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Development of a transverse to orogen parallel extension lineation in a complex collisional setting, Trans-Hudson Orogen, Manitoba, Canada

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Abstract

In the southeastern Trans-Hudson Orogen (THO), the wide dispersion in orientation of the L3 extension lineation from orogen-parallel to transverse is considered primary as it cannot be accounted for by simple overprinting of a single precursor orientation. Interpretation of the origin of this extension lineation is complicated by the fact that its gently northeast-plunging orientation at the north end of the study area is inconsistent with the evidence for sinistral, east side up movement of the steep oblique slip D3 faults. The hypothesis presented here to explain the complicated lineation pattern is based on evidence that the preceding period D2 southwest-directed transport, overlapped temporally and spatially with D3 northwest-southeast transpressional shortening. D2 and D3 are attributed to successive, but overlapping, collisional events. D3 transpressional shortening is interpreted to have propagated westward through the THO resulting in a prolonged and complex transition between D2 and D3 deformation regimes. The dispersion of the L3 extension lineation is interpreted to reflect the competing effects of both deformation regimes which appear to have been partitioned in the crust with D2 effects best developed in higher metamorphic grade rocks and D3 effects best developed in lower metamorphic grade rocks. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Orientation; Lineation; Trans-Hudson Orogen

1. Introduction

Variations in the attitude of extension lineations from steep to shallow and from transverse to orogen parallel have been encountered in many collisional belts. One possible explanation is that the extension lineation has been overprinted by subsequent deformation events, resulting in reorientation of older linear fabrics. This effect can generally be assessed using lower hemisphere plots of the lineation and related fabrics (e.g. Ramsay, 1967). In many areas where later deformation has not occurred, the variation from a transverse to orogen parallel extension lineation has been interpreted to reflect the kinematic partitioning of deformation into a combination of wrenching and thrusting, with the two types of faults typically linked at depth (e.g. Ibero–Amorican Arc in northern Spain (Brun and Burg, 1982), the Rehamna Massif in Morocco (Lagarde and Michard, 1986), and eastern Greenland (Holdsworth and Strachan, 1991). In other regions such as the Alps, Choukroune et al. (1986) and Ring et al. (1988) have found evidence for two distinct extension lineations that reflect the kinematics during phases of deformation separated by >60 Ma.

Although Hansen (1989) found evidence of an age difference between orogen parallel and transverse lineations in the Teslin suture zone, Yukon, she suggested that both orientations were related to a single progressive event, with deformation progressing from shortening at a high angle to the collisional margin, to margin-parallel translation.

Detailed analysis of data for the study area suggests that these hypotheses are not directly applicable to the Wekusko Lake region. Here, a prominent syn-metamorphic extension lineation L3 varies from a gently northeast-plunging structure (orogen parallel) at the north of the study area, to a steep ~east-plunging structure (transverse) in the south, although the orientation of the associated foliation (S3) remains relatively constant. This represents a change from subhorizontal to steep transport and is interpreted to reflect the relative influence of two competing deformation regimes. This interpretation is based on data from the surrounding region, which suggests that the effects of the earlier D2 event (southwest-directed transport) continued in the Wekusko Lake area during the early stages of D3

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northwest–southeast transpressional shortening. Development of the steep component of the L3 extension lineation is attributed to the initiation of D3 northwest–southeast transpressional shortening, whilst the gently northeast-plunging component of the L3 extension lineation is attributed to distributed subhorizontal ductile flow related to a continued component of D2 southwest-transport. The effects of continued D2 deformation on the L3 extension lineation are best developed in higher metamorphic grade rocks, whereas the D3 effects are best developed in lower metamorphic grade rocks, consistent with a change in rheology with increasing metamorphic grade at the time the lineation developed (i.e. an increase in paleodepth). This implies that the effects of D2 and D3 deformation may have been partitioned in the crust and may not have affected the same rocks at the same time.

D2 deformation is attributed to collision between the Archean Sask craton and juvenile Paleoproterozoic terranes of the Trans-Hudson Orogen (THO) (Reindeer Zone) at 1.84 Ga (Ansdell et al., 1995; Ashton et al., 1996), and D3 deformation is related to a later collisional event between the Archean Superior craton and the Reindeer Zone (Lewry, 1981; Green et al., 1985; Hoffman, 1988; Bleeker, 1990a,b) at 1.81 Ga. Southwest-directed D2 transport related to collision of the Sask craton continued after the initial collision of the Superior craton, while the effects of the later collision (D3) deformation) propagated westward from the boundary zone. This resulted in a complicated and protracted transition between D2 and D3 deformation regimes within the eastern Reindeer Zone near the boundary with the Superior craton, and produced the observed dispersion in orientation of the L3 extension lineation ranging from orogen-parallel to transverse.

2. Regional geology

The Paleoproterozoic THO represents the complex collision zone between three Archean cratons: Rae-Hearne, Superior, and the buried Sask craton (e.g. Lewry, 1981; Hoffman, 1988, 1989; Ansdell et al., 1995). The most extensive tectonic element of the THO is the Reindeer Zone (Fig. 1), which comprises a collage of dominantly juvenile volcano–plutonic terranes of intra oceanic arc and back-arc origin (e.g. Flin Flon belt; Lewry et al., 1990; Lucas et al., 1996) and sedimentary rocks principally derived from these terranes (e.g. Kisseynew belt; Bailes, 1980; Ansdell et al., 1995; David et al., 1996). The Reindeer Zone structurally overlies, at least in part, Archean crust of the Sask craton (Lewry et al., 1990, 1994; Ansdell

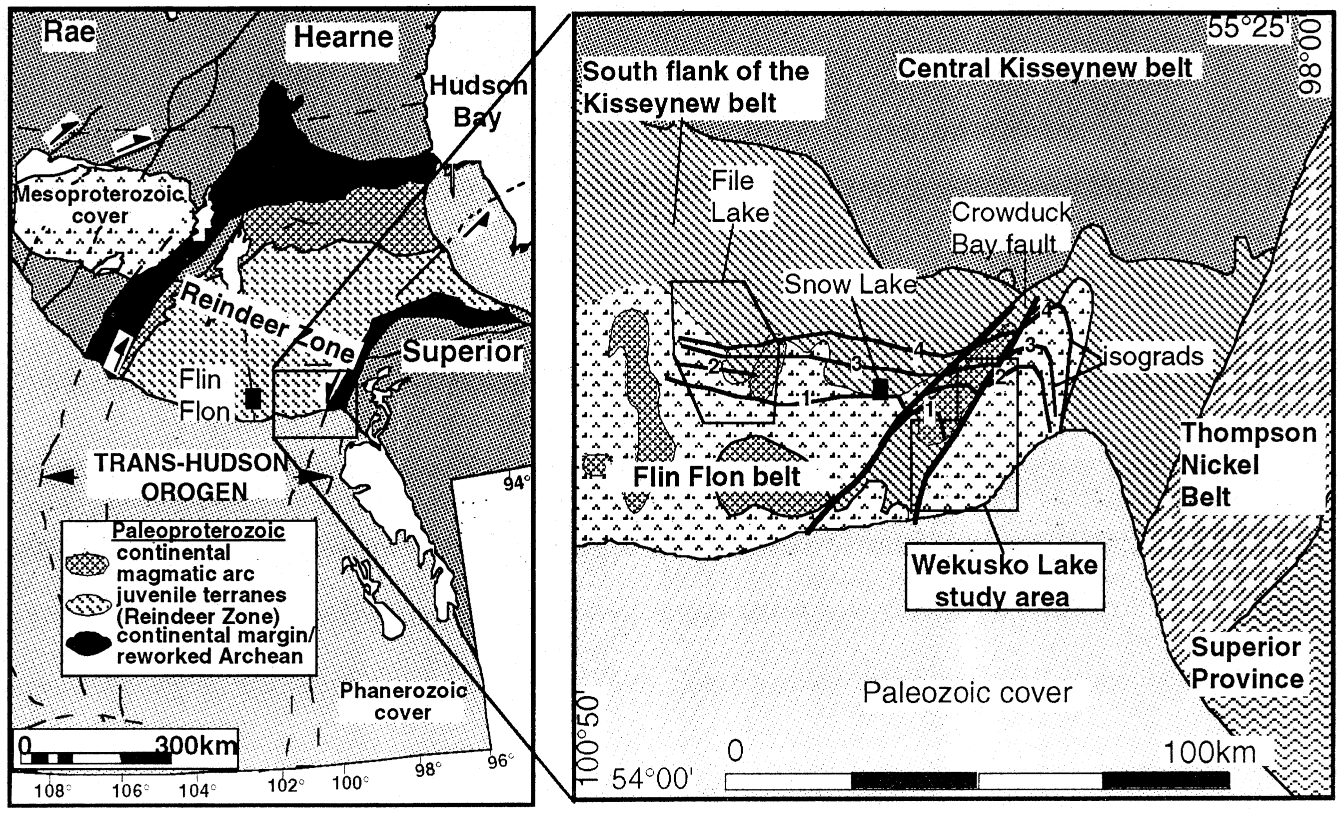


Fig. 1. (a) Simplified geological map depicting the location of the Trans-Hudson Orogen, and the Rae-Hearne and Superior provinces (after Hoffman, 1989). (b) Summary map of the Manitoba part of the Trans-Hudson Orogen (modified after Hoffman, 1988) showing the location of the study area and distribution of the main tectonostratigraphic packages. Isograds shown from File Lake to Wekusko Lake are numbered 1 to 4 from south to north: 1 = staurolite-in; 2 = sillimanite-in; 3 = sillimanite + almandine-in; 4 = K-feldspar + melt. Note that the boundary between the south flank and central parts of the Kisseynew belt approximately coincides with the garnet + cordierite isograd.

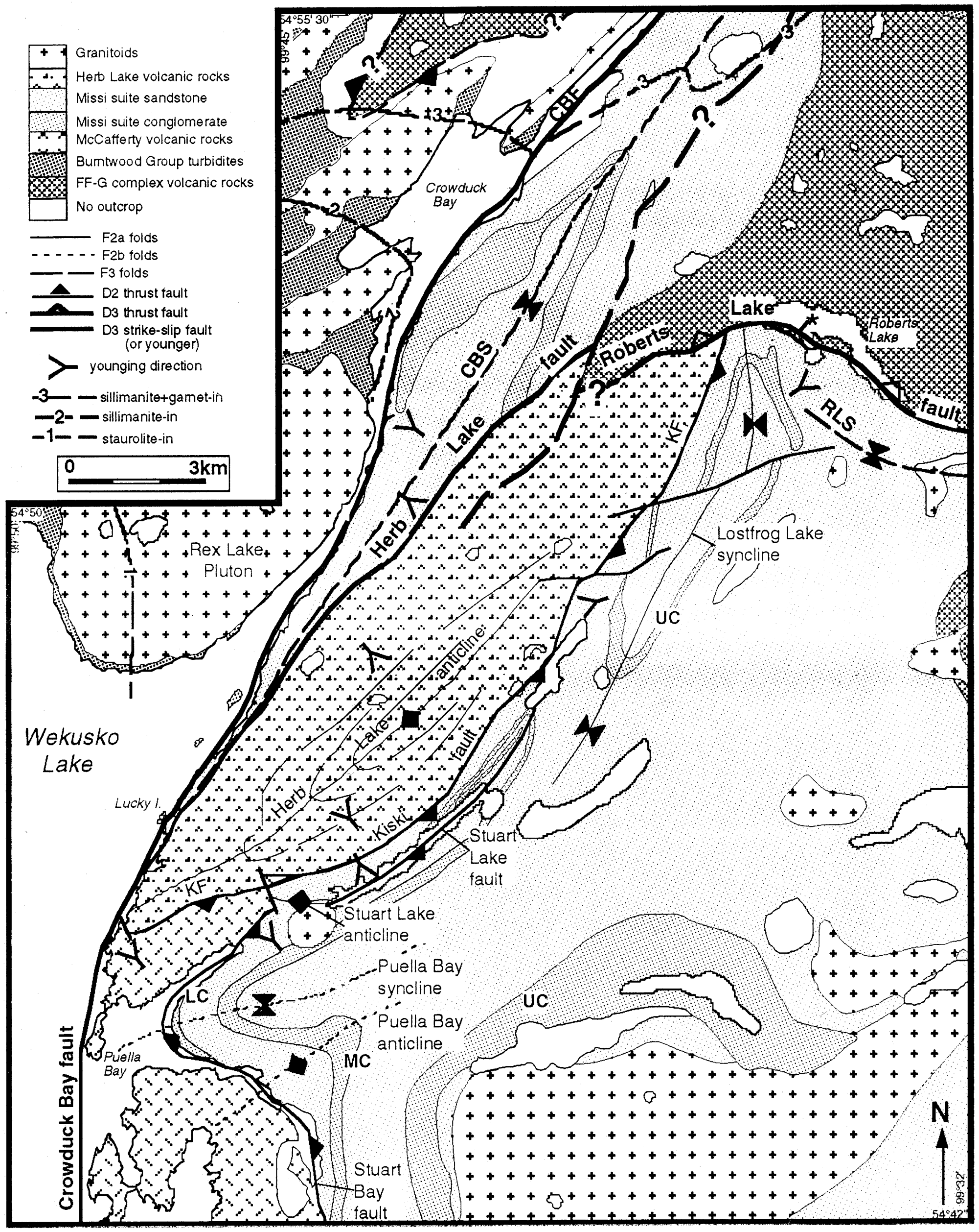


Fig. 2. Simplified geological map of the east Wekusko Lake area (based on Armstrong (1941), Frarey (1950), Gordon and Gall (1982) and this study). Key D3 structures discussed in the text include: Crowduck Bay, Herb Lake and Roberts Lake faults; and Crowduck Bay and Roberts Lake synclines. CBF = Crowduck Bay faults; CBS = Crowduck Bay syncline; FF–G = Flin Flon–Glennie complex; HLA = Herb Lake anticline; HLF = Herb Lake fault; KF = Kiski fault; RLF = Roberts Lake fault; RLS = Roberts Lake syncline; SBF = Stuart Bay fault; SF = Stuart Lake fault; LC = conglomerate, MC = Middle conglomerate, UC = Upper conglomerate.

et al., 1995). The Reindeer Zone is flanked by the boundary zones with the adjacent Archean Rae-Hearne and Superior cratons, which include reworked Archean rocks and Paleoproterozoic continental margin deposits (Fig. 1a; (Hoffman, 1989). An Andean type continental magmatic arc (Wathamun Batholith) lies along the margin between the Reindeer Zone and the Rae-Hearne craton (Meyer et al., 1992).

The east Wekusko Lake study area occurs within the southeastern part of the exposed Reindeer Zone near the boundary zone (Thompson Nickel Belt) of the Archean Superior craton (Fig. 1b). This area includes three major tectonostratigraphic packages (Fig. 2): (i) 1.92–1.88 Ga arc and ocean floor assemblages (Gordon et al., 1990; Stern et al., 1993, 1995a,b; Stern and Lucas, 1994; David et al., 1996) that were accreted to form the Flin Flon–Glennie complex of the Flin Flon belt at 1.88–1.87 Ga and intruded by successor arc pluton ca. 1.87–1.86 Ga (Lucas et al., 1996); (ii) 1.85–1.84 Ga Burntwood Group turbidites (Bailes, 1980; Zwanzig, 1990; David et al.,

Table 1
Brief descriptions of geologic units in the Wekusko Lake area. Interpretation of units and geochemical data from Shanks and Bailes (1977), Gordon and Gall (1982), Bails (1992), Gilbert (1993, 1994), Gordon and Lemkow (1987) and Ansdell and Connors (1995). Age data from Gordon et al. (1990), David et al. (1996), Stern et al. (1995a,b), Connors and Ansdell (1994b), Ansdell and Connors (1995) and Ansdell et al. (1999)

Unit	Description	Age
Granitoids	Granite to granodiorite to diorite to gabbro (largely calc-alkaline), felsic phases most common.	1832 + 4/−3 Rex Lake Pluton (Fig. 2); 1834 + 8/−6 Wekusko Lake Pluton (west of study area)
Missi suite	Fluvial sandstones and conflomerates	Eastern package — min. age of 1834–1832 Ma from cross cutting intrusions; western package — max. age of ~1834 Ma from detrital zircons and association with Herb Lake volcanic rocks
	Three conglomerate bands in eastern package and one in western package (Fig. 2)	
Herb Lake volcanic rocks	Mafic to intermediate to felsic flows, intrusions and volcaniclastics (tholeitic to calc-alkaline)	Two felsic flows — 1836 ± 1 and 1833 + 6/−2; subvolcanic porphyry 1836 + 6/−5 (similar age to Missi suite)
Burntwood Group	Turbiditic siltstones, mudstones and sandstones	Max. age ~1859 Ma from detrital zircons; Min. age ~1841 Ma from cross-cutting intrusions
McCafferty Liftover volcanic Rocks	Basaltic flows, turbiditic volcaniclastic units, and dacitic fragmental units, flows and intrusions	Min. age 1876 ± 2 Ma
Flin Flon–Glennie complex	Largely mafic volcanic rocks north of Roberts Lake (interpreted as ocean floor)	Inferred to be ~1.91–1.88 Ga similar to other Flin Flon–Glennie complex rocks

1996); and (iii) 1.85–1.83 Ga alluvial–fluvial sandstones of the Missi Group (Ansdell, 1993; Ansdell and Connors, 1995; Ansdell and Norman, 1995) (Figs. 1b and 2). In the eastern THO, all of these units are intruded by 1.84–1.83 Ga pluton (Gordon et al., 1990; David et al., 1996).

Other rock units exposed in the Wekusko Lake area include two locally recognised units (Table 1): (i) the Herb Lake volcanic rocks comprising ca. L835 Ga mafic to felsic flows, intrusions and volcaniclastic rocks which are coeval with the Missi Group sandstones in this area, and are considered part of the Missi Group; and (ii) the McCafferty Liftover volcanic rocks comprising mafic to intermediate flows and volcaniclastic units that have been dated at 1876 ± 2 Ma (Fig. 2; Ansdell and Connors, 1994; Ansdell et al., 1999).

3. Deformation and metamorphism

Recent studies have highlighted four distinct periods of deformation in the THO (Fig. 3): D1 1.88–1.87 Ga amalgamation of arc and ocean floor assemblages to form the Flin

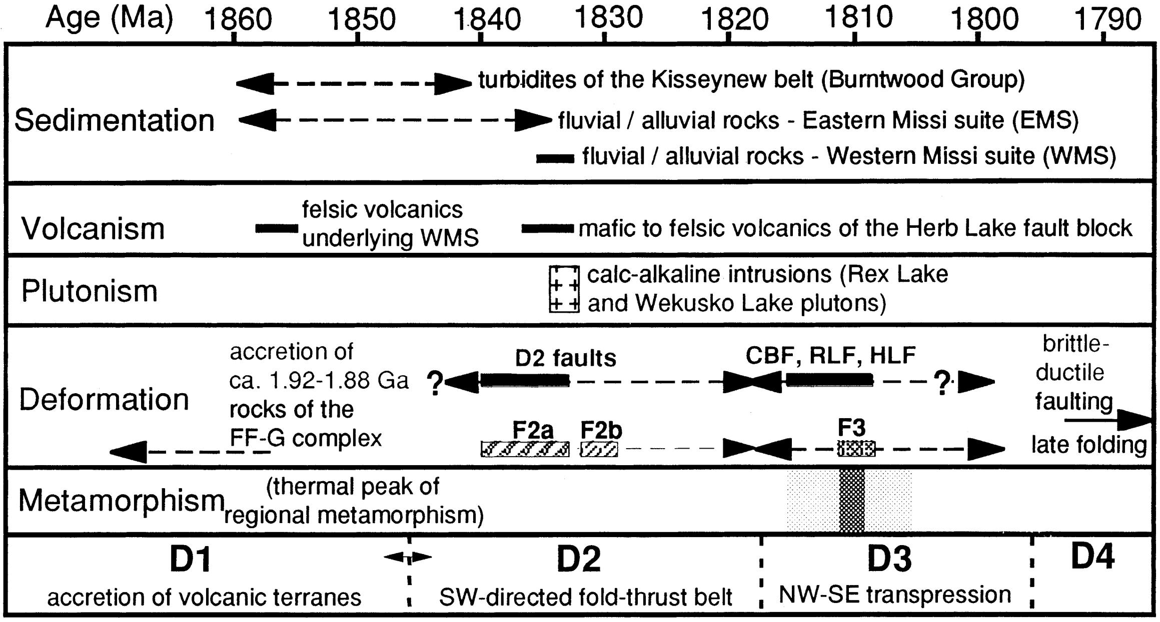


Fig. 3. Summary chart depicting the age and relative timing of structural generations, the thermal peak of regional metamorphism, magmatism, and deposition of major rock units in the Wekusko Lake area. Note that the 1.92–1.88 Ga Flin Flon–Glennie complex (FF–G) of the Flin Flon belt formed prior to the events discussed here. Refer to text for age constraints used in this chart and the source references.

Flon–Glennie complex of the Flin Flon belt, and subsequent shortening (transpression?) of the collage contemporaneous with emplacement of 1.88–1.84 Ga pluton (Lucas et al., 1996; Ryan and Williams, 1999); D2 southwest-directed thrusting (e.g. Zwanzig, 1990; Connors, 1996; Kraus and Williams, 2001) related to collision with the Sask craton (Ansdell et al., 1995; Ashton et al., 1996); D3 northwest southeast shortening related to collision with the Superior craton (Connors and Ansdell, 1994a; Kraus and Williams, 1994); and D4 brittle-ductile deformation associated with continued northwest–southeast shortening (Lucas et al., 1994; Fedorowich et al., 1995).

Note that the regional D2 structures are related to 1.88–1.87 Ga accretion and largely predate deposition of the Missi and Burntwood Groups, which comprise the main rocks of this study (Fig. 3). In addition, there is little evidence for post-D3 deformation in the study area. This paper focuses on the D3 phase of deformation and the reader is referred to Connors et al. (1999) for further details on the D2 stage of the deformation history.

3.1. D2 structures

In the east Wekusko Lake area, D2 deformation produced a series of faults that are interpreted as thrusts, folds (F2a) and a pervasive cleavage (S2a) which were overprinted by late stage folds (F2b) in the south of the area (Fig. 2; Connors et al., 1999). Although D2 structures at Wekusko Lake have been substantially reoriented during D3, the consistent evidence for ~southwest-directed displacement across the entire Reindeer Zone (e.g. Lewry et al., 1990; Zwanzig, 1990; Ashton et al., 1993; Norman et al., 1995; Connors, 1996) favours similar kinematics for the D2 structures at east Wekusko Lake (Connors et al., 1999). This reorientation is attributed to D3 folding (oroclinal rotation) of the entire eastern portion of the Reindeer Zone. D2 deformation initiated prior to the 1834 + 8/−6 Ma Wekusko Lake pluton (Gordon et al., 1990) in the Wekusko Lake area (Bailes, 1992) and prior to the 1839 ± Ma. Reed Lake pluton (Stern, pers. comm., 1997) 70 km to the west (Syme et al., 1995).

3.2. D3 folds, cleavage and lineations

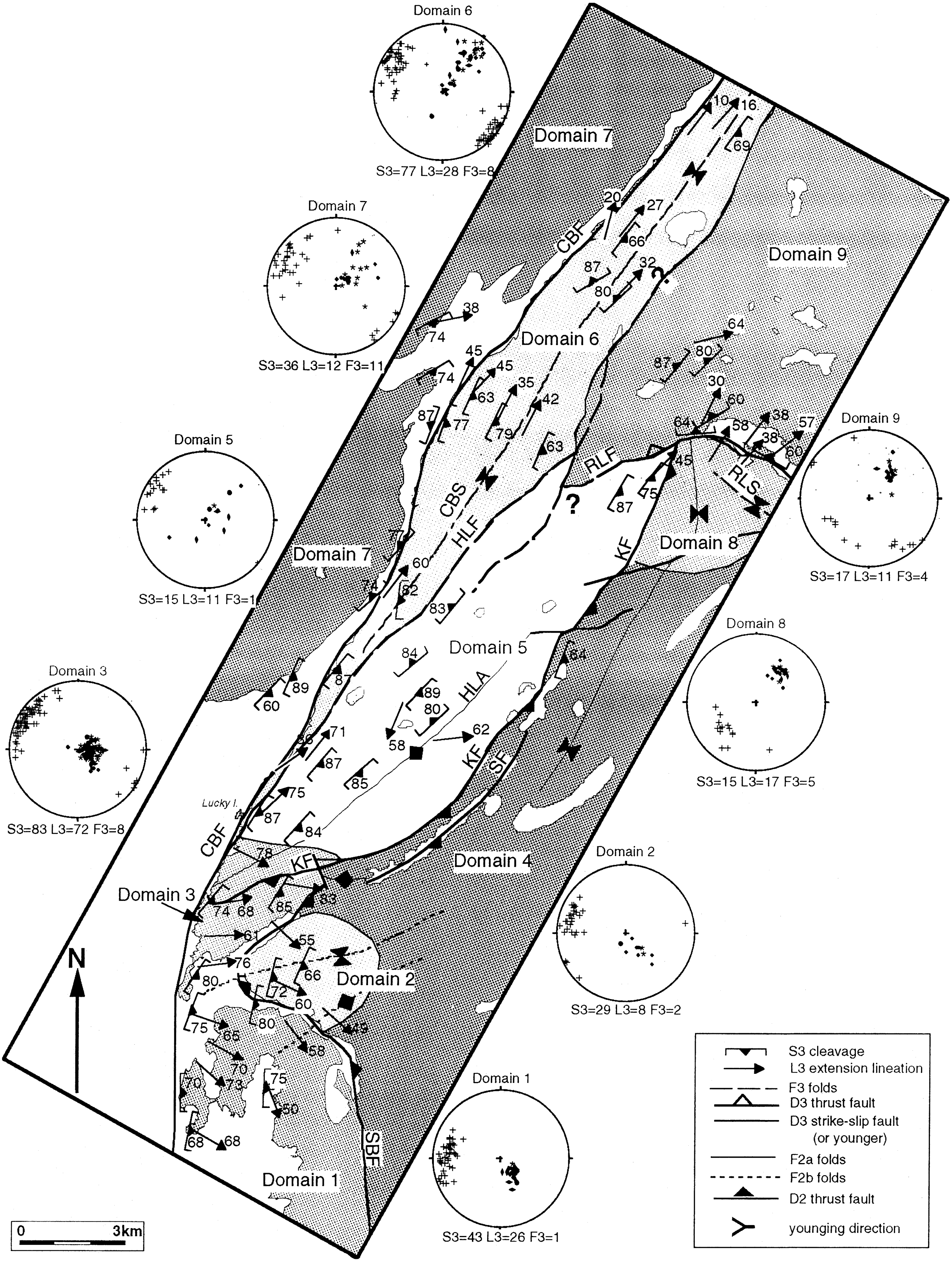
Development of D3 folds, cleavage and lineations is heterogeneous. The study area was divided into nine domains in order to assess the variations in both S3 and the L3 extension lineation (Fig. 4). These structures vary from pervasive in corridors along the D3 faults (i.e. Crowduck Bay and Roberts Lake faults) to weakly developed or absent elsewhere (e.g. domain 4 in Fig. 4). The regional variation in the development of D3 structures is interpreted to reflect strain localisation and partitioning during D3.

The S3 cleavage is typically steep and north- to northeast-striking (Fig. 4). In the corridor along the D3 Crowduck Bay fault, S3 is generally subparallel to the fault, However, the S3 cleavage is oriented clockwise to this D3 fault near the open bend where the fault changes trend from northeast to north (Fig. 4). In the southern part of the study area (Fig. 2), S3 is oblique to the S2a cleavage and locally forms a crenulation cleavage (Fig. 5a): both east and west of the Crowduck Bay fault, the asymmetric overprinting of S2a by S3 suggests a component of sinistral shear associated with S3 (e.g. Fig. 5a). This sinistral overprint of S2a by S3 is consistent across F3 fold hinges, suggesting it is not related to slip on fold limbs. In felsic to intermediate volcanic rocks of the Herb Lake package, S3 is typically defined by seams of concentrated white mica, which locally grade into 1–3 cm mica-rich shear zones (Fig. 5b). In the sandstones of the Missi Group and turbidites of the Burntwood Group, S3 is defined by alignment of micas and the older S2a is typically transposed and thus is rarely observed. The relationships between S3 and regional metamorphic minerals indicate that S3 effectively developed at peak regional metamorphic conditions (Table 2). For example, S3 wraps around staurolite porphyroblasts, but is overgrown by garnet in domains 7 and 8 (Fig. 5c). Hornblende porphyroblasts vary from aligned within S3 (and L3) to overgrowing the fabrics in domain 3 (Fig. 5d).

The L3 extension lineation is defined by stretched clasts (e.g. in conglomerates, volcaniclastics and breccias), elongate minerals (e.g. amphibole, micas, and sillimanite; Fig. 5e) and pods of minerals. The relationships between L3 and metamorphic minerals indicate that L3 developed during regional peak metamorphism similar to S3 (Table 2; Fig. 5e). The lineation forms the dominant fabric in some conglomerates, breccias and fine-grained felsic intrusions. It is best developed adjacent to the Crowduck Bay and Roberts Lake faults, following a pattern similar to the distribution of S3 (Table 2; Fig. 4).

The L3 extension lineation and S3 cleavage both display variations in orientation across the study area. S3 mimics the trend of the Crowduck Bay fault (varying from north- to northeast-striking), but also trends subparallel to the Roberts Lake fault (east–west in domains 8 and 9; Fig. 4). Correlation of the S3 cleavages between the Crowduck Bay and Roberts Lake fault zones is based on the observation that the S3 cleavage in staurolite–garnet–biotite schists adjacent to the Roberts Lake fault (asterisk on Fig. 2 shows location) wraps around staurolite and is overgrown by garnet similar to S3 along the Crowduck Bay fault (compare data for domains 7 and 8 in Table 2).

The L3 extension lineation shows a more dramatic variation in orientation, ranging from transverse (i.e. east- to southeast-trending) to parallel (i.e. northeast-trending) relative to the major D3 structures. Regardless of the orientation of the L3 extension lineation, it is always developed on the S3 cleavage. In domains 5–9, the L3 extension lineation plunges consistently to the northeast. However, the plunge varies systematically from 70 to 80° in the south to as low as ~20° in the north (Fig. 4; e.g. domain 6). To the south in domains 1–3, L3 is generally


Domain 6
S3=77 L3=28 F3=8
Domain 7
S3=36 L3=12 F3=11
Domain 5
S3=15 L3=11 F3=1
Domain 3
S3=83 L3=72 F3=8
Domain 9
S3=17 L3=11 F3=4
Domain 8
S3=15 L3=17 F3=5
Domain 2
S3=29 L3=8 F3=2
Domain 1
S3=43 L3=26 F3=1
Domain 7
Domain 9
Domain 6
Domain 7
Domain 5
Domain 8
Domain 4
Domain 3
Domain 2
Domain 1
CBF
CBS
HLF
HLA
RLF
RLS
KF
SF
SBF
Lucky I.
N
0 3km
S3 cleavage
L3 extension lineation
F3 folds
D3 thrust fault
D3 strike-slip fault (or younger)
F2a folds
F2b folds
D2 thrust fault
younging direction

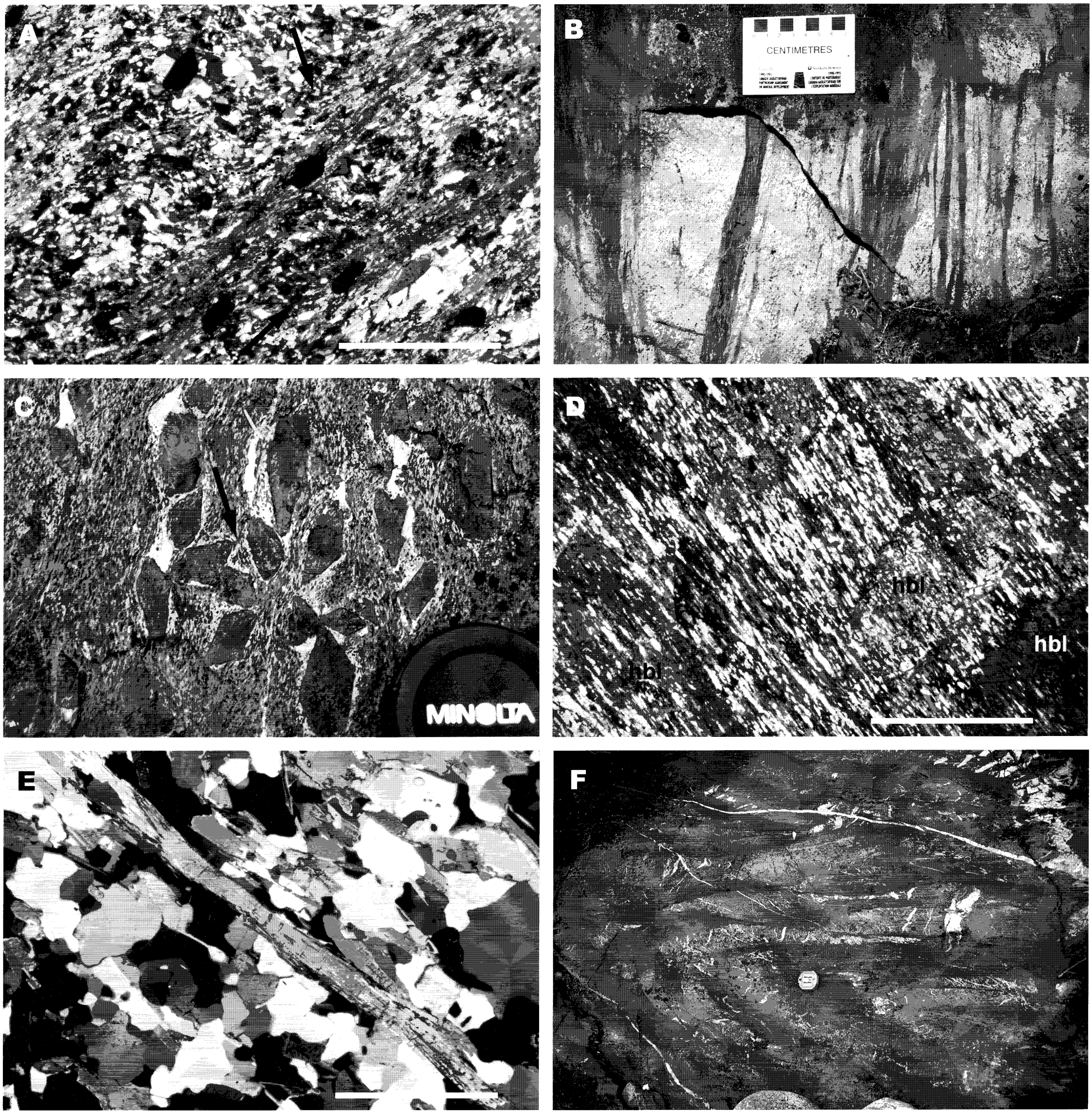


Fig. 5. (a) Photomicrogaph of mica-rich seams defining S3 in felsic volcanic rocks (domain 6). Note the folding of an earlier (S2a) cleavage (arrows) that merges into the mica-rich seams to form an S3 crenulation cleavage. Scale bar = 1 mm. (b) Mica-rich shear zones defining S3 in outrcop (domain 6). (c) S3 cleavage defined largely by biotite that anastomoses around staurolite porphyroblasts (domain 7). In thin section, millimetre scale garnet overgrows S3 in this sample. Lens cap is 65 mm. (d) Hornblende porphyroblasts overgrow the intense S3/shear zone fabric in altered mafic volcanic rocks along the Crowduck Bay fault (domain 3). Scale bar = 1 mm. (e) Elongate bunches of fibrous illimanite aligned in the L3 extension lineation (domain 6). Scale bar = 1 mm. (f) Small faults subparallel to the Crowduck Bay fault cut through the hinge of an F3 fold. Note the disruption of the competent sandstone layers that contain pre-D3 quartz veins (southern end of domain 6). Brunton compass for scale.

Fig. 4. Simplified geological map of the study area depicting the fault traces, extent of the nine structural domains, and the orientation of the S3 cleavage and the L3 extension lineation. Lower hemisphere equal area projections are shown for S3 (+), L3 (.) And F3 (*) for each domain except domain 4 where S3 and L3 are absent. Note the change from southeast-plunging L3 in domains 1–3 to northeast-plunging in the northern domains. CBF = Crowduck Bay fault; CBS = Crowduck Bay syncline; HLA = Herb Lake anticline; HLF = Herb Lake fault; KF = Kiski fault; RLF = Roberts Lake fault; RLS = Roberts Lake syncline; SBF = Stuart Bay fault; SF = Stuart Lake fault.

Table 2
Description of the L3 extension lineation, its distribution, its timing relative to peak metamorphism, and the overprinting relationships observed between L3/S3 and other structural generations. Refer to Fig. 4 for location and extent of the domains. Abbreviations: CBF = Crowduck Bay Fault, RLF = Roberts Lake Fault, bi = biotite, cb = carbonate, chl = chlorite, chtd = chloritoid, fsp = feldspar, gt = garnet, hbl = hornblende, qtz = quartz, sill = sillimanite, st = staurolite

Domain	Minerals/objects defining L3 extension lineation	Overprinting relationships	L3 development and distribution	S3/L3 timing relative to peak metamorphism
1	Fragments in volcanic breccias vesicles, cb pods, fsp and qtz in volcanic and intrusive rocks	L3 and S3 overprint S2a, and south limb of F2b fold	Lineation is well developed throughout most of this domain	
2	Clasts in conglomerate, qtz and fsp in all rock types, micas	L3 and S3 overprint S2a and hinge of F2b fold	Moderately well developed in west of domain, absent to east	chl and rare chltd aligned in S3, but bi and gt overgrow S3
3	Fragments in volcanic breccias, vesicles, cb pods, fsp and qtz in volcanic/intrusive rocks, bi pods in pillow selvages, amygdales	L3 and S3 overprint S2a, and north limb of F2b fold	Lineation is very well developed and is locally more intense than S3, L3 and S3 are most intense close to CBF	hbl varies from aligned in S3/L3 to random and cross cutting (Fig. 5d)
4	Not developed			
5	hbl and fsp in gabbro, hbl–rich pods, fsp phenocrysts in volcanic/intrusive rocks	Unclear	Poorly developed	
6	Conglomerate clasts, fragments in volcanic breccia, bi pods, chl pods, hbl and fsp in gabbro, sill in high grade rocks	S3 overprints S2a, but pre-S3/L3 structures are rare (S2a is subparallel to S3 except in F3 hinges)	Intense to moderate development, best developed and most intense close to CBF	S3 deflected by st, but overgrown by gt (Fig. 5c), local sill aligned in L3 (Fig. 5e)
7	bi in metasediments	S3 locally overprints S2a, but pre-S3/L3 structures are rare	Moderate development in schists, poor development in the large granitoids	S3 deflected by st, but overgrown by gt
8	Clasts in conglomerate, bi and qtz in metasediments, qtz and fsp in small granitoid	F3, S3, and L3 overprint S2a and F2a	L3 best developed close to RLF, not observed >800m from fault	S3 deflected by st, but overgrown by gt
9	hbl and fsp in amphibolites, cb pods in altered rocks	Little evidence, S3 locally overprints S2a	Moderate development close to RLF	hbl varies from aligned in S3 to random

steep, but gradually varies from northeast- to east- to southeast-plunging (Fig. 4). At any given location, the L3 extension lineation shows the same orientation on both sides of the Crowduck Bay fault (e.g. compare domains 6 and 7; Fig. 4). Extension lineations in the Hayward Creek area on the west side of Wekusko Lake (~3 km west of domain 1) plunge southeast similar to those in domain 1 (Gilbert, 1993).

F3 folds are best developed within the Burntwood Group turbidites and are tight to isoclinal with thickened hinges and thinned limbs. Hinges of mesoscopic F3 folds are commonly truncated or disrupted by cleavage-parallel faults (Fig. 5f). Map scale F3 folds include the Crowduck Bay syncline and the overturned Roberts Lake syncline, which sits in the footwall to the Roberts Lake fault. The F3 fold axes and S3/S2a intersection lineations are generally parallel (or subparallel) to the L3 extension lineation (Fig. 4); although the Herb Lake anticline has a similar orientation to D3 folds, this structure is interpreted as D2 because S3 clearly cuts across the hinge of this fold near the lake shore (Fig. 4, north part of domain 3).

3.3. Crowduck Bay fault

The Crowduck Bay fault (Gordon and Gall, 1982) strikes north to northeast and is interpreted to dip east similar to the S3 cleavage. The fault itself is poorly exposed, but its trace is indicated by truncation of units, juxtaposition of different units (Fig. 2), and intense fabric development (e.g. in the mafic pillow lavas of domain 3; Fig. 6a and b). The shearing is heterogeneous and lozenges of relatively undeformed pillows (1–20 in wide) are preserved between shear zone strands. The shear zone rocks are altered to chlorite–carbonate–quartz schist. The presence of hornblende porphyroblasts, which cut across the fabric of the altered mafic rocks, indicate that both alteration and ductile deformation initiated prior to or early during prograde metamorphism (Fig. 5d). The shear zone fabric associated with the fault is parallel to S3 outside of the fault zone and S3 becomes less well developed farther away from the fault. There are few kinematic indicators associated with the ductile fabrics along the Crowduck Bay fault. However, the southerly deflection of older structures (e.g. the F2a Herb Lake anticline, the D2a Kiski Fault and the F2b Puella Bay syncline) adjacent to the Crowduck Bay fault is consistent with sinistral displacement on the fault (Figs. 2 and 4). Rare dextral shears (510 cm wide and up to a few metres long) of uncertain age occur in felsic rocks outside the fault zone in the south of domain 6. In domain 3, veins and dykes adjacent to the fault show symmetrical boudinage

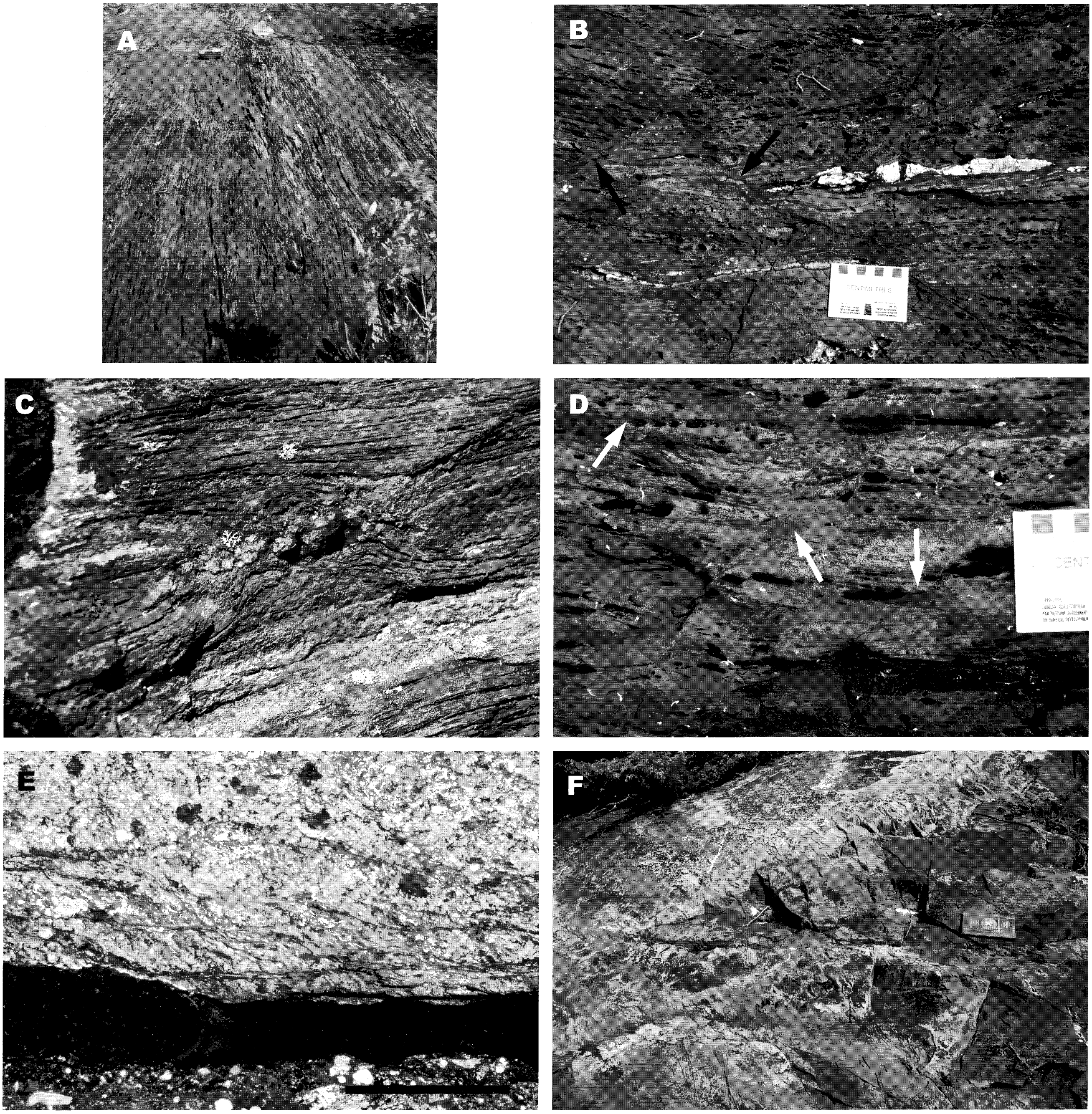


Fig. 6. (a) Intense S3 parallel fabric within mafic volcanic rocks along the Crowduck Bay fault (domain 3). Lens cap in foreground is 65 mm. (b) Close-up of the shear zone fabric shown in (a). Note the boudinage of a quartz vein that has been cut by later dextral fractures. The dextral fractures form part of a conjugate set (arrows) that is associated with later brittle-ductile movement on the Crowduck Bay fault. (c) Approximately symmetrical foliation boudinage in intense S3 fabric along the Roberts Lake fault. Note quartz filling boudin neck. Field of view is ~300 mm. (d) Pseudotachylyte filled fractures (arrows) occur parallel to the intense S3 parallel shear fabric along the Crowduck Bay fault and as conjugate fractures. (e) Sinistral shear bands parallel to pseudotachylyte-filled fracture along the Crowduck Bay fault. Scale bar = 1 mm. (f) Sinistral offset (~1 m) along pseudotachylyte-filled fracture that is subparallel to S3 and the Crowduck Bay fault. Notebook is 205 mm long.

in both the horizontal and vertical planes (i.e. chocolate tablet boudinage).

A component of dip-slip displacement on the Crowduck Bay fault is indicated by the juxtaposition of units along its length. The Burntwood Group turbidites occur on the west side of the fault, but the rocks east of the fault have been uplifted and eroded to remove the Burntwood Group, which is interpreted to have previously been thrust over the entire Wekusko Lake area (Connors et al., 1999). The component of dip-slip displacement on the Crowduck Bay fault decreases to the north until the Burntwood Group occurs on both sides of the fault at about 10 km north of Fig. 2 (Frarey, 1950).

3.4. Roberts Lake fault

The Roberts Lake fault (Frarey, 1950; Bailes, 1985) varies from southeast to southwest striking and dips 40–60° north, and is characterised by well developed planar and linear fabrics in the fault zone. The fault places mafic volcanic rocks of the North Roberts Lake block, which are unconformably overlain by Missi Group, over the top of Missi Group sandstones. Mafic rocks in the immediate hanging wall of the fault are altered to quartz carbonate ± biotite assemblages. The main cleavage and extension lineation associated with the fault are interpreted as S3 and L3 based on their timing relationships to peak metamorphic minerals (as discussed above) as well as the evidence for overprinting of an older cleavage (i.e. S2) by S3. S3 and L3 are best developed along the Roberts Lake Fault and show a consistent orientation on both sides of the fault. S3 is oriented subparallel to the Roberts Lake fault and L3 plunges to the northeast (Fig. 4). Similar to the relationships observed along the Crowduck Bay Fault, S3 intensifies close to the fault (Fig. 6c) and no overprinting relationships can be distinguished between S3 and the fabric in the fault zone. Foliation boudinage is locally observed near the fault (Fig. 6c), but it is roughly symmetrical and does not indicate a movement direction. In thin section, shear bands and oriented quartz aggregates (at an angle to S3) indicate a northeast over southwest sense of movement, parallel to the L3 extension lineation.

Frarey (1950) interpreted the Roberts Lake fault to die out west of Roberts Lake, but the absence of the middle and lower conglomerate units of the Missi Group in the footwall of this structure, and truncation of the D2a Kiski thrust fault, together suggest substantial movement on the Roberts Lake fault (Fig. 2). There is no evidence for the presence of the Roberts Lake fault to the west of the Herb Lake fault, suggesting that the Roberts Lake fault either merges with or is truncated by the Herb Lake fault (Fig. 2). Unfortunately, the area where the two faults approach each other is poorly exposed and the exact position of the Roberts Lake fault remains uncertain.

3.5. Herb Lake fault

The Herb Lake fault occurs along the contact of the western Missi Group and the Herb Lake volcanic rocks, but is not exposed in outcrop. This contact is generally subparallel to layering in both units and was previously interpreted as stratigraphic (Armstrong, 1941; Frarey, 1950). However, east of Lucky Island (Fig. 2), the hinge of the F3 Crowduck Bay syncline is truncated against the Herb Lake volcanic rocks to the east. The western Missi Group–Herb Lake volcanic package contact therefore must be a fault that was active syn- to post-F3 folding. The Herb Lake fault trends southwest and either merges with, or is truncated by, the D3 Crowduck Bay fault south of Lucky Island (Fig. 2).

3.6. Regional metamorphism

Peak metamorphic conditions in the Wekusko Lake area were attained coeval with development of the S3 cleavage and L3 extension lineation (Table 2). Metamorphic grade east of the Crowduck Bay fault ranges from biotite to sillimanite grade and increases northward and eastward (Gordon and Gall, 1982). Gordon and Gall (1982) mapped several isograds (Fig. 2), but the paucity of suitable rock types hampered their work. Briggs and Foster (1992) estimated *P–T* conditions of 525–625°C and 2.5–5 kbar in andalusite- and sillimanite-bearing rocks in the Niblock Lake area, ~7 km northeast of Roberts Lake. Peak metamorphic conditions in the Wekusko Lake area were attained at 1810 Ma (David et al., 1996).

3.7. Late-D3 to post-D3 deformation

Brittle-ductile structures that postdate S3 are widespread along the Crowduck Bay fault (Fig. 6d–f). These features include mm-scale, mica-rich shears, thin quartz veins, and fractures filled with cataclasite, pseudotachylyte, or gouge. Development of structures such as shear bands immediately adjacent to the pseudotachylyte bands indicates these cataclastic structures formed during brittle-ductile deformation (Fig. 6e). This suite of brittle-ductile structures typically occur at a small angle ($<10°$) to S3, and overprint both S3 in the wall rocks and the shear zone fabric developed along the fault. The cataclastic fractures are almost exclusively sinistral (~90%) in asymmetry (Fig. 6e and f), and offsets range from 10–200 cm, but average 40–100 cm.

There is little evidence for post-D3 deformation with the exception of a few east-northeast-trending faults and a northeast-plunging fold, which overprints the Roberts Lake fault and S3 (Fig. 2 and stereonet for domain 9 in Fig. 4). Post-D3 northeast- to east-plunging folds are more common to the north of the study area in higher grade rocks.

4. Discussion

In order to assess the significance of the dispersion in the L3 extension lineation it is necessary to consider several questions: (i) did this lineation form during a single deformation event or more than one; (ii) is the change in orientation primary or is it related to subsequent overprinting; and (iii) if it is primary then how did this variation in orientation develop and what does it tell us about deformation in the THO during this time period? First, however, it is necessary to assess the geometry of D3 structures in the study area in order to put the development of the L3 lineation into its proper geometry and structural setting.

4.1. Relationships between the Crowduck Bay, Herb Lake and Roberts Lake faults

Ductile movement on the Crowduck Bay fault is interpreted to have been coeval with development of S3 based on: (i) the strain gradient in S3 approaching shear zones associated with the fault; (ii) the close association between S3 and small scale mica-rich shear zones (Fig. 5b); (iii) the commonly sheared limbs on F3 folds (Fig. 5f); (iv) the consistent orientation of S3 and the L3 extension lineation across the fault; (v) the similar timing relationships of the fault zone fabric and S3 relative to peak metamorphism; and (vi) the similar orientation of the shear zone fabric and S3 relative to peak metamorphism.

The Crowduck Bay fault remains steeply east dipping and relatively straight throughout the study area (except for the main bend), is associated with a steep fabric, and shows no evidence of large scale overprinting by younger structures. In fact, the D3 structures represent the youngest major deformational event recognised in the study area. This, therefore, suggests that this structure formed as a steep fault. Although it has been inferred to have largely accommodated strike-slip motion, the juxtaposition of units across the fault suggests oblique movement, with the dip-slip component (east side up) increasing to the south.

Several observations along the Crowduck Bay fault favour a component of sinistral displacement rather than dextral: (i) the locally developed clockwise orientation of S3 relative to the fault; (ii) the sinistral asymmetry of overprinting of S2a by S3; (iii) the southerly deflection of older structures adjacent to the fault; and (iv) the abundant evidence for sinistral displacement associated with the post-S3 brittle-ductile structures along the fault zone. Although the age of the brittle-ductile structures on the Crowduck Bay fault cannot be directly constrained, this stage of movement is considered likely to represent the progression from ductile to brittle deformation resulting from post-metamorphic uplift and cooling in the Wekusko Lake area, and there is no reason to interpret any major changes in the sense of displacement on the fault. The small-scale dextral shears that have been noted outside the fault zone are of uncertain age and not considered significant given their rare occurrence. On a more regional scale, sinistral displacement is supported by detailed studies of other structures related to the collision of the Archean Superior craton, which is considered responsible for D3 deformation. These features include the boundary structure itself (e.g. Lewry, 1981; Green et al., 1985; Hoffman, 1988), as well as a series of subparallel structures in the Thompson Nickel belt (Fig. 1; Bleeker, 1990a,b).

The sinistral movement on the Crowduck Bay fault was combined with east-side-up dip-slip displacement that is interpreted to have occurred during the main ductile phase of deformation. If the dip-slip movement had occurred at a later time, then the L3 extension lineation should vary in plunge across the fault, and this is clearly not the case. The moderately north-dipping Roberts Lake fault is interpreted as a thrust fault based on several observations: (i) the rocks in the hanging wall are older; (ii) the footwall syncline verges southward; and (iii) locally developed shear bands indicate southwest displacement of the hanging wall. The spatial association between the Roberts Lake fault and S3/L3, and the consistent orientation of these fabrics from hanging wall to footwall across the fault (Fig. 4) indicate syn-D3 movement on this fault, similar to that on the Crowduck Bay fault. This interpretation is further supported by truncation of the D2a Kiski fault by the Roberts Lake fault (Fig. 2).

The Roberts Lake fault has previously been postulated to continue to the east of the study area as an unnamed fault that shows only minor displacement (Bailes, 1985). However, this is inconsistent with the significant movement on the rest of the fault. It is considered more likely that the fault either merges with, or is truncated by, the Niblock Lake fault (Fig. 7). The observation that the Niblock Lake

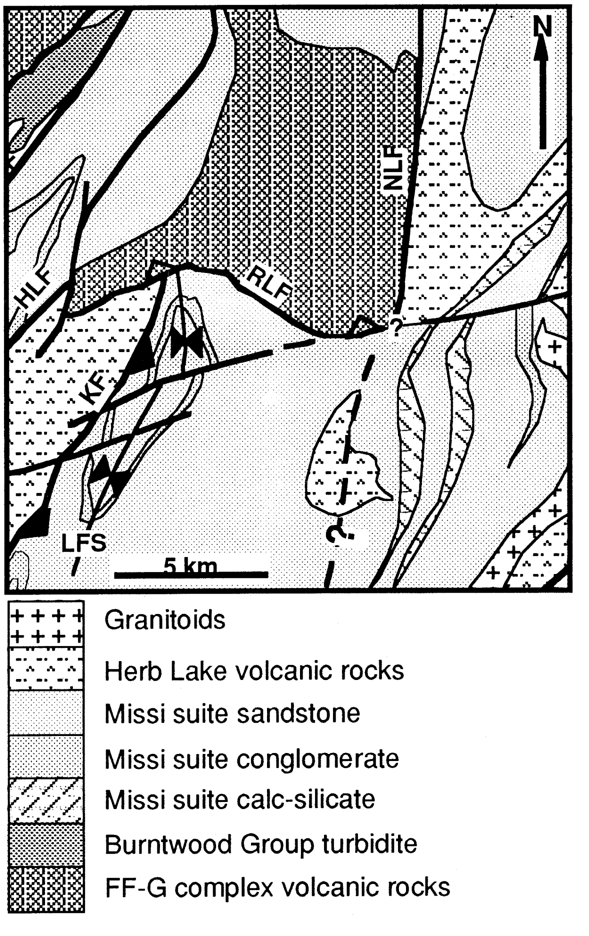


Fig. 7. Simplified geological map depicting the mapped position of the Niblock Lake fault (NLF) relative to the Roberts lake (RLF) and Herb Lake faults (HLF). It is unlikely that the Roberts Lake fault continues east of the Niblock Lake fault. The east–west fault in this area only has minor offset and is probably a later structure. CBF = Crowduck Bay fault; FF–G = Flin Flon–Glennie complex; KF = Kiski fault; LFS = Lostfrog Lake syncline.

fault 'intersects' the Roberts Lake fault at the point where displacement on the latter fault appears to suddenly die out, supports the interpretation that the Roberts Lake and Niblock Lake faults are indeed related. The minor fault to the east is more likely to represent the continuation of one of the late east-northeast-trending faults that cut the Lostfrog Lake syncline (Fig. 7).

The timing of movement on the Herb Lake fault is constrained by three observations: (i) it cuts an F3 fold hinge; (ii) it merges with, or is cut by, the D3 Crowduck Bay fault; and (iii) it merges with, or cuts, the D3 Roberts Lake fault. This requires that the Herb Lake fault was active at the same time as the other two faults (i.e. during D3). The Herb Lake fault probably formed as a splay to the Crowduck Bay fault, based on the similarities in orientation and age, and is therefore interpreted to have accommodated sinistral, east-side-up displacement.

In summary, the Crowduck Bay and Herb Lake faults are interpreted as steeply east dipping, strike-slip to oblique-slip faults with sinistral displacement, whereas the Roberts Lake fault is interpreted as a moderately dipping, south-verging thrust fault. The field and thin section evidence require that these three faults were active contemporaneously despite their variations in orientation and movement. Although the Niblock Lake fault has not been studied in detail, it is tentatively interpreted as a D3 steep, sinistral oblique slip fault similar to the Crowduck Bay and Herb Lake faults. Coeval thrusting on the Roberts Lake fault and interpreted sinistral displacement on the Herb Lake and Niblock Lake faults leads to the hypothesis that the Roberts Lake thrust fault formed at a restraining bend in the overall Crowduck Bay/Herb Lake–Niblock Lake fault system (Fig. 7).

The dip-slip component of the oblique movement on the Crowduck Bay fault increases to the south, as indicated by both the steepening extension lineation and the evidence for flattening at a high angle to the fault (i.e. chocolate tablet boudinage). This flattening, in conjunction with strike-slip movement, suggests that D3 deformation occurred in a transpressional deformation regime, with varying degrees of partitioning between strike-slip and northwest–southeast shortening components. This is the setting in which the complex pattern of the L3 extension lineation developed.

4.2. Two generations vs. primary variation vs. reorientation of L3

Despite the variations in orientation, the L3 extension lineation is interpreted to represent a single fabric generation based on several key observations: (i) the extension lineation is developed on the S3 cleavage regardless of its orientation or the orientation of S3; (ii) the variations from gentle northeast to steep northeast to steep southeast plunges are gradational (Fig. 4); and (iii) there is no evidence for an age variation for L3 across the study area (i.e. it shows the same timing relationships with respect to metamorphic assemblages regardless of its orientation; Table 2). The L3 extension lineation is therefore attributed to D3 synmetamorphic deformation throughout the study area.

The critical question now is whether or not the variation in the orientation of the L3 extension lineation is primary or whether it was reoriented during subsequent deformation. There are four main hypotheses involving reorientation of L3 that can be tested in this context: (i) folding; (ii) reorientation due to deformation within the plane which contains the lineation (i.e. the S3 cleavage); (iii) progressive rotation of the S3 cleavage; and (iv) late block rotation.

In order to determine whether the variation in L3 results from folding of a single precursor orientation, all measurements of the extension lineation were plotted on a lower hemisphere projection (Fig. 8a and b). The L3 lineations show a locus which gives a very weak preference to a partial small circle around an axis of ~30° toward 90° with a half apical angle of 45°, and an even weaker preference for a great circle with a pole of 15 → 291 (Fig. 8a and b). Poles to S3 were also plotted on a lower hemisphere projection to test for folding and show a weak preference about a great circle defining a y-girdle with a fold axis of 74 → 110 (Fig. 8). The preference, however, is considered weak in all cases, and no post-D3 folds of similar orientation have been observed along the Crowduck Bay fault where L3 changes plunge (both the F2a Herb Lake anticline and the F2b Puella Bay syncline are overprinted by S3 and U; Figs. 2 and 4). More importantly, S3 and the Crowduck Bay fault remain steep northeast-striking even where L3 varies from gentle (20°) northeast-plunging to steep (80°) northeast-plunging, confirming that a simple fold cannot explain the variation in

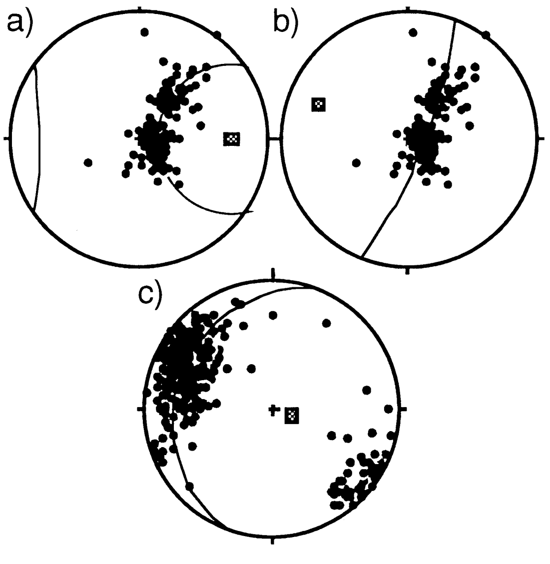


Fig. 8. Equal angle lower hemisphere projections of L3 extension lineation measurements for all domains ($N = 185$) and poles to S3 from domains 1–7 ($N = 283$; S3 readings from domains 8 and 9 are left out due to the obvious folding of S3, which is unrelated to the variation in L3). (a) L3 shows a weak preference to a small circle with an axis plunging 30 → 090 and a half apical angle of 45°. (b) The 'best fit' great circle to the L3 data is a poor fit and is sufficient to explain the variation in the data. (c) Poles to S3 show a poor fit to great circle with a pole of 74 → 110.

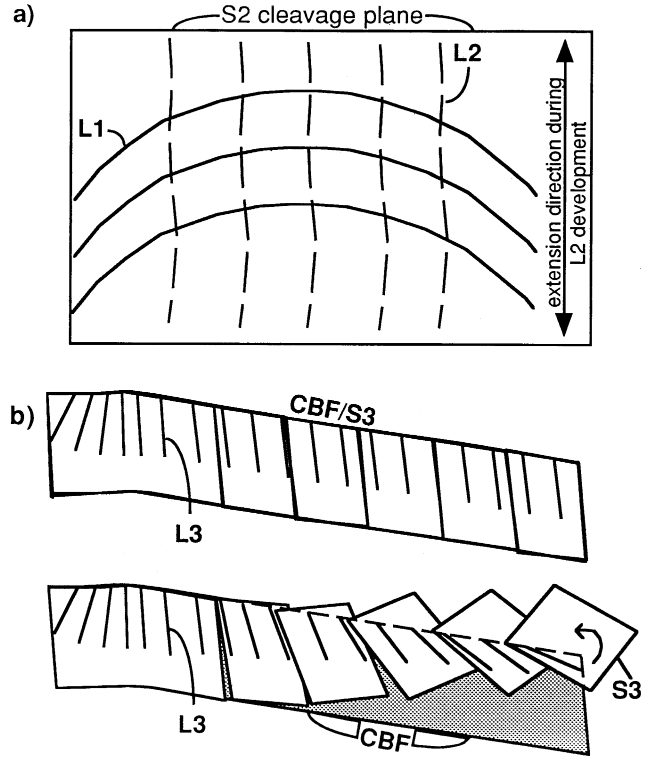


Fig. 9. (a) Reorientation of an early (L1) due to extension parallel to the plane in which the L1 lineation developed. In this example, the younger L2 lineation is at a high angle to the older L1 lineation. (b) A possible mechanism for overprinting an early steep lineation by rotation of the cleavage plane in which the lineation developed. View looking west at the Crowduck Bay fault and the S3 cleavage parallel to the fault.

the extension lineation. This also implies that the bend in the Crowduck Bay fault is likely to be primary, and is supported by the observation that the angle between S3 and the fault changes at the bend.

The second hypothesis involves reorientation of a lineation without obvious folding of the plane in which it lies. For example, Holcombe et al. (1991) described marked folding of an older, subhorizontal extension lineation within the plane of a younger, steep foliation, which was associated with a steep extension lineation (Fig. 9a). However, this hypothesis is difficult to apply to the Wekusko Lake area, where the effects of post-D3 deformation appear to be relatively minor.

The third hypothesis can be best evaluated in the area north of Lucky Island where the L3 lineation trends northeast, but the plunge varies from ~80° to ~20°. In this region, progressive rotation of the S3 cleavage about an axis perpendicular to the cleavage (anticlockwise, looking west) could account for the transition in the plunge of the lineation (Fig. 9b). However this would require a rotation of at least 60°, which is difficult to envisage without uplift of significantly deeper structural levels to the north. Although the metamorphic grade does increase to the north, it only varies from garnet–staurolite–biotite (in turbidites) to sillimanite–bearing (sillimanite–muscovite–quartz–K-feldspar in sandstones) within the area where the change in plunge occurs. In addition, no structures that could have accommodated this rotation and uplift have been observed.

The final hypothesis involves late rotation of fault blocks along the Crowduck Bay fault and represents a variation on the previous hypothesis. Whereas the previous hypothesis involved a similar degree of rotation of the S3 cleavage on both sides of the fault, this one necessarily involves differential rotation of separate fault blocks on either side of the fault. Although the L3 extension lineation changes orientation along the length of the Crowduck Bay fault, the orientation is always consistent across the fault (Fig. 4). This, therefore, precludes any late block rotation in order to account for the variations in the orientation of the L3 extension lineation.

The four hypotheses evaluated here cannot adequately account for the observed dispersion in the L3 extension lineation. The variation in the lineation is therefore interpreted as primary, as is the bend in the Crowduck Bay fault near Lucky Island.

4.3. Primary development of the L3 extension lineation

In order to assess the significance of a primary variation in the L3 orientation, it is critical to evaluate its relationship with the major faults. First, the orientation of the L3 extension lineation along the Roberts Lake fault is uniformly northeast-plunging (Fig. 4, domains 8 and 9), consistent with south-directed thrusting on this north-dipping structure. In contrast, the entire variation in the L3 orientation can be observed along the length of the Crowduck Bay fault, suggesting a more complex movement pattern associated with this structure (Fig. 10).

One obvious feature to consider in order to explain the more complex movement pattern is the bend in the Crowduck Bay Fault, which roughly corresponds to the change in trend of the extension lineation from NE to SE. If this change in the fault orientation resulted in a buttress effect during fault movement, then it is possible that it had an influence on the orientation of the lineation. However, given that this bend represents a releasing bend during sinistral displacement on the fault, rather than a restraining bend, it is considered unlikely that the bend is responsible for much, if any, of the dispersion in the lineation orientation. It is also considered unlikely that 'scissor-style' movement on the fault is responsible for the change in lineation orientation. This style of fault movement would result in a change in the dip-slip component of displacement from normal to reverse along the fault, whereas the fault consistently shows east-side-up displacement throughout the study area.

There is first-order congruence between the shallowing of the plunge of the L3 extension lineation and the increase in metamorphic grade from south to north along the Crowduck Bay fault. This style of geometric change is common in thrust belts, and where these structures developed coeval

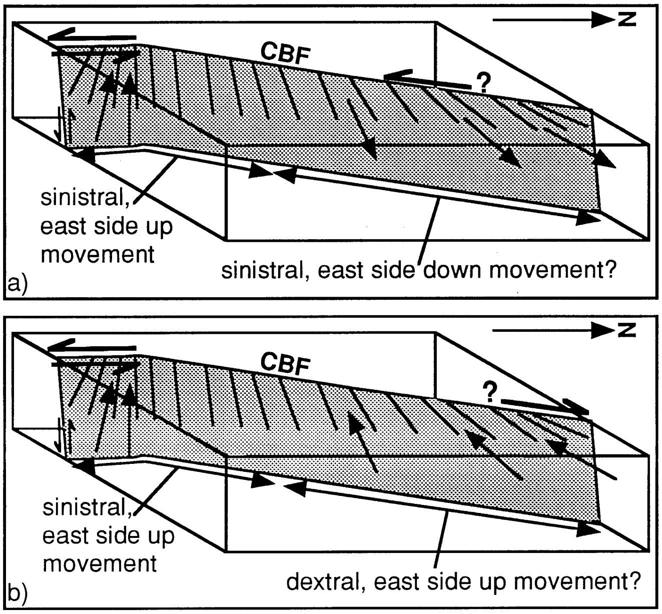


Fig. 10. Schematic block diagram depicting the variation in the orientation of the L3 extension lineation along the length of the Crowduck Bay fault. Kinematic indicators and relationships between the major faults imply sinistral, east block up movement. The southeast-plunging L3 along the south part of the fault is consistent with this sense of movement. However, the northeast-plunging component along the north part of the fault implies either sinistral, east block down (a) or dextral, east block up displacement (b) and is not consistent with the rest of the data.

with metamorphism, the change in structural style can be interpreted to have occurred with paleodepth at the time the structures formed (c.f. Murphy, 1987). A transition from steep to shallow structures with paleodepth can be interpreted to reflect increasing shear strain with depth (e.g. Sanderson, 1982) and/or a change in rheology with depth. The latter interpretation is favoured here given that the rheology is likely to have changed significantly with the change in metamorphic grade with paleodepth. Although this interpretation can explain the change from a steep NE plunge to a gentle NE plunge, it cannot directly account for the change from the steep NE to the steep SE plunge along the southern part of the Crowduck Bay fault.

In fact, when the change in orientation along the length of the Crowduck Bay fault is considered in relation to the displacement on the fault, a significant problem is evident. The southeast-plunging L3 lineation (at the south end of the study area) and the component of east-side-up movement together indicate sinistral movement on the Crowduck Bay fault, assuming that displacement was parallel to L3 (Fig. 10). This interpretation is consistent with the kinematic interpretation of the Crowduck Bay–Herb Lake–Roberts Lake–Niblock Lake fault system, outlined above, as well as the regional interpretations. However, along the north part of the Crowduck Bay fault, the NE-plunging orientation of the extension lineation suggests *east block down* movement during sinistral displacement, assuming that displacement was parallel to L3 (Fig. 10). The orientation of the L3 lineation on the northern part of the Crowduck Bay fault is therefore inconsistent with the rest of the evidence for sinistral transpression with east block up displacement.

This inconsistency suggests that the structural setting cannot be explained by a simple D3 sinistral-strike/oblique-slip system with a thrust fault (Roberts Lake fault) developing in a restraining bend. This implies a complexity in the deformation regime during this stage of deformation in the Wekusko Lake area. A look at the deformation regime in the surrounding region at this time provides a possible explanation for this phenomenon.

4.4. The transition from D2 to D3 deformation

The timing of D2 and D3 deformation events relative to regional metamorphism appears to vary across the southeastern THO and may provide an explanation for the apparent inconsistencies in the D3 structural model discussed above. D2 folds and thrust faults at both Wekusko Lake and File Lake, which occurs ~60 km to the west (Fig. 1b), initiated prior to ca. 1835 Ma plutonism (1839 + 5/−4 Ma at Reed Lake (Stern, pers. comm., 1997); 1834 + 8/−6 Ma at Wekusko Lake (Gordon et al., 1990); and 1832 ± 2 Ma at File Lake (David et al., 1996)). In the File Lake area, south-directed thrusting continued until after the peak of thermal metamorphism (ca. 1810 Ma; Figs. 11 and 12a and b; Connors, 1996; David et al., 1996; Connors et al., 1999). At File Lake and Snow Lake (Fig. 1b), upright northeast-trending D3 folds formed soon after the metamorphic peak and are attributed to ~northwest–southeast shortening at a high angle to the earlier D2 transport direction (Fig. 12c; Kraus and Williams, 1994; Connors, 1996). In contrast, the D3 structures described in this paper, initiated within the east Wekusko Lake area *during* peak

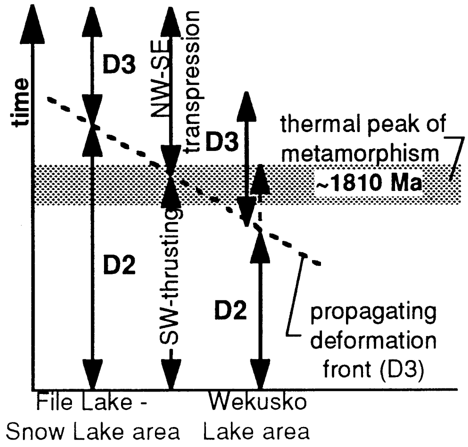


Fig. 11. Diagram summarising the timing relationships between D2 southwest-directed thrusting, D3 northwest–southeast transpression and peak metamorphism at File Lake and Wekusko Lake. The shaded zone indicates the timing of the thermal peak of metamorphism. This diagram shows that D2 southwest-directed thrusting and D3 transpressional northwest–southeast shortening both occurred during peak metamorphic conditions.

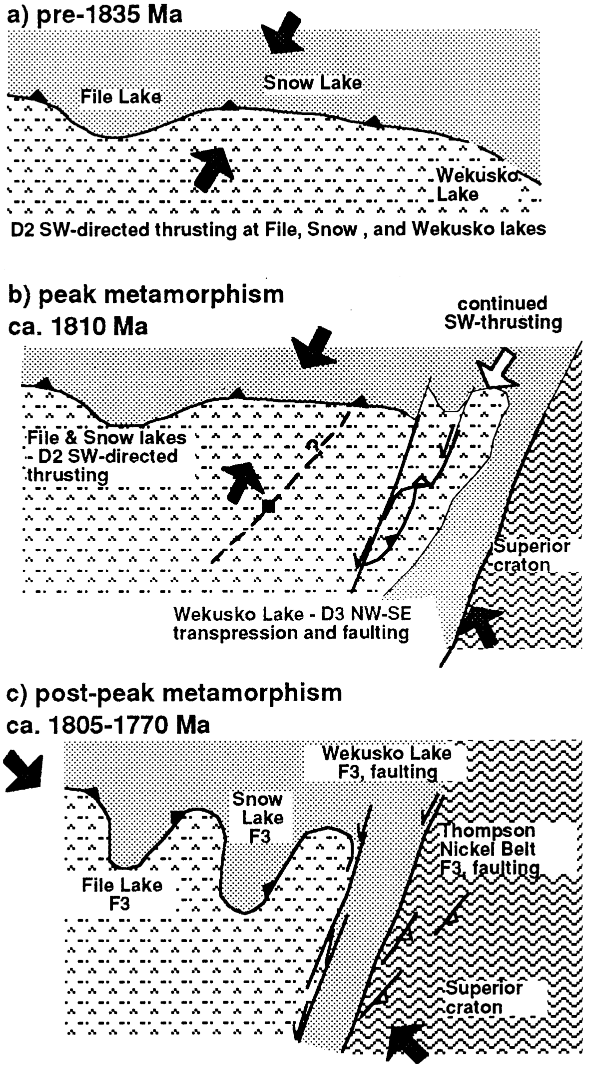


Fig. 12. Schematic representation of the relative timing of D2 and D3 deformation in the eastern THO. (a) The first stage of D2 southwest-directed transport initiated throughout the eastern THO prior to ca. 1835 Ma plutonism. The transport direction is inferred to be southwest at Wekusko Lake similar to that throughout the THO. (b) At the time of peak metamorphism, southwest-directed transport continued at File and Snow Lakes, but transpressional northwest–southeast shortening had initiated at Wekusko Lake. (c) Northwest–southeast shortening progressively moved westward after the metamorphic peak and resulted in map scale folds at File and Snow lakes. The data for the Thompson Nickel belt is taken from Bleeker (1990a,b).

metamorphism (Figs. 11 and 12b). The effect of D3 deformation in the east Wekusko Lake area was to reorient D2 structures into a regional-scale, moderately northeast-plunging F3 antiform (Fig. 12b) with several D3 faults cutting through its hinge and eastern limb (Fig. 12b and c).

This difference in timing of D3 deformation relative to metamorphism (Figs. 11 and 12b) implies that either: (i) D3 deformation initiated at the eastern edge of the orogen and progressed westward; or (ii) a metamorphic front propagated eastward, with peak metamorphic conditions being reached during southward thrusting at File Lake (D2), but not until D3 northwest–southeast transpressional shortening at Wekusko Lake. The metamorphic isograds are consistently ~east–west striking west of Wekusko Lake (e.g. Fig. 1b; Bailes and McRitchie, 1978; Gordon, 1989; Kraus and Menard, 1997), and therefore do not support an eastward propagating metamorphic front. A westward propagating deformation front is therefore proposed to account for the change in the style of deformation during regional peak metamorphism (Fig. 12b), which is assumed to be contemporaneous from at least File Lake to east Wekusko Lake (Fig. 1b). The interpretation of a west-propagating deformation front suggests that the transition from D2 southwest-directed thrusting to D3 northwest–southeast transpressional shortening spanned regional peak metamorphism and may have been prolonged and complex.

Given the evidence for D2 southwest-directed thrusting to the west of the study area, during development of the D3 structures at Wekusko Lake, it is reasonable to assume that, although the development of the major D2 structures shown in Fig. 2 was already complete at this time, a component of southwest-directed transport continued in the east Wekusko Lake area (Figs. 11 and 12b). In this scenario, development of the gentle northeast-plunging component of the L3 extension lineation is interpreted to reflect distributed subhorizontal ductile flow related to a continued component of D2 shortening, whilst at the same time the steep D3 structures developed due to the initiation of northwest–southeast transpressional shortening (Fig. 13). The gradual steepening of the lineation and the increasing dominance of steep structures, dip-slip movement, and flattening strain towards the southern part of the area, suggest that the effects of D2 overlap with D3 and die out rapidly to the south (at the current level of exposure). This implies a transition from a subhorizontal to steep transport direction, due to the relative influence of the two competing deformation regimes (Fig.

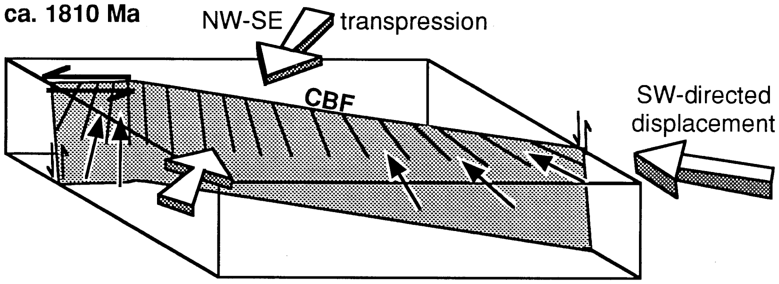


Fig. 13. Schematic block diagram depicting the combined effects of coeval southwest-directed transport and northwest–southeast transpression in the Wekusko Lake area. These competing deformation regimes resulted in disturbed subhorizontal flow along the northern part of the Crowduck Bay fault where a continued component of D2 deformation dominated and steep oblique-slip movement on the southern part of the fault where D3 transpressional shortening dominated. The competing effects of the two deformation regimes resulted in the observed dispersion in the orientation of the extension lineation.

13). The increasing component of transpressional shortening to the south is consistent with the increasing dip-slip offset and the chocolate tablet boudinage.

It is important to note that the change from D3 dominant to D2 dominant style of deformation occurs with increasing metamorphic grade to the north. As discussed previously, the change from a steep northeast plunge to a gentle northeast plunge is interpreted to reflect a change in rheology with increasing metamorphic grade (i.e. an increase in paleodepth). D3 transpressional shortening appears to have dominated higher in the crust at lower metamorphic grade (garnet–biotite grade), whereas D2 southwest-thrusting dominated at a deeper level in the crust at a higher metamorphic grade (staurolite–garnet–biotite to sillimanite–biotite to K-feldspar melt). This interpretation implies that, although the two deformation events overlapped in time, they may have been largely partitioned within the crust and may not have affected the same rocks at the same time.

4.5. *The role of the Superior craton during the D2–D3 transition*

The north-northeast-trending boundary between the Thompson Belt (Superior craton) and the Reindeer Zone (Fig. 1) has been interpreted as a sinistral strike-slip fault by most workers (e.g. Lewry, 1981; Green et al., 1985; Hoffman, 1988; Bleeker, 1990a,b). Bleeker (1990a,b) suggested that oblique collision between the Superior craton and the Reindeer Zone (THO) occurred at ca. 1.80 Ga and was partitioned into sinistral strike-slip motion along the boundary fault and orthogonal convergence in the Thompson Belt to the east. Previous studies (e.g. Hoffman, 1989; Lewry et al., 1990; Connors, 1996; Hajnal et al., 1996; Ryan and Williams, 1996, 1999; Kraus and Williams, 2001) have shown that structures related to oblique collision with the Superior craton are distributed across the THO and reflect northwest–southeast shortening and sinistral transpression associated with structures parallel to the Superior boundary (i.e. orogen parallel). The similarity in the orientation of structures and sense of movement, and the proximity of the Wekusko Lake area to the boundary with the Superior craton (~50 km; Fig. 1), together suggest that the D3 transpressional structures in the east Wekusko Lake area are related to the oblique collision between the Reindeer Zone and the Superior craton. This implies that collision with the Superior craton was initiated 10 My earlier than previously interpreted at 1810 Ma, the estimated age of peak metamorphism (David et al., 1996), because D3 structures formed at peak metamorphic conditions in the Wekusko Lake area (Figs. 3 and 12).

The older D2 structures are attributed to an earlier collisional event between the juvenile rocks of the THO (Reindeer Zone) and the Sask craton prior to ca. 1.84 Ga (Ansdell et al., 1995; Ashton et al., 1996). The evidence for coeval D2 (southwest-thrusting) and D3 (northwest–southeast transpressional shortening) deformation in the eastern THO suggests that post-collisional convergence between the Reindeer Zone and the buried Sask craton continued through to the oblique collision between the Reindeer Zone and the Superior craton at ca. 1810 Ma. The competing effects of the two collisions resulted in migration of the D3 deformation front from the Superior–Reindeer boundary zone westward across the Reindeer Zone, generating a complex deformation regime that may have been partitioned within the crust at ca. 1810 Ma in the east Wekusko Lake area. The observed dispersion in the L3 extension lineation in the study area is attributed to the contemporaneous activity of D2 and D3 deformation regimes at peak metamorphic conditions.

5. Conclusions

In general terms, the variation in the extension lineation at east Wekusko Lake is attributed to a combination of both steep and subhorizontal displacement, similar to the interpretations of Holdsworth and Strachan (1991), Lagarde and Michard (1986), Brun and Burg (1982) and Hansen (1989). However, there is no evidence that partitioning of strike-slip) and thrust deformation on to separate faults (c.f. Lagarde and Michard, 1986; Holdsworth and Strachan, 1991), is responsible for the change in the extension lineation, as it occurs along the strike of the Crowduck Bay fault, and neither is there evidence for a temporal progression from thrust to strike-slip faulting during lineation development (c.f. Hansen, 1989). The interpretation presented here is most similar to that of Brun and Burg (1982), who proposed a combination of thrust and strike-slip motion on a single fault, which they related to collision between plates with irregular margins. The interpretation favoured here suggests that the subhorizontal and steep components of displacement on the Crowduck Bay fault may reflect the combined effects of two successive, but overlapping, collisional events that may have been partitioned within the crust.

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