-fault-controlled minor granitic intrusions are similar in age to the dated intrusions, it is probable that the extensional movements were Grenvillian. On the basis of all available U–Pb geochronological data, Gower and Krogh (2002) concluded that Grenvillian tectonism in the Lake Melville terrane mostly occurred between 1080 and 1040 Ma, and terminated by 1020 Ma. As the extensional-fault-controlled minor intrusions are late syntectonic, their emplacement age is estimated to be between 1045 and 1025 Ma.

DISCUSSION

LABRADORIAN

Evidence for a severe Labradorian deformational and high-grade metamorphism event has been summarized for coastal eastern Labrador by Gower *et al.* (1997), and for the whole of the eastern Grenville Province (Labrador and adjacent Quebec) by Gower and Krogh (2003). Geochronological data demonstrate that the most intense period of tectonism was short-lived, having occurred between 1665 and 1655 Ma, followed by less intense tectonism continuing to ca. 1620 Ma. Quiescence was achieved by 1600 Ma. Deformation involved the uplift of lower-crustal rocks that had been metamorphosed to upper amphibolite or granulite facies. In the southern Groswater Bay terrane, rocks are exposed that had been subjected to conditions of 10 to 12 kb and 750 to 800°C. Available data suggests that exposed rocks in the Hawke River and Lake Melville terranes had

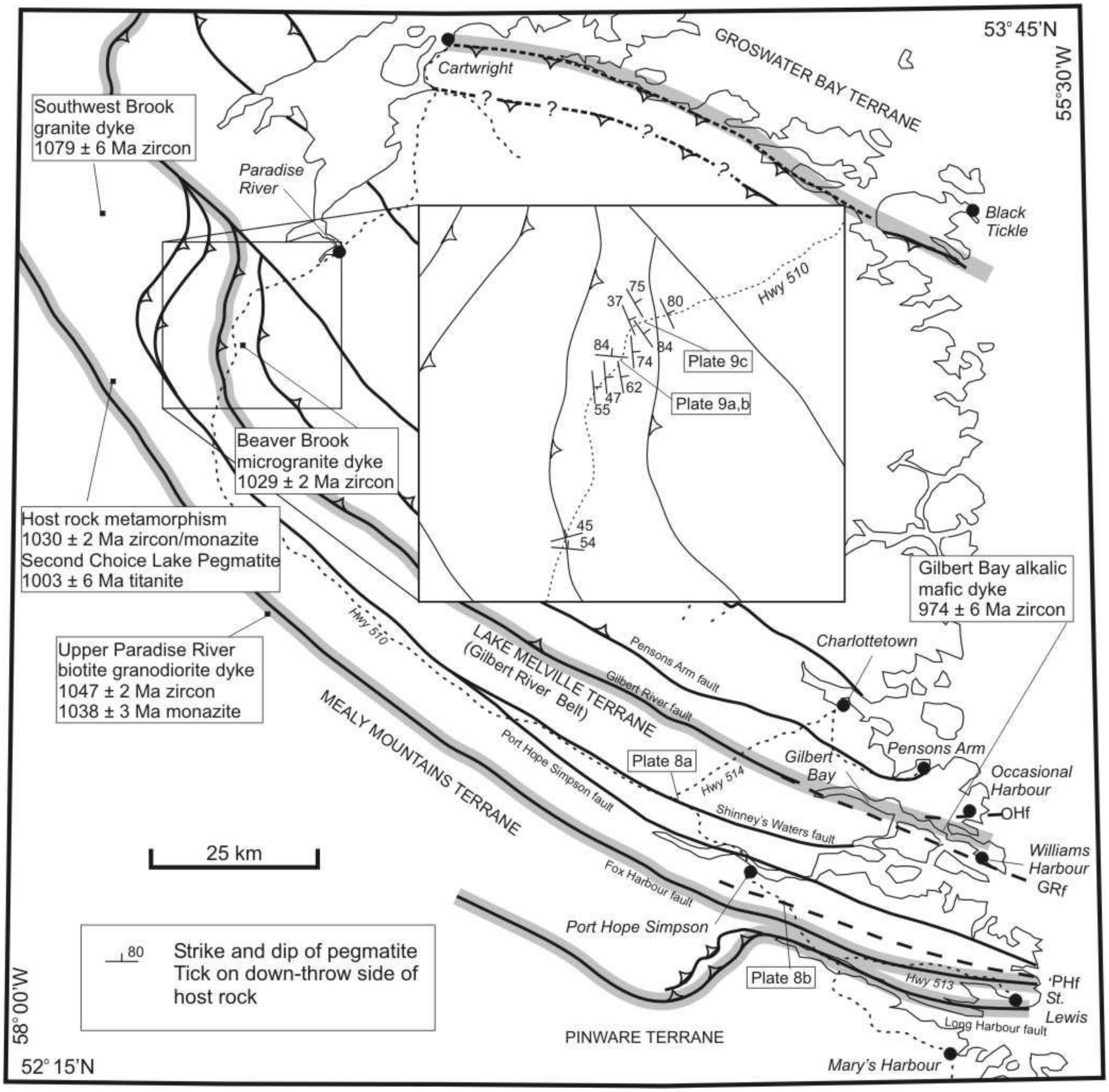
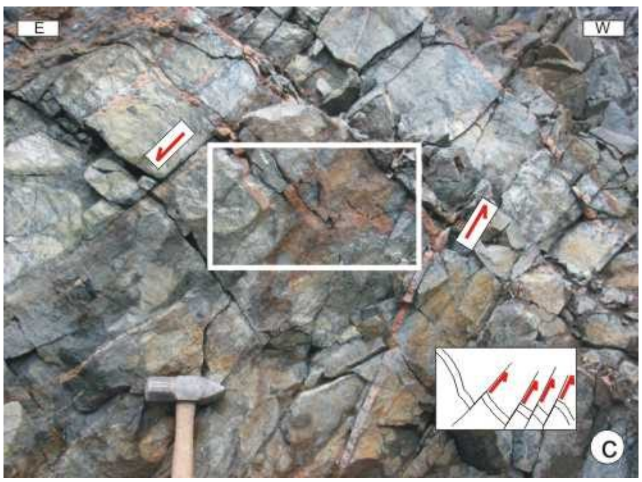


Figure 6. *Locations where extensional structures occupied by minor granitoid intrusions were observed. OHf - Occasional Harbour fault, GRf - Gilbert River fault and PHf - Petty Harbour fault.*

experienced a somewhat lower metamorphic regime (6 to 10 kb, 650 to 900°C). No geothermobarometric data have been obtained from the Mealy Mountains or Pinware terranes, but mineral assemblages indicate that granulite-facies conditions were reached in places. That the high-grade assemblages in the Groswater and Hawke River terranes were the product of Labradorian metamorphism is demonstrated by Labradorian titanite ages in the Hawke River terrane and only partially reset pre-Grenvillian Ar–Ar ages in the Groswater Bay terrane, thus denying a severe Grenvillian metamorphic overprint (Gower, 2003).

In the context of the geochronological and metamorphic constraints outlined in the previous paragraph, combined with potential field data, offshore seismic reflection data and geodynamic models, Gower *et al.* (1997) postulated that Labradorian orogenesis involved doubly vergent tectonism. Envisaging southward subduction, they suggested that the



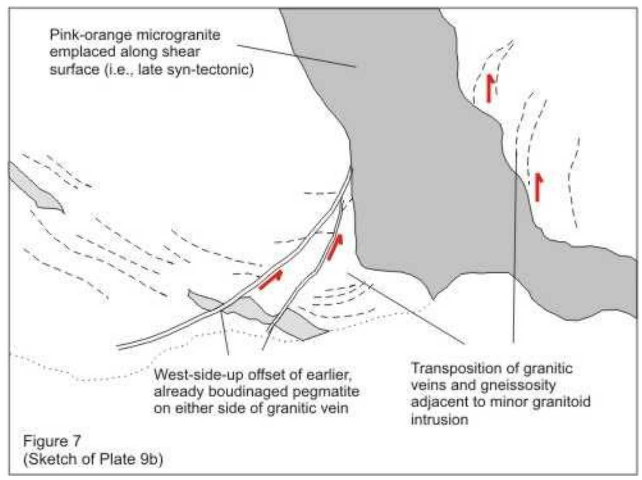


Figure 7. *Sketch of Plate 9b highlighting points of structural interest.* **Plate 9.** *Examples of extensional faults occupied by late-syntectonic minor granitoid intrusions: a) slightly boudinaged pink pegmatite occupying shear surface; sense of movement (west-side-up) indicated by transposition of earlier fabrics adjacent to pegmatite (CG04-217); b) earlier minor granitoid intrusions and gneissosity in their host rock, reoriented due to transposition adjacent to later 3-m-wide pink–orange microgranite (CG04-209); and c) extensional, faulting of a minor granitoid vein (sketch is of boxed area) (CG04-216).*

northern Hawke River and Groswater Bay terranes represented pro-shears, and the southern Hawke River terrane and south to the northern Pinware terrane represented retro-shears. In other words, the northern Hawke River terrane and areas farther north were thrust to the north, whereas the southern Hawke River terrane and areas farther south were thrust to the south. All thrust- and reverse-sense kinematic data supports this model. Note that the thrusts at the northern boundary of the Hawke River terrane have a much shallower dip (ca. 40°S) than the reverse-sense faults close to the southern boundary, which are dominantly 60 to 90°N.

In the earlier subsection entitled 'High-Grade Mylonite', reference was made to sinistral metric extensional shears that cut dextrally transcurrent mylonite. Scott *et al.* (1993) have dated a leucogranite from one-such extensional shear (located in Figure 2) that is interpreted to have been intruded during ongoing sinistral strike–slip deformation. As the leucogranite provided an age of 1664 +14/-9 Ma it appears conclusive that the high-grade mylonites in the Gilbert River Belt must be Labradorian also. It is noted that this conclusion appears to be at variance with U–Pb geochronological evidence from elsewhere in the Lake Melville terrane (mostly farther northwest) for high-grade Grenvillian tectonism between 1080 and 1040 Ma (Corrigan *et al.*, 2000; Gower and Krogh, 2002). As much interpretation relies on the dated leucogranite evidence, confirmation from other examples is essential. Are field relationships regarding the leucogranite unequivocal? Could the 1664 Ma zircons be inherited? Could there be both Labradorian and Grenvillian high-grade mylonites?

PINWARIAN?

Scott *et al*. (1993; sample S401) determined the age of a pink-weathering aplitic vein, collected 9 km southwest of St. Lewis, to be 1509 +11/-12 Ma. The vein crosscuts mylonitic fabric but can be traced to where it becomes transposed into parallelism with the fabric. Lacking any other evidence for Pinwarian deformation at the time, Gower *et al.* (1996) suggested, alternatively, that the pre-granite-vein mylonitization could be Labradorian and the post-granite-vein mylonitization Grenvillian. In the face of subsequently obtained geochronological data from other parts of the eastern Grenville Province, which provided independent evidence for Pinwarian deformation and metamorphism, Gower and Krogh (2002) acknowledged that supporting evidence existed for Scott *et al*.'s (1993) interpretation (although maintaining the viability of Gower *et al*.'s 1996 stance). Interpretation has not advanced since then, except to note that the geochronological site can now be identified as within a region characterized by steep oblique-slip movements.

GRENVILLIAN

Lower-Crustal Channel Flow?

Gower *et al.* (1997) offered a model whereby the Lake Melville–Mealy Mountains terrane boundary defines the northeastern lateral ramp and dextral transposition zone to Grenvillian allochthonous terranes that were transported northwest on frontal ramps located farther west. This concept is revisited here in the light of lower-crustal channel-flow models advanced by Beaumont *et al.* (2001). As an explanation of tectonism in frontal zones of collisional orogens, the model envisages a melt-weakened zone in the lower to middle crust, coupled with ductile extrusion, driven by denudation, of high-grade metamorphic rocks between coeval normal- and thrust-sense shear zones. In the eastern Grenville Province, the concept has been applied to the Manicouagan region by Rivers *et al.* (2002) and to the Cape Caribou area by Rivers and Krauss (2004). Both areas are indicated in Figure 1.

From the partial preservation of pre-Grenvillian ^{40}Ar–^{39}Ar and K–Ar ages (Gower, 2003), taken in conjunction with Labradorian titanite ages (Gower and Krogh, 2002), it is clear that the eastern part of the Groswater Bay terrane and the adjacent Hawke River terrane escaped severe Grenvillian metamorphism, so there appears to be no possibility that this region might represent the eastward extension of an extruded channel.

Where, then, might it be located? In the context of current models envisaging eastern Labrador as a collisional flank, interpretation should be directed at what happens at the side of the orogen, rather than at its leading edge. Geometrically, one could draw the flank as a single vertical plane normal to the sub-horizontal, low-viscosity slab-like channel, and against which the channel abruptly terminates. Intuitively, it seems more likely that the flank would be a zone of some width, distinguished by higher heat flow, lower viscosity, subhorizontal transport and structural complexity at the front-flank syntaxis. It would only be characterized by rocks having high-pressure mineral assemblages where the front merges with the flank.

If a channel-flow model is to be applied to eastern Labrador, then the 'zone of some width' referred to in the previous paragraph would have to be the southeast-trending part of the Lake Melville terrane (i.e., the Gilbert River belt). Its width is 20 km at its southeast end (between the Gilbert River and Fox Harbour thrusts), but widens to 50 km in a northwest direction, before it turns southwest and becomes frontal. Note, however, that, whereas ductile extrusion in the frontal region is sandwiched between coeval thrust- and normal-shear zones, ductile extrusion at a right-hand flank (i.e., eastern for a north-verging orogen) must be between a dextral shear on the outer side of the zone and a sinistral shear on the inner side. If the top of the channel in frontal regions was being eroded more rapidly than its base (and, consequently, extruded faster), one would also expect dextral shear within the flanking zone. The essence of the model, as it might apply to eastern Labrador, is illustrated in Figure 8.

In assessing the potential applicability of the model, an obvious question to be asked is whether shear-sense indicators at the margins of the Lake Melville terrane conform to model predictions. The kinematic requirements on the outer side of the channel flank (Lake Melville–Hawke River terrane boundary) are met by the Gilbert River fault. Its dextral sense of movement, southeasterly plunging lineations and, in consequence, north-side-down dip-slip component are consistent with the model, and the low-grade nature of the fault in the Gilbert Bay area is in keeping with its location distant from the channel front. On the other hand, the kinetic requirements for sinistral shear on the inner side of the channel flank (Lake Melville–Mealy Mountains terrane boundary) are not met, and, in fact, evidence points to dextral movement. Across the English River fault (Figure 1), northwest of the region addressed in this study, dextral shear-sense was first reported by Gower *et al.* (1985), and was further recorded by Corrigan *et al.* (2000). On the basis of a pegmatite dated to be 1013 ± 4 Ma and considered to be syntectonic, Corrigan *et al.* (2000) interpreted the shearing to be Grenvillian. Farther south, at the side where a biotite granodiorite dyke was dated to be 1047 ± 2 Ma (Figure 6), the discordantly intruded pelitic gneiss clearly shows evi-

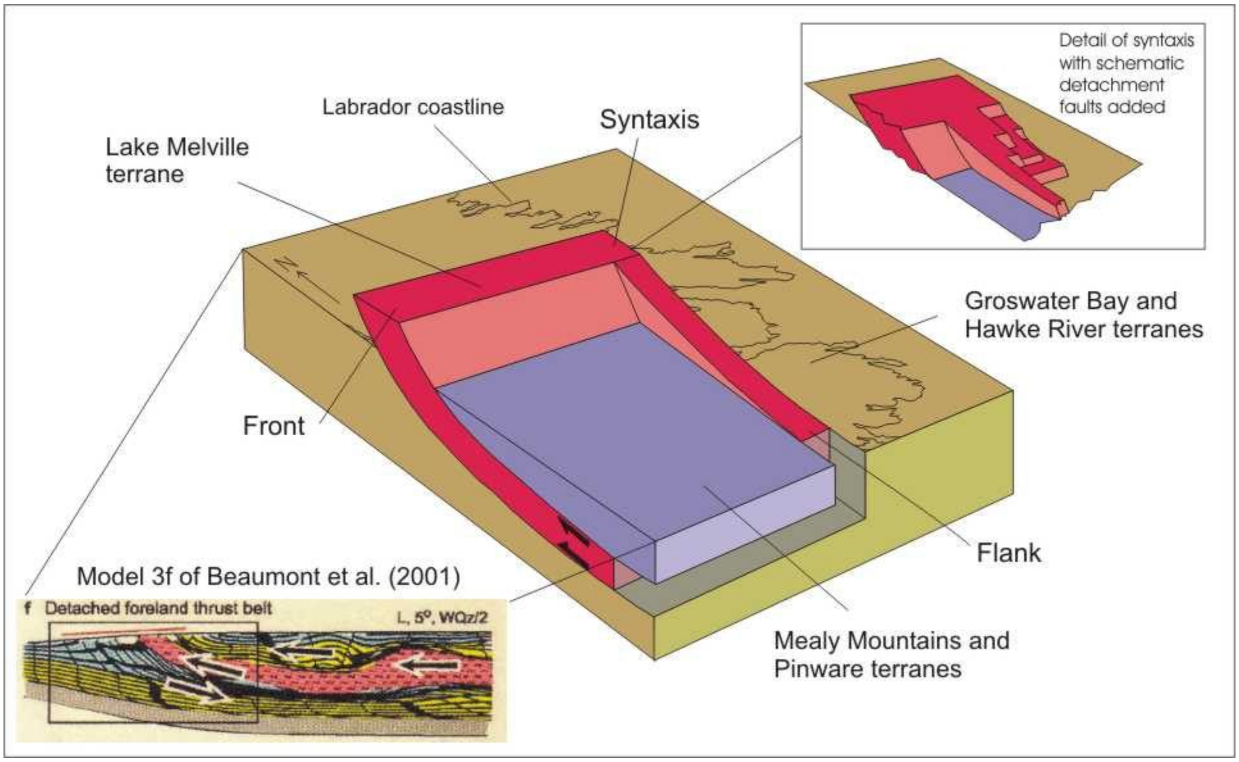


Figure 8. *Highly simplified block diagram illustrating the relationship between frontal thrusting and flanking transcurrent faulting in terms of a channel-flow model (cf. Beaumont* et al., *2001, lower left inset), with the caveat that the up-thrust wedge would have been eroded as it emerged rather than existing as illustrated. The model implies that channel-flow and ductile extrusion of the partially melted Lake Melville terrane are driven by surface denudation at the steep, north-facing edge of a plateau underlain by low-viscosity material. In the Beaumont* et al. *(2001) inset, blue is weak upper crust, yellow is medium-strength middle crust, pale brown is strong lower crust, and pink is the melt-weakened channel-flow zone. The red line above the model surface indicates the denudation front.*

dence of strike–slip dextral shear sense (Plate 6f), and there is no evidence of subsequent sinistral displacement.

The only hint that there might have been sinistral displacement at the southern boundary of the Lake Melville terrane comes from the earlier noted asymptotic anticlockwise-sense approach of lineation azimuth into parallelism with the Fox Harbour fault, coupled with speculation regarding how the Mealy Mountains terrane might have moved relative to the Pinware terrane. Validation of this concept includes demonstration that the change in orientation occurred with progressive strain, and, besides, other mechanisms could explain the pattern. A progressive strain regime has been neither demonstrated nor denied.

Krauss and Rivers (2004), when applying Beaumont *et al*.'s (2001) channel-flow model to the Cape Caribou allochthon (belonging to the frontal part of the allochthonous terranes), advocate an evolutionary series of orogenic events, whereby detachment of the Mealy Mountains terrane from the Cape Caribou allochthon followed thrusting due to collapse of the upper part of the orogenic wedge, as it exceeded critical taper. Regardless of the channel-flank model being discussed here, lack of evidence for sinistral displacement between the Mealy Mountains and Lake Melville terranes raises questions regarding the robustness of evidence for Grenvillian detachment of the Mealy Mountains terrane. Gower and Krogh (2002) commented that Grenvillian geochronological and structural data from the area could be best explained by invoking more than one Grenvillian orogenic event (mostly likely at ca. 1040 and 1010 Ma). Whether reconciliation can be achieved between predicted sinistral and observed dextral inner-flank displacements by invoking two-stage (or more) orogenesis, or some other mechanism, remains to be determined.

The channel-flow model provides an explanation for high-grade metamorphic assemblages within a narrow frontal zone (cf. Rivers *et al*., 2002). Along the flank of a channel the situation would be somewhat different. Progressing southeastward, one would anticipate the thrusting influence to decrease as a strike–slip regime becomes dominant, so there would be no compelling reason for high-grade rocks to be exhumed in distal regions. Nevertheless, the increase in garnet abundance crossing the southern boundary of the Lake Melville terrane in a northern direction is obvious. Also apparent is that the garnet commonly forms retrograde plagioclase-rich (plus biotite and quartz) 'ghost-garnet' pseudomorphs. Given the earlier-presented evidence for Labradorian thrusting, the interpretation advocated here is that the high-grade rocks are mostly Labradorian, with a retrograde Grenvillian overprint. Possibly, high-grade assemblages in the frontal (east-northeast-trending) part and northwestern end of the flank of the Lake Melville terrane are Grenvillian, whereas those in the southeast part are largely Labradorian. Such a model could reconcile many of the apparent contradictions that currently exist regarding the timing of deformation in the Lake Melville terrane. This thesis needs to be tested by systematic U–Pb and Ar–Ar geochronological investigations along the length of the flank.

Extensional Movements

Extensional features can be explained as a consequence of the Lake Melville terrane moving northwest relative to the Hawke River terrane. Where their mutual terrane boundary has a northwest trend, the movement sense is dextral. Where the boundary trends north or northeast, however, the effect would be for the Lake Melville terrane to split from the Hawke River terrane. The existence of detachment structures localized to the area southwest of Paradise River is, therefore, where they would be expected. Note that this interpretation is consistent with the determination of Hanmer and Scott (1990) that the dip-slip component of dextral transcurrent movement on the Gilbert River fault during Grenvillian tectonism was north-side-down, regardless of whether or not channel-flow models are invoked. It is predicted that detachment features will be found to exist northwest of Paradise River, where other sections of the boundary between the Lake Melville and Hawke River terrane have a similar north to northeast trend. The region where they are likely to occur was mapped in 1981 (Gower *et al*., 1982) when kinematic information was not routinely collected. It has not been revisited since.

It was argued earlier that the detachments are Grenvillian on the basis of geochronological data, obtained from granitoid intrusions in the vicinity. It is noted that detachment and down throw of the Hawke River terrane relative to Lake Melville terrane provides a good explanation for the preservation of Labradorian U–Pb titanite ages in the Hawke River terrane versus Grenvillian U–Pb zircon, monazite and titanite ages in the Lake Melville terrane. Previously, the assumption that the thrust-sense kinematic indicators at the western end of the Hawke River terrane were of Grenvillian age made it difficult to understand how Labradorian U–Pb titanite ages could be preserved on, what would have been, the upthrust side. The enigma is now resolved by accepting that titanite closure occurred after Labradorian thrusting ceased, but that the Lake Melville terrane was uplifted during Grenvillian tectonism.

That the detachments exist at all may be the consequence of region being close to the front-flank syntaxis. On the flank, a lateral ramp is the inevitable corollary of tectonic uplift of high-grade metamorphic rocks along the northwest-verging front (again, regardless of whether or not channel-flow models are being considered). Given a ductile regime, it seems unlikely that the lateral ramp would be vertical. Instead, it is easy to envisage that there could be a northeast-verging 'spill-over' corner effect in the changeover from northwest-directed frontal thrusting to dextral flanking strike–slip movements, resulting in the edge of the Lake Melville terrane being draped over the Groswater Bay terrane. The pattern of northwest-vergent thrusts, northwest-striking strike–slip faults and overturned, northeast-vergent isoclinal faults depicted by Gower *et al.* (1985) is consistent with such a concept. The area southeast of this 'spill-over' bulge is where detachment is located and would be predicted (schematically illustrated in Figure 8, upper right inset).

CONCLUSIONS

On the basis of shear-sense observations, four types of displacements are recognized. i) Thrusting / reverse faulting under ductile, high-grade conditions took place on both the northern and southern flanks of the Hawke River. ii) Steep, north-side-up, oblique-slip movements involving a component of dextral strike-slip movement, also under high-grade conditions, occurred at the eastern end of the Mealy Mountains terrane. iii) Both high- and low-grade, dextral transcurrent shear-sense indicators occur in the southeast Lake Melville terrane (Gilbert River belt). The high-grade movements also include a north-side-up, dip-slip component, whereas the low-grade movements involve a lesser north-side-down, dip-slip component. iv) Extensional faulting and concomitant minor granitic intrusion emplacement occurred along the western flank of the Hawke River terrane.

The thrust- and reverse-sense shearing occurred during doubly vergent Labradorian tectonism. The timing of both steep and shallow high-grade, oblique-slip, dextral and north-side-up movements is less certain. Structural and geochronological constraints suggest a Labradorian age for those in the southeasternmost Lake Melville terrane, but regional geochronological, metamorphic and structural data from farther north in the Lake Melville terrane argue in favour of high-grade Grenvillian dextral displacements. Low-grade mylonitization along the Gilbert River fault and branch structures can be conceptually linked to the pegmatite-filled extensional faults and to demonstrate that, relative to the Hawke River terrane, the Lake Melville terrane was uplifted and displaced dextrally during Grenvillian tectonism.

The channel-flow concept of Beaumont *et al.* (2001) is evaluated as it might apply to the side of a Grenvillian collisional orogen, represented in eastern Labrador by the Lake Melville terrane. Application of the model is compromised because, not only can predicted sinistral-sense movements on the southwest flank of the Lake Melville terrane not be convincingly demonstrated, but dextral-sense movements can. Potential use of the model is also hampered by continuing uncertainty as to the relative roles of Labradorian versus Grenvillian high-grade deformation.

ACKNOWLEDGMENTS

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