TECTONICS, VOL. 29, TC5013, doi:10.1029/2009TC002537, 2010

Softening the lower crust: Modes of syn-transport transposition around and adjacent to a deep crustal granulite nappe, Parry Sound domain, Grenville Province, Ontario, Canada

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Received 17 May 2009; revised 29 April 2010; accepted 7 May 2010; published 28 September 2010.

[1] The Parry Sound domain is a granulite nappe-stack transported cratonward during reactivation of the ductile lower and middle crust in the late convergence of the Mesoproterozoic Grenville orogeny. Field observations suggest the following with respect to the ductile sheath: (1) Formation of a carapace of transposed amphibolite facies gneiss derived from and enveloping the western extremity of the Parry Sound domain and separating it from high-strain gneiss of adjacent allochthons. This ductile sheath formed dynamically around the moving granulite nappe through the development of systems of progressively linked shear zones. (2) Transposition initiated by hydration (amphibolization) of granulite facies gneiss by introduction of fluid along cracks accompanying pegmatite emplacement. Shear zones nucleated along pegmatite margins and subsequently linked and rotated. The source of the pegmatites was most likely subjacent migmatitic and pegmatite-rich units or units over which Parry Sound domain was transported. Comparison of gneisses of the ductile sheath with high-strain layered gneiss of adjacent allochthons show the mode of transposition of penetratively layered gneiss depended on whether or not the gneiss protoliths were amphibolite or granulite facies tectonites before initiation of transposition, resulting in, e.g., folding before shearing, no folding before shearing, respectively. Meter-scale truncation along high-strain gradients at the margins of both types of transposition-related shear zones observed within and marginal to Parry Sound domain mimic features at kilometer scales, implying that apparent truncation by transposition originating in a manner similar to the ductile sheath may be a common feature of deep crustal ductile reworking. **Citation:** Culshaw, N., C. Gerbi, and J. Marsh (2010), Softening the lower crust: Modes of syn-transport transposition around and adjacent to a deep crustal granulite nappe, Parry Sound domain, Grenville Province, Ontario, Canada, *Tectonics*, *29*, TC5013, doi:10.1029/2009TC002537.

1. Introduction

[2] Pervasive ductile deformation in the middle levels of doubly thickened crust plays a major role in orogenic processes (e.g., channel flow or emplacement of ductile nappes) and although melting controls much of such deformation [e.g., *Beaumont et al.*, 2001; *Rosenberg and Handy*, 2005], other processes remain significant. Thus, the spatial and temporal distribution of rock strength throughout the crust serves as critical input for conceptual and numerical models predicting strain distributions and related processes.

[3] The Central Gneiss Belt of Ontario (Figure 1) makes up much of the southwestern Canadian Grenville Province. The Central Gneiss Belt, comprising exclusively high-grade metamorphic rocks, represents the deep levels of a doubly thickened orogenic crust and is thus a natural laboratory for the study of deep orogenic processes and rheology. Several massif-like regions within the Central Gneiss Belt resisted deformation during Grenvillian orogenesis. Yet, in places, much of the softer portions of the orogenic crust surrounding the “hard lumps” appear to have been derived from these relatively rigid blocks. This study considers the specific nature of the softening processes that formed a ductile envelope at the margins of one of these blocks as well as numerous shear zones within.

[4] The Parry Sound domain is a granulite facies gneiss klippe that lies within a stack of upper amphibolite facies thrust sheets in the Central Gneiss Belt. Along part of its contact with the amphibolite facies sheets, it exhibits a newly recognized, amphibolite facies carapace derived from Parry Sound domain granulites (tp, Figure 1). Necessary consequences of this recognition include a reevaluation of the character and geometry of the southwestern and southeastern boundaries of the Parry Sound domain. This type of structural and rheological modification may be important for understanding deep crustal nappe emplacement [cf., *Culshaw et al.*, 2006; *Jamieson et al.*, 2007], as well as providing insight into the significance of geometry of gneissosity of different ages at these and comparable boundaries.

2. Domain Tectonostratigraphy

2.1. Polycyclic and Monocyclic Domains

[5] The individual major units of the Central Gneiss Belt, “domains,” have been interpreted as thrust sheets [*Davidson et al.*, 1982; *Davidson*, 1984; *Culshaw et al.*, 1997; *Carr et al.*, 2000].

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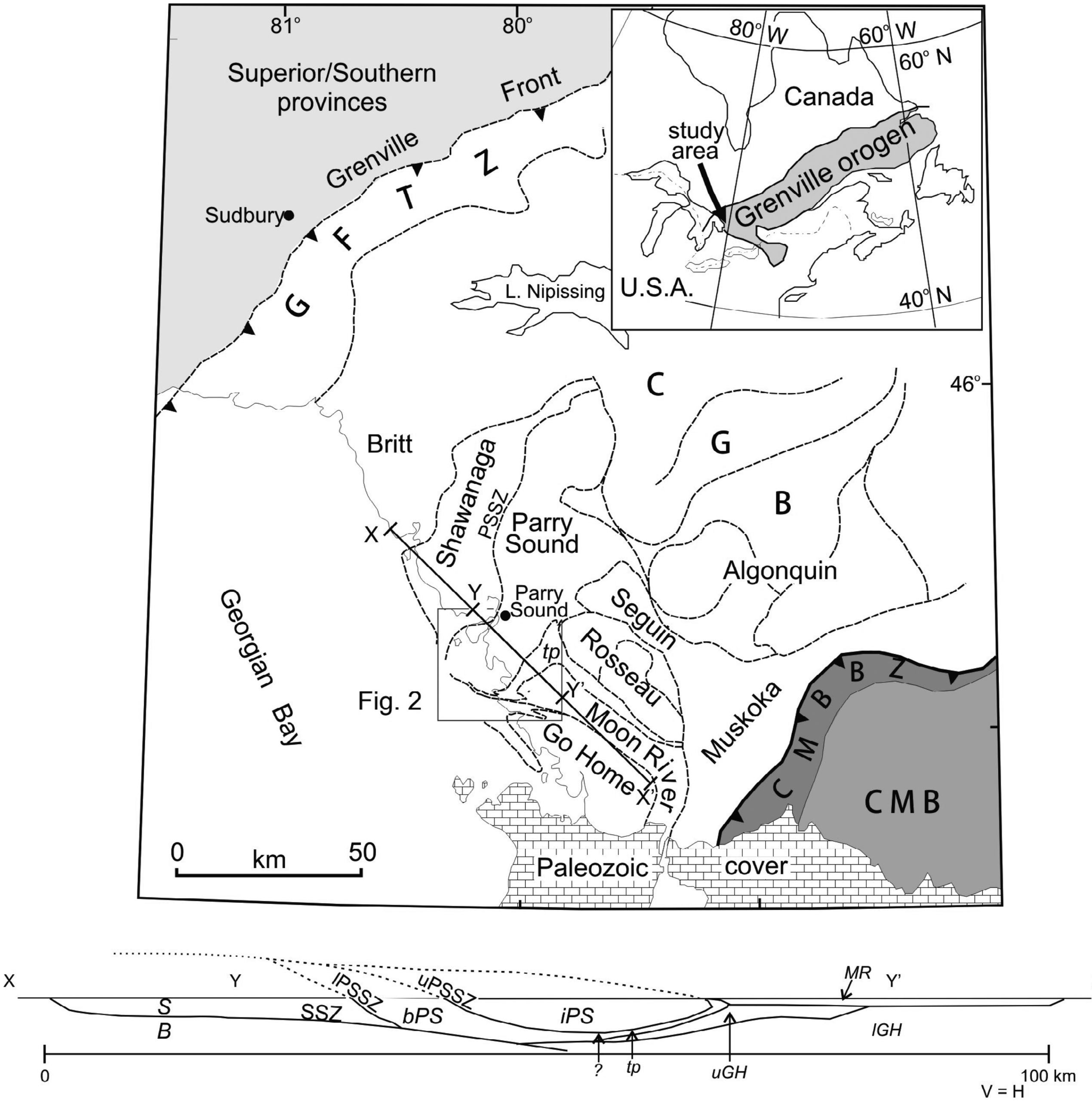


Figure 1. Location of study area (Figure 2). Lithotectonic subdivisions. GFTZ, Grenville Front Tectonic Zone; CMBBZ, Central Metasedimentary Belt Boundary Zone; CMB, Central Metasedimentary Belt; CGB, other domains of the southwestern Central Gneiss Belt. Central Gneiss belt domains on cross-section X-X′: B, Britt; S, Shawanaga; bPS, basal Parry Sound; iPS, interior Parry Sound; MR, Moon River; uGH, upper Go Home; lGH, lower Go Home. Other structures or tectonic units: lPSSZ, lower Parry Sound shear zone; uPSSZ, upper Parry Sound shear zone; SSZ, Shawanaga shear zone; tp, transposed gneiss (new unit), limit of confidently projected extent indicated (see text for discussion). Cross section after *White et al.* [1994] and *Culshaw et al.* [1994, 1997].

[6] Polycyclic domains (units affected by both Grenvillian and mid-Proterozoic metamorphism) lie at the lowest structural level of the Central Gneiss Belt. Along Georgian Bay, these include, in the north, the Britt domain, containing Paleoproterozoic to Mesoproterozoic polycylic ortho- and paragneiss of Laurentian affinity. In the south the lower Go Home and lower Rosseau domains consist of predominantly amphibolite facies orthogneisses and migmatites of Laurentian heritage and contain a minor polycyclic component (Figures 1 and 2). The extensional (top to the southeast)

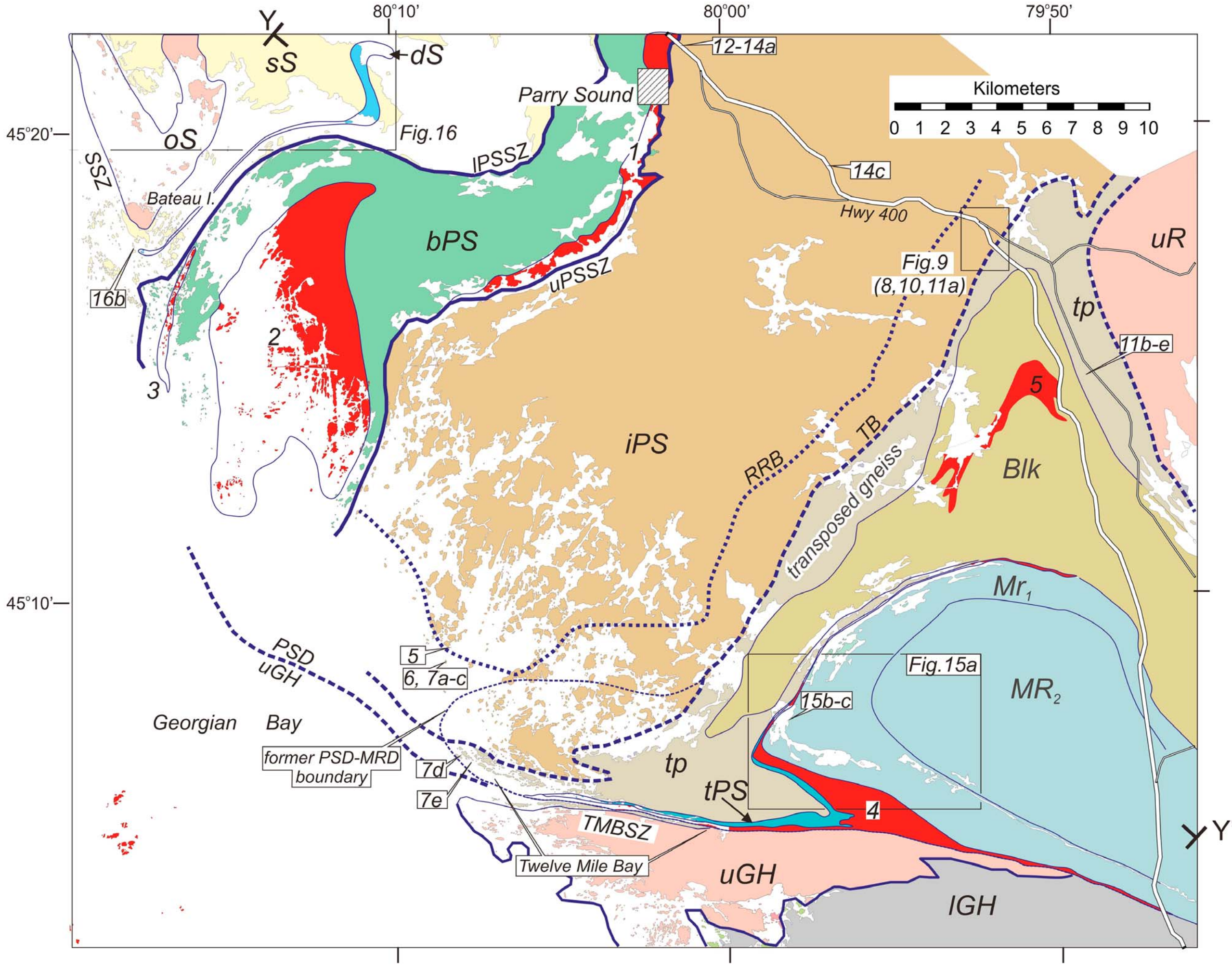


Figure 2. Southwest end of Parry Sound domain and parts of contiguous domains between Highway 400 and Georgian Bay. Shawanaga domain: oS, Ojibway; sS, Sand Bay gneiss associations; dS, Dillon Schist. Parry Sound domain: bPS, basal Parry Sound; iPS, interior Parry Sound; tPS, Twelve Mile Bay assemblage; tp, transposed gneiss unit. Moon River domain: MR$_{1-2}$, interior subdivisions of Moon River domain. Domain of uncertain affinity: Blk, Blackstone gneiss association. Go Home domain: uGH and lGH, upper and lower. Structure: lPSSZ (heavy blue line), boundary at base of Parry Sound domain within lower PSSZ; uPSSZ (heavy blue line), lithological boundary separating lower and upper Parry Sound domain at top of upper PSSZ; TMBSZ, Twelve Mile Bay shear zone; TB (heavy blue line, medium dashes), boundary of untransposed Parry Sound domain gneiss (locally retrogressed with retrograde shear zones) with transposed gneiss; unmarked heavy blue line with medium dashes southwest of TB, extrapolated Parry Sound domain-uGH boundary (see Figure 4) and probable western limit of tp; RRB (blue line, short dashes), approximate limit of retrogression and outcrop scale shear zones within Parry Sound domain; thin blue line, short dashes, former Parry Sound domain–Moon River domain boundary [*Davidson*, 1984] which further northeast coincides with the lower boundary of tp; SSZ, Shawanaga shear zone. Anorthosite and related units: 1–4, anorthosite to leucogabbro gneiss; 5, Blackstone Lake complex of ultramafic rock and lesser anorthositic gneiss. Figure locations: outlined by boxes or point locations indicated by number.

Shawanaga shear zone (Figure 1) is coincident with and reworks a segment of the Allochthon Boundary Thrust which, throughout the Grenville Province [*Ketchum and Davidson*, 2000], separates polycyclic from hanging wall monocyclic domains which have only experienced Grenvillian metamorphism in the interval approximately 1160–1000 Ma. The latter include Shawanaga, upper Go Home, and upper Rosseau and Moon River domains (Figures 1 and 2) which comprise predominantly amphibolite facies ortho- and paragneisses that originated in approximately 1500–1350 Ma continental magmatic arcs [*Carr et al.*, 2000; *Rivers*, 1997; *Slagstad et al.*, 2004a].

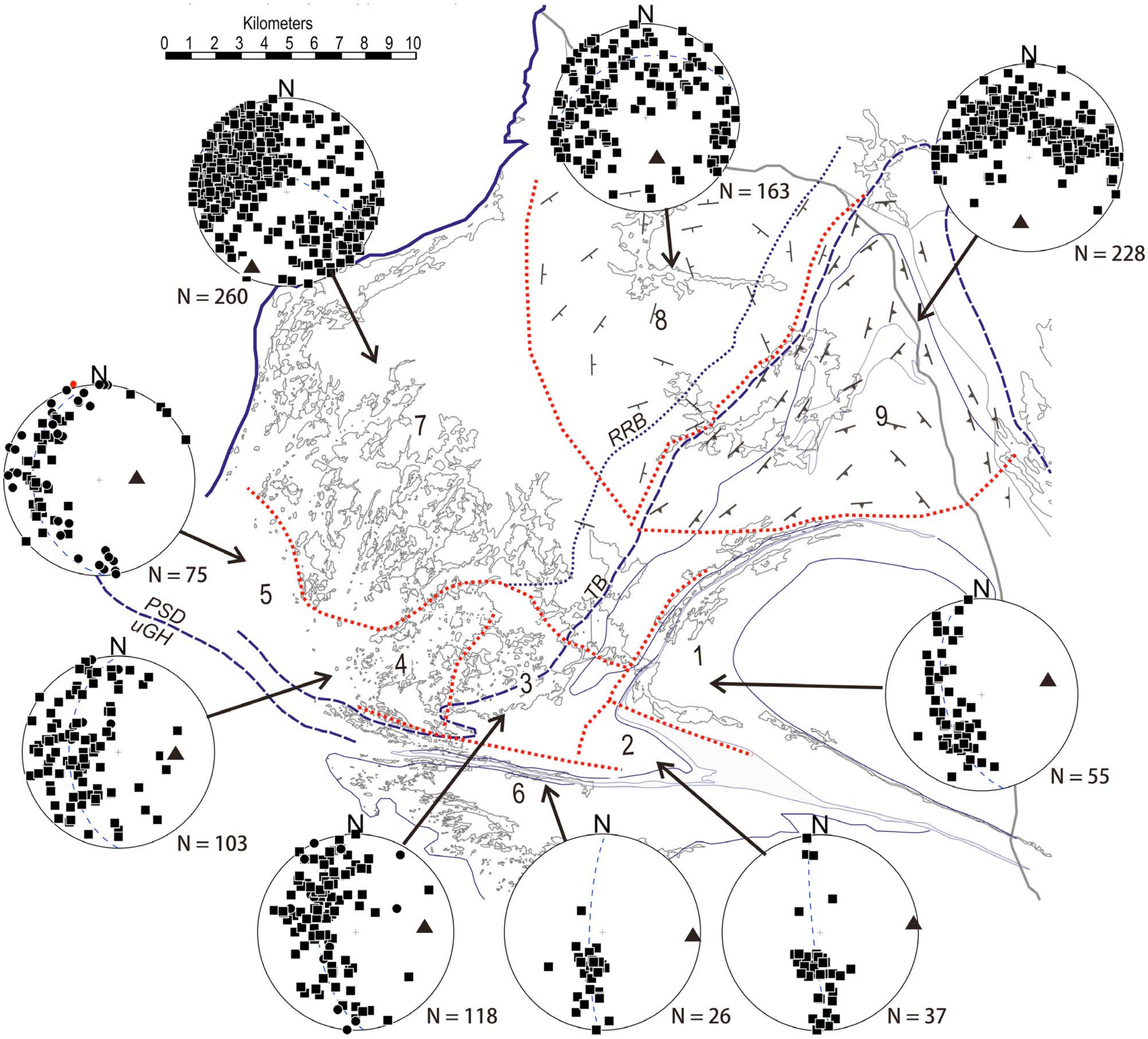


Figure 3. Summary of structure in interior Parry Sound domain and parts of Moon River domain (strike and dip directions indicated for zones 8 and 9). Poles to gneissosity, squares; shear zones, closed circles (zones 3–5 only); number of data indicated; lower hemisphere equal area projection. Triangles on stereo nets are calculated inflections of wall rock layering into shear zone. Unit boundaries and roads as in Figure 2. Zones 3 (north part), 4, and 5 approximately correspond to the "zone of reworking" referred to in text.

2.2. Parry Sound Domain

[7] One of the monocyclic units, the Parry Sound domain (Figures 1 and 2) has several components. The lower Parry Sound shear zone (lower PSSZ) separates the basal Parry Sound domain from Shawanaga domain and is reworked at its western end by the Shawanaga shear zone. The basal Parry Sound domain contains a mixture of orthogneiss, anorthosite, and rocks of supracrustal origin. The dominant fabric-forming mineralogy represents amphibolite facies assemblages that overprint an earlier granulite facies metamorphic event [*Hicks*, 1992; *Wodicka et al.*, 2000]. The upper Parry Sound shear zone (upper PSSZ) separates the basal Parry Sound domain from the interior Parry Sound domain. The upper PSSZ contains both mylonitic granulite gneisses of interior Parry Sound domain protolith and, at lower levels, amphibolite facies high strain gneisses derived from basal Parry Sound domain as well as deformed anorthosite and granitoid orthogneiss sheets. Prominent in the upper PSSZ are thrust sense rotated feldspar and LS fabrics (down-dip lineation) coplanar with widespread northeast striking granulite facies LS fabrics within the interior Parry Sound domain (Figure 3, zone 7). The fabrics are related to the thrusting along the upper strand of the PSSZ within the

Parry Sound domain as early as approximately 1160 Ma. The upper and lower PSSZ converge close to the town of Parry Sound where the two may be distinguished on the basis of protolith. The interior Parry Sound domain is dominantly granulite facies orthogneisses (granitic, through intermediate to mafic compositions) with approximately 1400–1300 Ma igneous ages [*Wodicka et al.*, 1996]. These LS tectonites are accompanied by high-strain layered granulites especially toward the domain margins. The interior Parry Sound domain retains granulite textures but is partly to thoroughly recrystallized at amphibolite facies in a mantle surrounding an unretrogressed core, a zone of reworking (outside the RRB, Figure 2). Much of the retrogression occurs adjacent to shear zones, most less than 1 m wide, which locally form linked systems, offset layering by only a few meters and are often associated with pegmatite.

2.3. Transposed Gneiss Unit: Ductile Mantle of Interior Parry Sound Domain

[8] Toward the Parry Sound domain margins, the zone of reworking gives way to the transposed gneiss unit, a new unit we introduce here. In this unit, Parry Sound domain structures are reworked such that a continuous horizon of new gneissosity is developed by amphibolite facies retrogression and heterogeneous transposition of interior Parry Sound domain fabric to form an envelope around the southern end of the domain (Figure 2).

[9] In detail, the boundary of the transposed gneiss is coincident with the Parry Sound domain–Moon River domain boundary as formerly recognized [*Davidson et al.*, 1982; *Davidson*, 1984] except at its southwest end (Figure 2). The northeastern segment of the transposed gneiss is deformed by an open, gently south plunging, synform (Figure 3, zone 9), the northwest limb of which overlies discordant southwest trending structures in the Parry Sound domain (Figure 3, zone 8) and follows a change of magnetic pattern (Figure 4) southwest toward Twelve Mile Bay (Figures 3–4) where dips change from southeast to NNE across a synform-antiform pair (Figure 2 and zone 1, Figure 3). The transposed gneiss projects along magnetic and bathymetric trends from the Twelve Mile Bay shear zone (see below) to the northwest (Figure 4 and Figure 1, projected extent in cross section). The mapped and projected exterior boundary of the transposed gneiss abuts more than one domain and clearly is not simply a boundary between two domains (Figure 4). As is implicit in the above summary, we interpret the transposed gneiss unit to be a single unit which separates several domains from Parry Sound domain (Figure 1).

2.4. Twelve Mile Bay Shear Zone

[10] The name "Twelve Mile Bay shear zone" signifies the belt of north dipping, highly strained rocks derived from the Twelve Mile Bay assemblage (a thin unit of anorthosite and metasediment with metamorphic history similar to basal Parry Sound domain), the interior Parry Sound domain, and the underlying upper Go Home domain (Figure 2). The occurrence of sparsely developed sinistral and dextral (younger) kinematic indicators associated with linear fabric elements (parallel to inferred hinge lines; Figure 3) suggest a polyphase history for the shear zone. This conclusion is supported by the continuation of strongly deformed units (Twelve Mile Bay assemblage, anorthosite, and the transposed gneiss unit; Figure 2) out of the shear zone northeastward beneath the Moon River domain as well as the inland continuation of an ESE Twelve Mile Bay trending fabric, which suggest, respectively, an early phase in common with initial development of the transposed gneiss and a later one shared with Moon River domain.

2.5. Moon River Domain

[11] The units of the Moon River domain (MR_1 and MR_2; Moon River gneiss association) contain uniform pink and gray gneisses, both of which are leucosome-rich and commonly layered (Figure 2). The Blackstone Lake gneiss association (Blk), consisting of gray gneisses of predominantly granodioritic composition with pink leucocratic lenses, is of uncertain but possible Parry Sound domain heritage. The lower structural boundary of the Moon River domain with Parry Sound domain is inferred to be along the extent of the Twelve Mile Bay assemblage and associated anorthosite across which leucosome-rich migmatitic Moon River domain rocks with no indication of granulitic heritage (but with some evidence for transposed origin, see below) change to the transposed gneiss derived from Parry Sound domain material (Figures 2 and 4).

3. Chronology of Domain Assembly

3.1. Construction of Parry Sound Nappe Stack

[12] In a geochronological framework, the first three episodes of the tectonic history of the allochthonous monocyclic domains involve building the Parry Sound domain nappe stack before or in the early stages of northwest transport of the monocyclic thrust sheets [*Wodicka et al.*, 1996]. Emplacement of the Parry Island anorthosite at approximately 1163 Ma and intermediate pressure–high temperature metamorphism in the basal Parry Sound domain [*Wodicka et al.*, 2000] are (apparently) synchronous with high temperature–high pressure granulite facies metamorphism in the interior Parry Sound domain at approximately 1160 Ma [*van Breeman et al.*, 1986; *Wodicka et al.*, 2000]. Thrusting of the interior Parry Sound domain along the upper PSSZ (Figures 1 and 2) immediately followed (1159–1157 Ma) [*van Breeman et al.*, 1986; *Tuccillo et al.*, 1992; *Wodicka et al.*, 2000] and caused an upper amphibolite facies overprint in the footwall (upper part of the basal Parry Sound domain) [*Wodicka et al.*, 2000]. An amphibolite facies overprint in the lower part of the basal Parry Sound domain is interpreted as marking overthrusting of the interior Parry Sound domain and the upper part of the basal Parry Sound domain onto the lower part of the basal Parry Sound domain at about 1120 Ma [*Wodicka et al.*, 2000].

3.2. Transport of Allochthons

[13] A step-like younging of metamorphic ages downward across the PSSZ toward the contact with the Shawanaga domain covering the period approximately 1160–1100 Ma

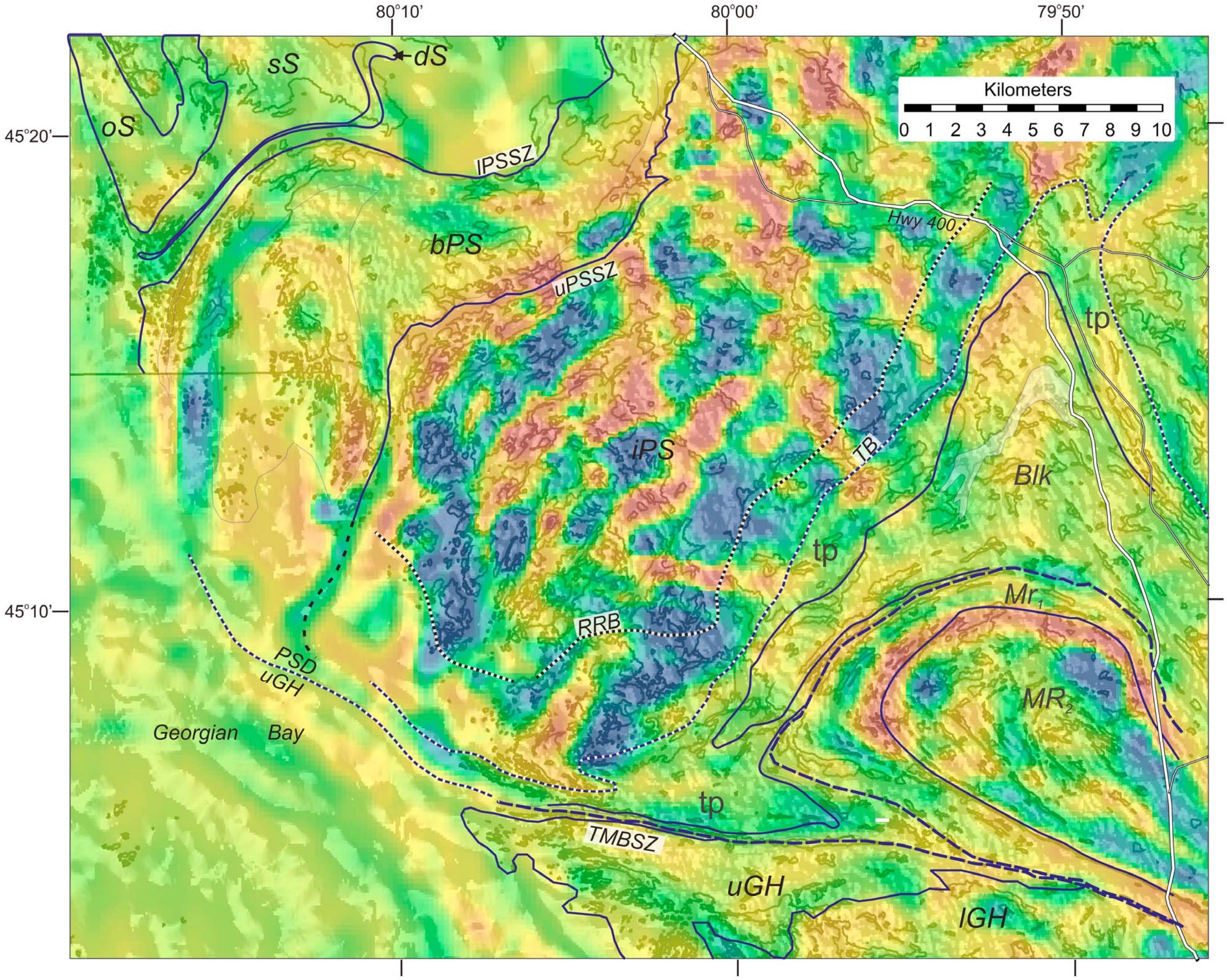


Figure 4. First vertical derivative of total magnetic field [*Canadian Aeromagnetic Data Base*, 2008] draped on topography and bathymetry (courtesy of U. S. NOAA, National Geophysical Data Center) for southwest end of Parry Sound domain and parts of contiguous domains between Highway 400 and Georgian Bay. Key for first vertical derivative magnetic map: dark blue to green, 0.212–0.023 nT/m; light green to yellow, 0.024 to −0.045 nT/m; yellow to red, −0.046 to −0.186 nT/m. Unit boundaries as in Figure 2. The Parry Sound domain-uGH boundary (coarse dashed blue line; lower boundary of tp in west) is projected along bathymetric ridges and magnetic anomalies; a second dashed line indicates projection of uPSSZ.

(1152-1143-1130-1103 Ma) [*Krogh*, 1997; *Krogh and Kwok*, 2005] only partly coincides with the chronology outlined above internal to the Parry Sound domain. The youngest ages of the spectrum (1105–1100 Ma) are however matched at the opposite margin of the Parry Sound domain by ages for metamorphism, deformation and pegmatite emplacement in the newly defined transposed gneiss unit, both in the NE of the unit and along the Twelve Mile Bay shear zone as well as further south in the Moon River domain [*van Breeman and Davidson*, 1990; *Krogh and Kwok*, 2005]. This symmetric pairing of ages in tectonites on opposite margins of the Parry Sound domain suggests similar age of formation of tectonites of the lower PSSZ and the transposed unit, an event(s) postdating assembly of the nappe stack and imposed during its transport.

[14] These events at the margins of the Parry Sound domain overlap with the beginning of the fourth major episode, which dominates metamorphism and deformation in allochthonous monocyclic domains exterior to the Parry Sound domain. In the Shawanaga and Moon River domains, ages of metamorphism and pegmatite emplacement are estimated in the interval 1090–1036 Ma [*Ketchum and Krogh*, 1997; *Krogh*, 1997; *Bussy et al.*, 1995; *Krogh and Kwok*, 2005; *Tuccillo et al.*, 1992; *Slagstad et al.*, 2004a; *Heaman and Le Cheminant*, 1993] with formation of volumetrically significant migmatites in the range 1050–1036 Ma

[*Slagstad et al.*, 2004a; *Bussy et al.*, 1995; *Krogh and Kwok*, 2005]. Migmatization in the upper Go Home and upper Rosseau domains, as pervasive as in the Shawanaga and Moon River domains, is presumably similar in age. The age of a pegmatite emplaced during progressive deformation of the extensional Shawanaga shear zone (tops sheared to southeast) is approximately 1020 Ma [*Ketchum et al.*, 1998].

4. Models of Domain Evolution

[15] A thrust-stacking model of evolution of the domains partially explains the tectonostratigraphy and sequence of ages [e.g., *Davidson*, 1984; *Wodicka et al.*, 2000] but specifically accounts for neither the regionally penetrative deformation fabrics, including the foliation-parallel domain boundaries evident on cross sections, nor the two early phases of deformation restricted to the Parry Sound domain. A conceptual model proposing syntectonic progression from stacking of thrust sheets to penetrative ductile flow [*Culshaw et al.*, 1997] has been superseded by a numerical model based approach [*Jamieson et al.*, 2007] in which impingement of a hard lower crustal block into an early formed thrust stack (e.g., early deformation within Parry Sound nappe stack) caused expulsion and cratonward transport and deformation of nappes (e.g., formation of transposed gneiss and lower PSSZ on margins of Parry Sound domain). During the period of cratonward nappe expulsion, mid-crustal units become involved in a channel-like flow detaching the stiff superstructure from the variably ductile nappes below. In the model interpretation the Moon River, Shawanaga, upper Go Home, and upper Rosseau domains (Figure 2) may represent the midcrustal material, while the Parry Sound domain and lowermost domains (Britt and lower Go Home and lower Rosseau; Figure 1) are lower crustal nappes. These models produce a good approximation of the spatial arrangement of the domains, timing of deformation, conditions of metamorphism, and gross geometry of major deformation features and emphasize the near-pervasive nature of elevated ductile strain. An important point is the models specifically predict early thickening followed by flow (pre-1100 Ma thickening including assembly of Parry Sound domain nappe stack; post-1100 Ma transport history common to monocyclic allochthonous domains). Further, the pervasive nature of the flow explains why gneiss geometry and deformation level are identical and continuous from lower PSSZ down through the Shawanaga domain [*Culshaw et al.*, 1994]; its dynamic and polyphase nature explain features such as Shawanaga shear zone reworking of both the Allochthon Boundary Thrust and the lower PSSZ as well as the suggested polyphase history of the Twelve Mile Bay shear zone.

5. Reworking Domain Margins

5.1. Introduction

[16] Processes illustrated both in the zone of progressive structural reworking and retrogression near Twelve Mile Bay and within and adjacent to the northeast part of the transposed unit are significant for understanding the rheological evolution of the ductile sheath around the margins of the interior Parry Sound domain and may have wider applications. Below, we describe the structures and macroscopic features associated with these processes, focusing primarily on locations marginal to and within the transposed gneiss unit but, in order to highlight the importance of the processes, including other locales such as the northwest margin of the Parry Sound domain (described by others at various scales) [e.g., *Davidson*, 1984; *White and Mawer*, 1992].

5.2. Pegmatites

[17] We describe the pegmatites more fully in the context of individual reworking processes, where emphasis is placed on the field evidence for the central role played by pegmatites and amphibolite facies retrogression in initial stages of transposition. Here we note that pegmatites and amphibolite facies retrogression are present from the earliest stages not only in nearly all shear zones and transposed gneiss in the southwest Parry Sound domain but also within the interior as well as in parts of the PSSZ.

[18] Pegmatites throughout the Parry Sound domain margin are remarkably similar in composition and initial grain size. They consist of quartz–K feldspar–plagioclase ± hornblende ± biotite. The bulk composition of the single pegmatite analyzed to date is in the granite field [*Cox et al.*, 1979]. We have observed no light element–bearing phases, supporting the interpretation that these pegmatites are essentially fluid-rich granitic magmas that have experienced little differentiation. Grain sizes in undeformed pegmatites are commonly in the 2–5 cm range for most phases.

5.3. Initiation of Transposed Unit Adjacent to Twelve Mile Bay Shear Zone: Regional Aspects

[19] In the zone of progressive structural reworking and retrogression of interior Parry Sound domain granulites, north of Twelve Mile Bay shear zone, narrow, variably oriented shear zones transpose retrogressed Parry Sound domain gneissosity and may form linked systems or networks (for summary of mineralogical changes, see Table 1). Continuing displacement and thickening of such linked shear zones [cf., *Fusseis et al.*, 2006] evidently led to the development of the thick zones of transposed gneiss along Twelve Mile Bay (Culshaw et al., manuscript in preparation, 2110). The shear zones and wall rock layering define cylindrical systems (zones 3 and 4, Figure 3) [*Hanmer*, 1984] that have similar plunge to the shallowly plunging, overturned antiform and upright synform (outlined by Twelve Mile Bay assemblage and anorthosite; zones 1 and 2, Figure 3) lying farther east. Northeastward, the boundary of the zone of reworking and retrogression is parallel to but beneath that of the transposed gneiss [*Culshaw et al.*, 2004]. Systems of meter-scale shear zones, typical of those in the zone of reworking, underlie islets at the limit of outcrop (compare zone 5 with zones 3 and 4, Figure 3). These systems are cylindrical, as those farther east, although plunges are significantly steeper (zone 5, Figure 3). The location of the islets with more steeply plunging systems together with the bathymetric and magnetic patterns suggests the zone of

Table 1. Summary of Mineralogy in Wall Rock and Shear Zones[a]

		Mineralogy	
Location	Composition	Unsheared PSD gneiss	Shear zone
iPSD	Mafic	Cpx-Opx-Pl-Hbl±FeOx	Pl-Hbl-Bt-Ttn-Opq
	Granitoid	Pl-Qtz±Kfs±Cpx±Opx±Hbl±Opq±Bt±Grt	
Zone of Reworking	Mafic	Pl-Hbl-Cpx±Opx±Gr±Qtz±Opq±Ttn	Hbl-Pl-Ttn±Cpx±Opq
	Granitoid	Pl-Qtz-Hbl-Kfs-Bt±Cpx±Opx±Opq	Pl-Qtz-Kfs-Bt±Opq
Transposed Gneiss	Mafic	Hbl-Pl-Qtz-Opq±Grt±-Grt±Cpx±Bt±Ttn	Hbl-Pl±Ttn±Qtz±Bt±Cpx±Grt±Opq
	Granitoid	Pl-Qtz-Kfs-Hbl±Opx	Pl-Qtz-Hb±Kfsl±Bt±Ttn±Opq
PSSZ-Mill Lake	Mafic	Pl-Grt-Cpx-Hbl-Opx-Q	Hbl-Pl-Bt-Scp-Q

[a] Interior Parry Sound Domain (iPSD), zone of reworking north of Twelve Mile Bay Shear Zone, transposed gneiss (Twelve Mile Bay and Hwy 400), extensional structure in upper PSSZ along Hwy 400, Parry Sound. Abbreviations: as in the work of *Kretz* [1983], except: Opq, opaque mineral, generally Fe-oxide.

retrogression and reworking can be projected parallel to the extrapolated extent of the transposed horizon (Figure 2).

5.4. Initiation of Transposed Unit Adjacent to Twelve Mile Bay Shear Zone: Outcrop Scale

[20] Focusing on a series of outcrops in the zone of reworked gneiss north of Twelve Mile Bay, we describe field observations and relations relevant to understanding the part played by pegmatites and accompanying fluids and fractures in the process of initiating transposition-related shear zones (Figures 5 and 6).

[21] A 50 m wide, exposure of partially retrogressed layered granitoid and mafic granulite, located close to the boundary of the zone of reworking but within largely unretrogressed granulite (Figure 5), serves as an example of the initiation of the inferred process. The outcrop has three clusters of thin (approximately 0.5–2 cm wide) pegmatite-, granitoid-, and rare quartz-filled veins, each cluster being separated by several meters free of veins. The veins are interspersed with healed fractures and occasional thick (up to approximately 80 cm wide) pegmatites, located in the center of shear zones. The thin veins are predominantly parallel, vertical, and perpendicular to the strike of the granulite layering (NNE, the regional trend of the granulites).

[22] The most primitive of these structures, predominantly in mafic granulite, are healed fractures with millimeter-scale rims of amphibole after pyroxene in the host (Figure 5a i). These may later become filled with quartz and feldspar and generate transcurrent (dextral) motion displacing younger granite-filled veins (Figure 5a ii). Such younger veins typically occur in en echelon arrays which have both extensional and contractional step overs (Figures 5a iii, 5b i, 5c i, and 5d i). All veins evince evidence of brittle fracture such as delicately tapered vein tips (e.g., Figures 5a iv, 5d i, and 5f ii). The walls of many of the veins display evidence of lateral displacement in the brittle stage (Figures 5a ii, 5b ii and iii, and 5c i). Some granite-filled veins formed by brittle fracture have amphibolitized margins containing shear fabrics that indicate a transition to ductile vein-parallel displacement (Figures 5d and 5e). These narrow vein-centered ductile shear zones may be precursors of wider pegmatite-centered (Figure 5f iii) ductile shear zones that deform the brittle-stage veins (Figure 5f i-ii). The healed fractures, veins, and shear zone-centered pegmatites at this location are interpreted as a series of snapshots illustrating a progression from dextral shear-fracturing and filling under high fluid pressure to dextral ductile shear.

[23] An island situated approximately 1 km SSW of the last exposure illustrates both the initial role (as in the previous examples) and subsequent fate of the pegmatites in the development of linked shear zones in the zone of reworking (Figure 6). Relevant to this study are the relations within a unit of layered gneiss containing a well defined system of shear zones (yellow lines in unit 3, Figure 6a). The shear

Figure 5. Granite-filled (quartz-feldspar) veins and dykes in southwest extremity of Parry Sound domain (for location, see Figure 2). (a) Healed fractures with amphibolized margins i, cut syn-granulite granite vein concordant with layering (trending left to right); ii, healed fracture of same generation as i, is now partially quartz-feldspar filled and has relatively wide amphibolized and sheared (dextral) margin; iii, young granite vein has left-handed extensional step over consistent with sinistral shear and is associated with brittle fracture-type tapered vein tips, iv. (b). Array of linked en echelon granite-filled brittle fractures illustrating typical vein spacing (in intermediate granulite), left-handed extensional step overs, e.g., i, and vein-parallel sinistral brittle displacement, ii and iii. (c) Granite-filled vein with right-handed extensional step over, i, consistent with dextral displacement of layering. (d). En echelon veins with granite fill and amphibolized margins in mafic granulite; left-handed step over of tapered vein tips, i, lacks extensional structure, compatible with dextral shear during initial brittle fracturing and continued in ductile regime (fabric in amphibolized margin, arrowed). (e) Detail of a foliated granite-filled brittle fracture now ductilely deformed; dextral displacement of layer (bottom) mirrored by amphibole rich shear fabric at vein margins, i, and fabric within the vein; granulite facies assemblages (glt) flank amphibolite (am). (f). Shear zone (left of line, SZ) deforms granite veins e.g., i, with brittle features, e.g., tapered tips at i and ii; the shear zone center contains a thin pegmatite (highlighted at iii) and deforms older layering (iv); width of photo approximately 1.5 m. Scale in Figures 5a–5e given by 2.5 cm diameter of coin; most veins in the images lie parallel and strike perpendicular to NNW trend of granulite layering.

zones of the system are all dextral, curve anticlockwise with increasing displacement (Figure 6a), and many have deformed pegmatite (foliated and/or displaying pinch and swell structure) lying parallel the median line (center) of the shear zone (i.e., cross-cutting the gneiss layering but parallel and within the shear zone; Figure 7b). Thin deformed pegmatites running at a low angle to individual shear zones account for no more than one or two percent of the total. Comparable to the veins illustrated in Figure 5, the undeformed mafic wall rock (Figures 6a and 7b) between the shear zones contains granulite facies mineralogy, usually in a state of partial retrogression (Table 1), while the shear zones themselves (yellow lines, Figure 6a), whose margins are defined by the layer curvature (Figure 7b), contain thoroughly retrogressed amphibolite facies rock (Table 1). There are other features that link processes on the island to those recognized at the outcrop shown in Figure 5. For example, as at the vein outcrop, unfoliated pegmatite (Figure 7a) cuts unit 3 layered gneiss at a high angle only where there are few, low-displacement shear zones and the strike of the gneiss is unrotated relative to regional preshear zone strike (N20E; "few SZs," unit 3, Figure 6a). Similarly,

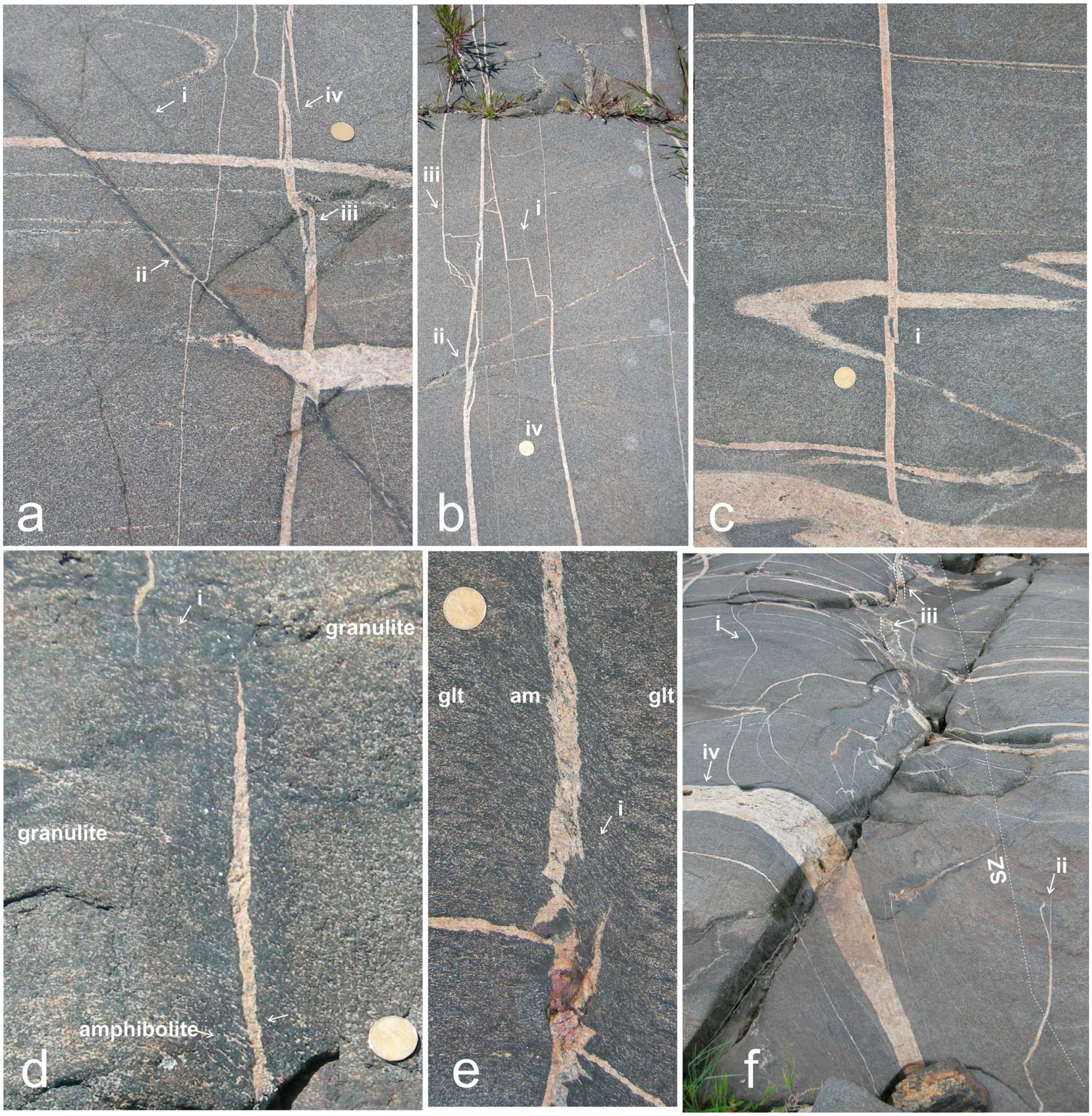


Figure 5

Figure 6. Shear zone network and pegmatites in southwest extremity of Parry Sound domain. (a) Oblique air photograph of Matches Island (location, Figure 2); unit 1, mafic gneiss; unit 2, hornblende-biotite-plagioclase gray gneiss; unit 3, layered gneiss with granitoid and mafic layers; shear zones highlighted in yellow are separated by shear zone walls consisting of layered gneiss (e.g., "SZ wall"); a corridor of high shear strain ("rotated SZs") is separated from least deformed parts of unit 3 ("few SZs", above and below dark dashed lines); location of parts of Figures 6 and 7 indicated by boxes. (b) Close up of unit 1 showing an undeformed thick pegmatite (trending bottom left to upper right) cutting unsheared wall rock; marker horizon shows dextral offset. (c) Detail of shear zone system in unit 3; granitoid layers are twisted into high displacement, shear system of linked dextral shear zones ("SZ a"); to right of this system are many minor shear zones with lesser displacements and most decorated with pegmatites (thin white lines within shears), wall rock layering (mafic and granitoid) is perpendicular to the shear zones in most cases.

amphibolite on a small island (unit 1, Figure 6a, top right) strikes parallel to the regional trend and is cut by thick unfoliated pegmatites (Figure 6b) trending parallel to the previously described veins. As with some granitoid-filled veins at the first location, there is no ductile shear fabric in the amphibolite flanking the pegmatite but dextral brittle offset is evident (compare Figures 6b and 5c). Another link is the presence in some shear zone walls in unit 3 of deformed veins directly comparable to features in the vein array (compare Figure 7c and Figure 5f).

[24] Figures 7d and 7e illustrate two features of the culmination of the process of transposition within Twelve Mile Bay shear zone that mirror some just described from the zone of reworking. The presence of disaggregated pegmatite in the transposed gneiss highlights its ultimate fate in the process of transposition (contrast Figures 7a and 7d); clearly

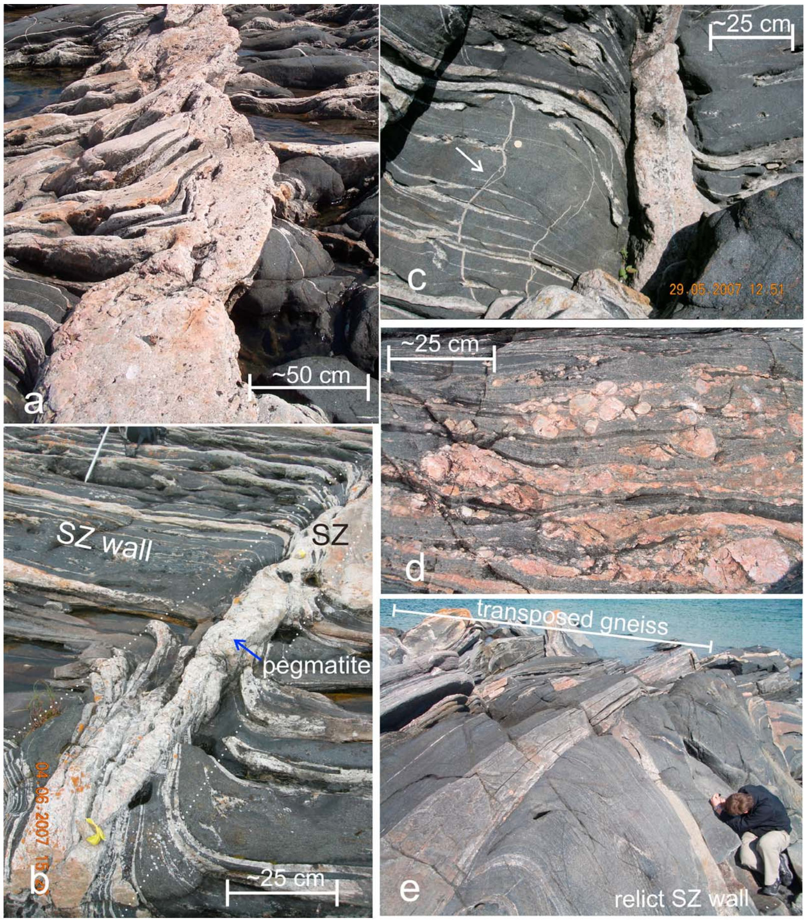


Figure 7. (a) Undeformed pegmatite (i.e., unfoliated, no pinch and swell) emplaced in a fracture with irregularly but weakly deformed walls (from "few SZs", Figure 6). (b) Typical pegmatite decorated shear zone. (c) Deformed granitoid veins (arrow) in wall of pegmatite-decorated shear zone (compare Figure 5f). (d) Disaggregated pegmatite in transposed, mafic layered tonalitic gneiss of Twelve Mile Bay shear zone (width approximately 2 m; location, Figure 2). (e) Detail from a wide swath of transposed gneiss with relict of untransposed mafic gneiss with wall rock-shear zone geometry comparable to that shown by shear zones in Figure 6c (location, Figure 2).

the transposition process outlasts pegmatite emplacement. Disaggregation of pegmatites is mirrored by a major decrease in proportion of shear zone walls relative to transposed gneiss compared to that present at the initiation of shear zones. We suggest large displacement shear zones (e.g., SZa, Figure 6c) link and merge to form wide zones of transposed gneiss with few relicts of wall rock (contrast Figures 6a, 6c, and 7e).

[25] A synthesis of the field data suggests the following interpretation of the sequence leading to transposition of the Parry Sound domain granulite. (1) Intact granulite is fractured under elevated fluid or magmatic pressure; the "fluid" is a component of a hydrous granitoid magma derived from migmatites similar to those below the Parry Sound domain [*Slagstad et al.*, 2004b]; if only H_2O enters, healed fractures with amphibolized rims result (Figure 5a i), otherwise vein fill is quartz, granite or pegmatite (Figures 5a–5f). (2) For the mafic rocks the following reaction is appropriate: Grt + Cpx + H_2O = Hbl + Pl + Qtz. The nature of the strain regime forces brittle fractures with predominant dextral separation (Figures 5a ii and 5c i) which with hydrous softening of the immediate walls of the vein may develop to dextral ductile shears (Figures 5d–5e). (3) Veins and pegmatites are not emplaced into ductile shear zones but predate them (Figures 5d–5f, 6a, and 7a); only amphibolite facies rock is ductilely sheared, i.e., the fluid accompanying pegmatite intrusion softens the granulite (Figures 5d–5e and Table 1). (4) Although the pegmatites were emplaced approximately parallel to the Twelve Mile Bay shear zone, the shear zones rotate with increasing strain to align layering close to the Twelve Mile Bay shear zone trend (note in Figure 6a the orientation of wall rock layering in area "rotated shear zones" compared to that in the arrowed area "shear zone wall"); with further rotation in the transposed gneiss the pegmatites deform and ultimately disaggregate (Figure 7d).

5.5. Initiation and Development of Northeast Segment of Transposed Unit

[26] The zone of reworking, northeast and inland from Twelve Mile Bay lies below the transposed unit. In sympathy with this structural location, shear zones here have similar metamorphic setting (amphibolization and related pegmatite emplacement) but different kinematics compared to those north of Twelve Mile Bay shear zone which overlie the transposed unit. In the northeast, amphibolite facies, thrust-sense shear zones are associated with pegmatites within steeply dipping granulite gneiss of the Parry Sound domain beneath southeast dipping transposed gneiss (Figure 8 and location, Figure 9). Examples of these shear zones include one with a “ramp and flat” structure, boudinage of overlying mafic wall rock indicated by a scar fold (arrow, Figure 8a), transposition (“truncation”) of steep granulite gneissosity and hinge-perpendicular transport (Figure 8a; compare Figure 14a). No footwall of the shear zone is exposed, making interpretation of the geometry of this structure problematic. The nature of smaller pegmatite associated shear zones in the steep granulites is clearer and also reminiscent of some examples already described (Figures 8b–8d). All the narrow, gently inclined pegmatite sheets have marker horizons showing top to northwest separations. But their structural state ranges from undeformed with sharp tips (Figure 8b) and step overs to planar with a thin mantle of grain size reduction (Figure 8c), to boudinaged fragments contained within sheets of grain size reduction (Figure 8d). The step over and displacement sense in the unmylonitized example are consistent with syntectonic vein emplacement, as in examples previously discussed. As in previous examples, the mylonitized veins show abrupt reorientation of granulite layering at their boundaries (Figure 8d).

[27] Figure 9 shows details of structure within the northeast end of the transposed gneiss close to its boundary with the underlying zone of patchy retrogression and reworking in the Parry Sound domain (location Figure 2). Across this boundary, the steeply dipping layered gneissosity of the granulites gives way abruptly to southeast dipping gray granitoid amphibolite facies gneisses. These gneisses are derived by transposition from rock with textures ($G_{f,}$; locations 4–6, Figure 9) suggesting thoroughly retrograde Parry Sound domain protoliths [*Culshaw et al.*, 1989, 1997, 2004] and consistent with the Parry Sound domain-type protolith ages from within this unit outlined by *Krogh and Kwok* [2005] and field observation farther south (see below). Remnants of pegmatites are present in transposed granitoid gneiss close to the boundary but less dismembered pegmatites are common in mafic members as well as in granitoid gneiss to the south of the location depicted in Figure 9. Overall the level of transposition, which is comparable to that within the Twelve Mile Bay segment, may be taken as typical of the transposed gneiss.

[28] Sections, northeast and southwest of Highway 400, serve to illustrate the nature of the reworking (Figure 9, locations 4, 5, and 6). Location 6 displays apparent truncation at map scale of the old gneissosity by the transposed gneiss of the shear zone. The structure of location 5 is simpler: a buttress of amphibolite abuts steep old (Parry Sound domain trend) gneissosity that is transposed to a wide swath of gneiss moderately inclined to the southeast. The transposed gneiss is in turn locally affected by outcrop scale extensional shear bands (arrows at southeast end of section 5, Figure 10). The northwestern end of location 4 is a small transposition system (map, Figure 10) showing the familiar apparent truncation of older gneissosity by transposition forming in a shear zone. In this case, the older gneissosity is steeply dipping before incorporation into the moderately dipping shear zones (section 4, Figure 10). An isolated remnant of old gneiss is truncated on upper and lower margins (map Figure 10 and Figure 11a). The most southeastern sequence on the detailed map shows tight folds of old gneiss with axial surfaces near parallel to the transposition foliation, an apparent intermediate step in the transposition process. This tightly folded sequence gives way upward to transposed gneiss that forms the shallowly inclined limb of a large open asymmetric fold, in which old gneissosity forms the steep limb. The subjacent flat lying transposed gneiss is clearly formed from the steep old gneissosity (above vertical arrow, Figure 10) and contains winged feldspars showing northwest thrust sense parallel the hinges and lineation associated with transposition (map, Figure 10). Envisaged as a single entity, sections 4–6 represent a network of shear zones, characterized by along strike variability (Figure 10). Comparison of the sections 4 and 5 (which are 75 m apart along strike of the transposition foliation) gives an idea of the degree and scale of the heterogeneity of the structures, the differences between section 5 and section 4 being marked (compare at correlation arrows, Figure 10). Nevertheless, although calculated hinges display a scale dependence (compare Figure 9 net 4 and nets on Figure 10 for same section), these transposition systems are cylindrical with most hinges sampled at finest scale trending south to SSE (Figures 9–10, nets), comparable stereo net geometry to that north of Twelve Mile Bay (zones 3–5, Figure 3).

[29] Whereas sections 4–6 show how quite voluminous older material may be preserved in a transposed host, essentially freezing in a partial record of the transposition process, on the eastern limb of the south trending synform close to the boundary with the upper Rosseau domain (Figure 2), transposed gneiss is more voluminous. Old, untransposed

Figure 8. Shear features near contact of Parry Sound domain with transposed gneiss unit. (a) Thrust sense shear zone in Parry Sound domain gneiss. Outcrop sketch shows parts obscured in photo mosaic; hanging wall is layered tonalitic and intermediate granulite gneiss of interior Parry Sound domain (squares, stereo net) underlain by sheared amphibolite facies tonalitic migmatitic gneiss (circles, stereo net); pegmatites, orange; triangle on stereo net is calculated inflection line of shear zone. (b–d) Outcrop sketches of small pegmatite related shear zones in the layered retrogressed granulite. Figure 9 shows locations and shear zone attitudes for Figure 8a (location 1, Figure 9) and Figures 8b–8d (location 2, Figure 9).

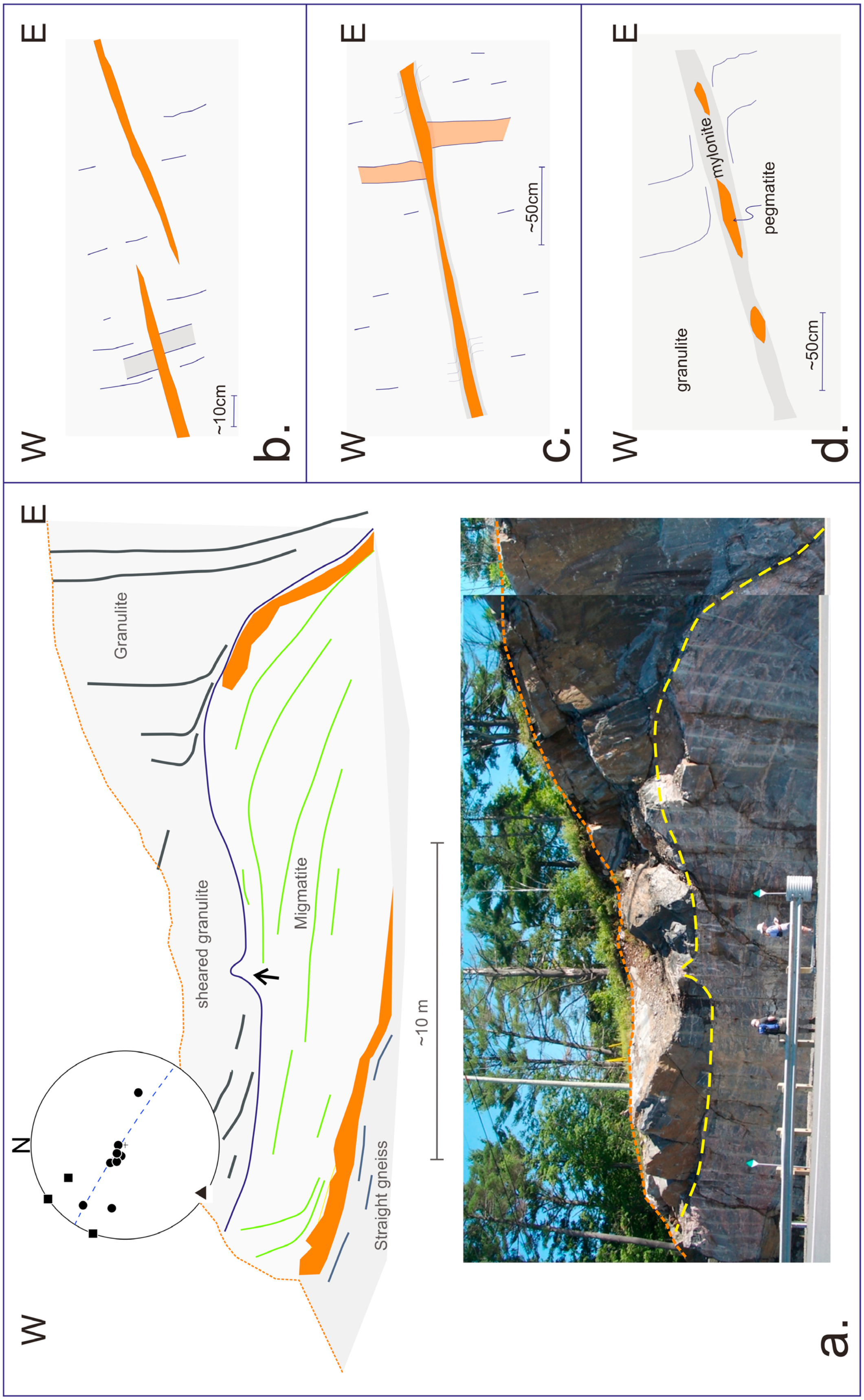

W
E
Granulite
sheared granulite
Migmatite
Straight gneiss
N
~10 m
a.
W
E
~10cm
b.
W
E
~50cm
c.
W
E
granulite
mylonite
pegmatite
~50cm
d.

Figure 8

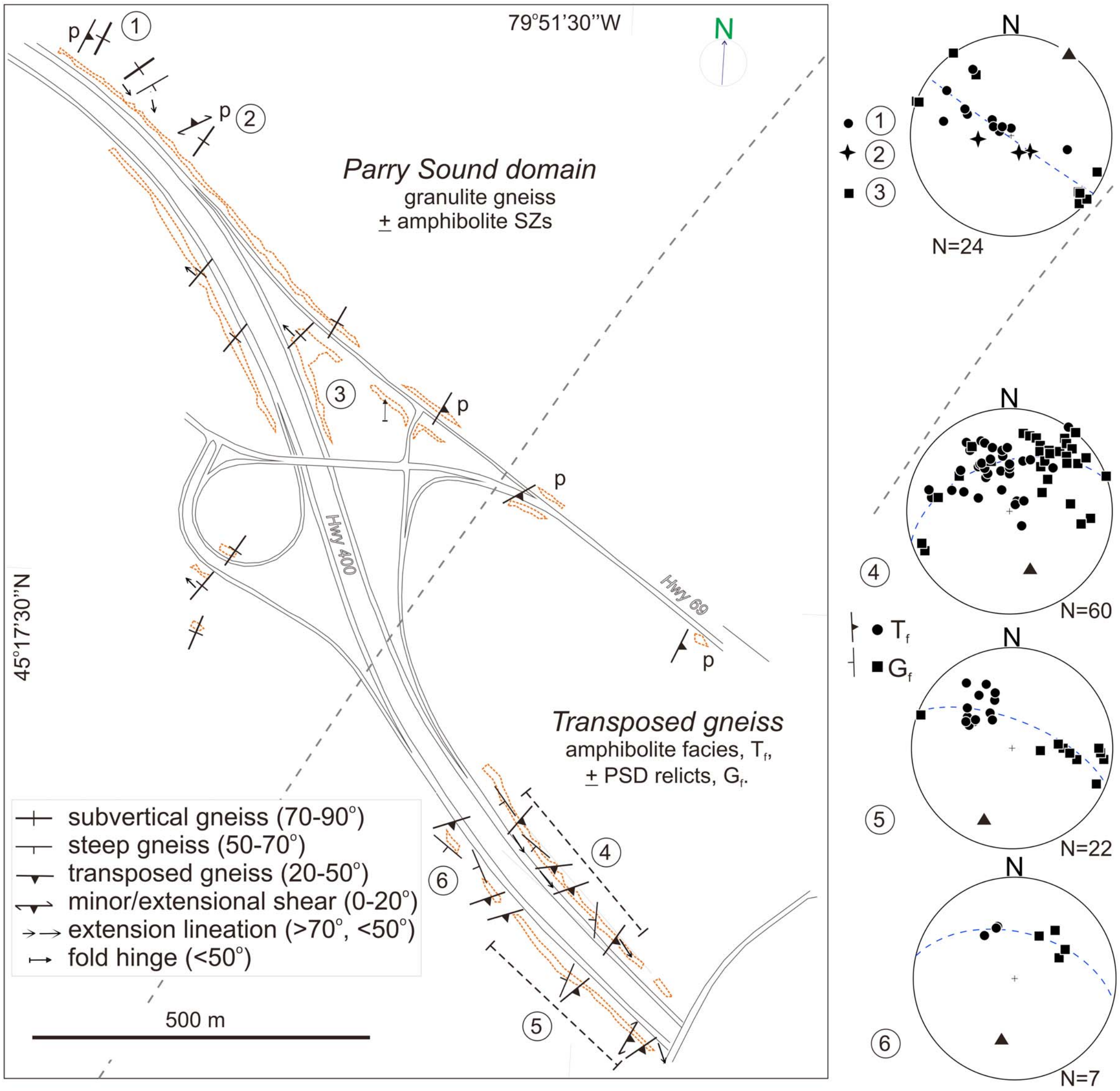


Figure 9. Structures at boundary between Parry Sound domain and transposed unit along Highway 400 (Figure 2). Subvertical layered partially retrogressed granulite gneiss northwest of the boundary, typical of the Parry Sound domain interior, has local pegmatite related shear zones (p, e.g., locations 1 and 2); structures summarized in lower hemisphere stereographic projections keyed to locations 1–3 (poles to gneissosity; 1 and 2 illustrated in Figure 11; location 3, characteristic steep Parry Sound domain gneissosity); triangle, the calculated axis in stereo net for locations 1–3 is consistent with northwestward displacement on shear zones. To southeast, gray granitoid gneiss (transposed gneiss, T_f) shows evidence of derivation by reworking of a protolith texturally resembling Parry Sound domain gneiss (G_f). Locations of sections shown in Figure 10, 4–6; p, locations where pegmatite is important accompanying outcrop scale shear reworking; lower hemisphere stereographic projections of poles to gneissosity for locations 4–6 show transposed gneissosity (T_f; circles) and untransposed gneissosity (G_f; squares); triangles on stereo nets are the calculated inflection lines for locations 4–6, "1," and illustrate the geometry of transposition (folding and shearing) of older gneiss (G_f) into transposed gneiss (T_f).

gneiss with Parry Sound domain protolith occurs mostly in isolated, small remnants (compare Figures 11b–11d with Figure 11a, the isolated old gneiss remnant of section 4) with hinges approaching the trend of the regional synform (Figure 11c). Nevertheless, some larger remnants preserve Parry Sound fabric almost unaltered (Figure 11e). These relations suggest the gneissosity in the eastern limb of the synform is a transposed foliation comparable to, but more penetrative than that illustrated in Figures 9 and 10.

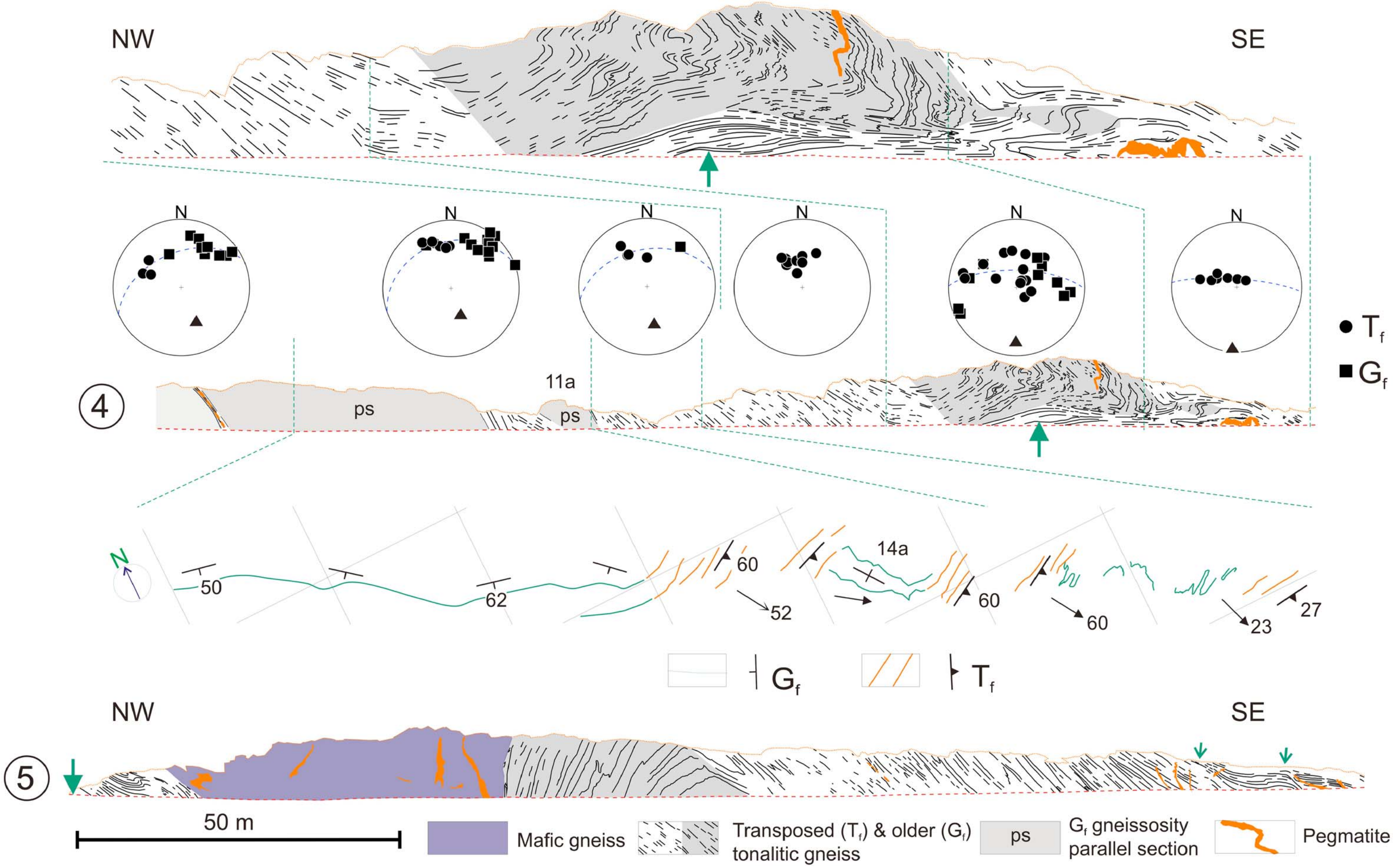


Figure 10. Sections 4 and 5 (Figure 9) showing details of transposition in unit tp. Panel above section 4, detail of SE of section 4; panel below section 4, form line map (location indicated with lines) illustrates reworking of older gneissosity (green, G_f) to form transposed gneiss within shear zones (orange, T_f) by “truncation” (left, NW) and folding (right, SE); mineral lineation (open arrow), fold hinge (closed arrow); domains for stereo nets indicated by lines linking upper detail and section 4; triangles on stereo nets are the calculated inflection lines. Green closed arrows show along strike correlation points of sections 4 and 5; in sections 4 and 5, open arrows at SE end of section 5 show extensional shears. V = H in all sections.

Figure 11. Relicts of untransposed gneiss in transposed gneiss unit. (a–d). In all photos the transposed and untransposed gneiss are indicated (T_f , G_f, arrow). Locations: (a) Figure 10 and (b–d) Figure 2. Gneiss type include tonalitic (light shades), amphibolite (dark). Unlabeled arrow indicates intersection lineation in Figure 11c. (e) Large relict of retrogressed layered granulite (darker shading and steep form lines) within transposed gneiss (shallowly inclined form lines); net symbols as Figure 10. Outcrop sketch traced from photo mosaic; most of outcrop is 3–4 m tall. Location shown in Figure 2.

5.6. Reworking Within Parry Sound Shear Zone and Parry Sound Domain Interior

[30] An extensional shear zone system with associated pegmatites deforms granulite facies mylonitic gneisses of the upper PSSZ near the town of Parry Sound (Figures 2 and 12). Compared to the example from the environs of the transposed gneiss (Figure 2), the system is not known to be the precursor of a zone of transposition and is may be of different age. Nevertheless this example highlights the rheological role of pegmatites and associated amphibolization at different locations and times within the Parry Sound domain. As in the previous examples the shear zones (and wall rock foliation) form a cylindrical system, albeit with a shallowly plunging axis. The wall rocks are mafic granulites of the PSSZ and the shear zones contain amphibolite facies assemblages (Table 1). The shear zones persist along strike

Figure 12. (a) Cross section and (b) map of mafic and granitoid straight gneiss of Parry Sound shear zone deformed by normal sense ductile shear zones (numbered) associated with pegmatite dykes and veins. Stereo nets on map show orientation of planar and linear fabrics; the best fit great circle of poles to planar features is included on the lineation stereo net; the concordance of lineations from within and between shear zones is consistent with a southeast direction of extension; triangle on stereo net is calculated inflection line of shear zones. (c) Photo shows scar fold (formed when external layering flows into space between boudins) from location 7. Box shows location of Figure 13a. Location: Figure 2.

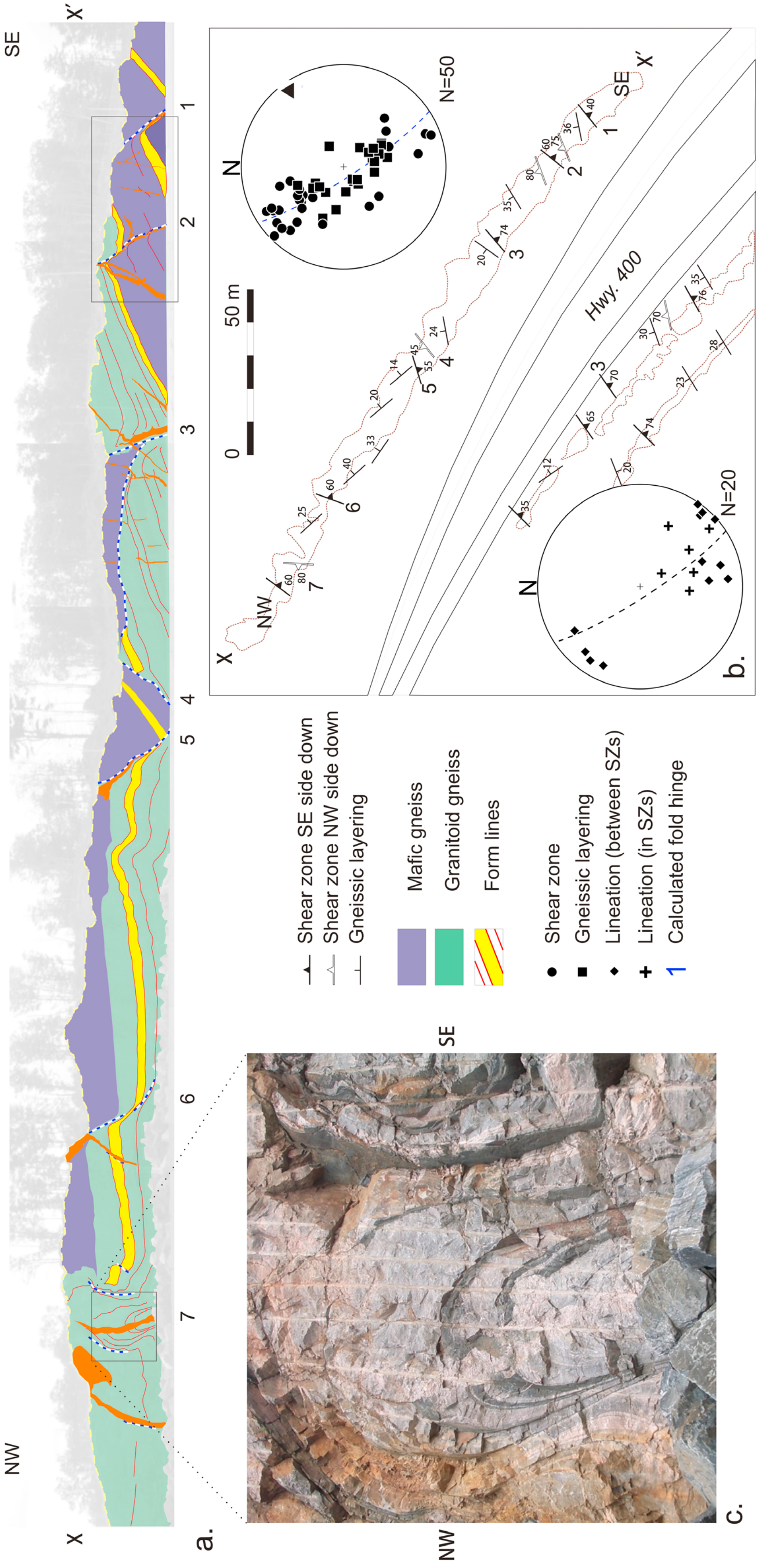

SE
X'
NW
X
a.
1
2
3
4
5
6
7
SE
NW
c.
Shear zone SE side down
Shear zone NW side down
Gneissic layering
Mafic gneiss
Granitoid gneiss
Form lines
Shear zone
Gneissic layering
Lineation (between SZs)
Lineation (in SZs)
Calculated fold hinge
0
50 m
N
N=50
Hwy. 400
N
N=20
b.

Figure 12

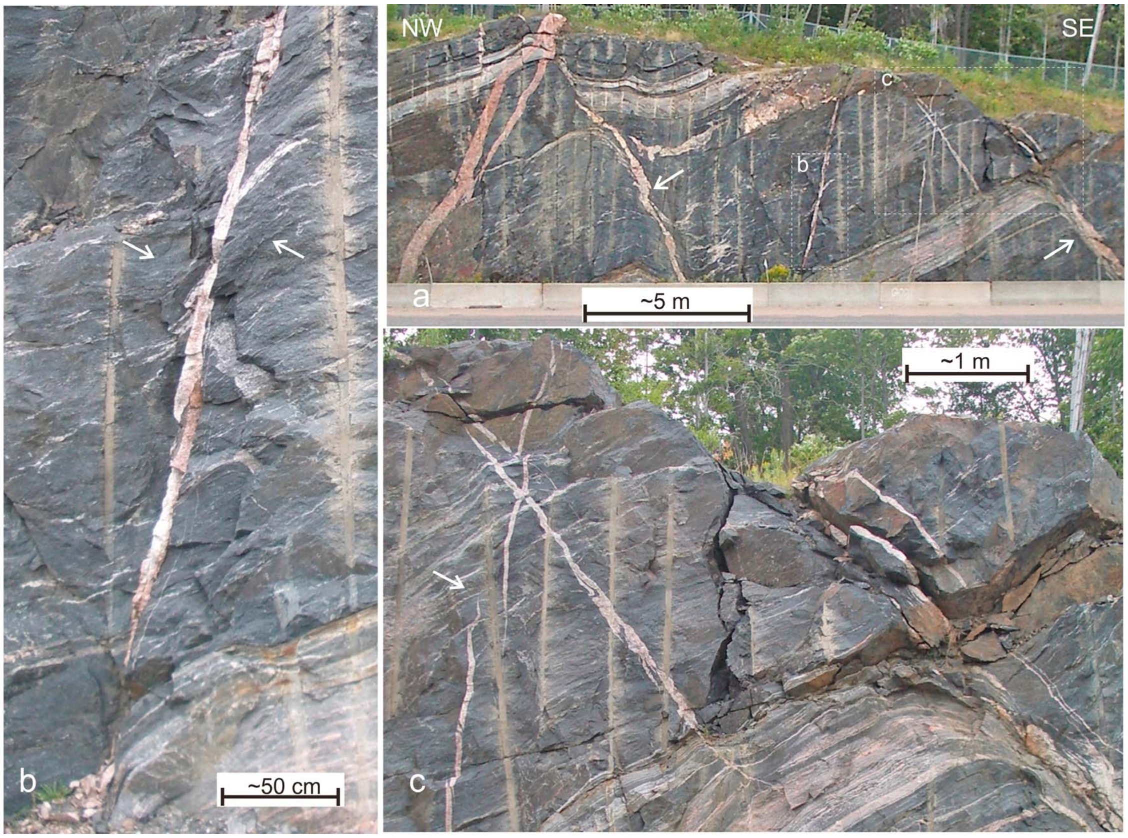


Figure 13. Details of pegmatite dykes and veins related to normal sense shear zones; location shown in Figure 12. Viewing direction indicated. (a) Arrows show location of pegmatites in shear zones. (b) Detail of pegmatite vein in shear zone wall with localized normal (northwest side down) shear along margin (curving foliation, arrowed); this vein dips counter to main dextral shear zones (compare with Figure 13a); note attenuated tip of vein, typical of brittle fracture. (c) Conjugate pair of pegmatite-filled fractures; right southeast dipping pegmatite is concordant with main shear zone (compare with Figure 13a); pegmatite pair dipping left, counter to the main shear zone, has right-handed contractional step over (arrow), appropriate for sinistral shear along the vein walls, as in Figure 13b.

for 50–100 m, although dip separation changes, and most die out at greater distances; the shear zones thus represent a system of limited lateral extent. Most of the shear zones are planar with normal sense although one is apparently listric (between 6 and 5, Figure 12a) and an isolated gently inclined shear may be a segment of a listric shear (highlighted between 3 and 4). As in the transposed gneiss examples, shear zone profiles are abrupt, in that wall rock layering is deflected into the shear zone over a few centimeters (see also the highly amplified scar fold filling the neck of a megaboudin; 7, Figures 12a and 12c). The abrupt profiles of the shear zones on the cross section are reflected in the map pattern (between 6 and 5, Figure 12b) which shows shear zones and wall rock foliation defining apparent truncations. Such features are found at similar scale in the transposed gneiss (e.g., map, Figure 10) and are typical of map patterns of some larger scale Central Gneiss Belt shear zones. The relation of pegmatites to the shear zones varies. Some deformed pegmatites lie within the normal sense shear zones (1, 2, 3, 5, Figure 12). Others are undeformed but lie parallel to the shear zones within the wall rock (Figures 13a and 13c). Others, dipping counter to the shear zones in the wall rock become conformable on entering the shear zones (6, Figure 12) and one cuts across a shear zone (2, 3, Figure 12). Pegmatites dipping counter to the normal shear zones may develop ductile shear along their margin (Figures 13b and 13c) and all, having tapered tips and en echelon arrangement, are clearly crack filling (e.g., step over of tapered crack tips, Figure 13c). Step-over sense, shear sense, and relative timing are consistent with syntectonic vein emplacement. These relations are interpreted to show that the pegmatites and the shear zones are governed by a conjugate fracture system with a gently inclined extension direction and, played a similar role, with respect to the shear zones, in petrological-rheological change as those in the example from the zone of reworking adjacent to the transposed unit.

[31] Abrupt profiles, likely reflecting the width of the initially retrogressed (softened) volume in which the shear zones formed, are characteristic of the examples illustrated so far. Figure 14a shows another example of “truncation” in

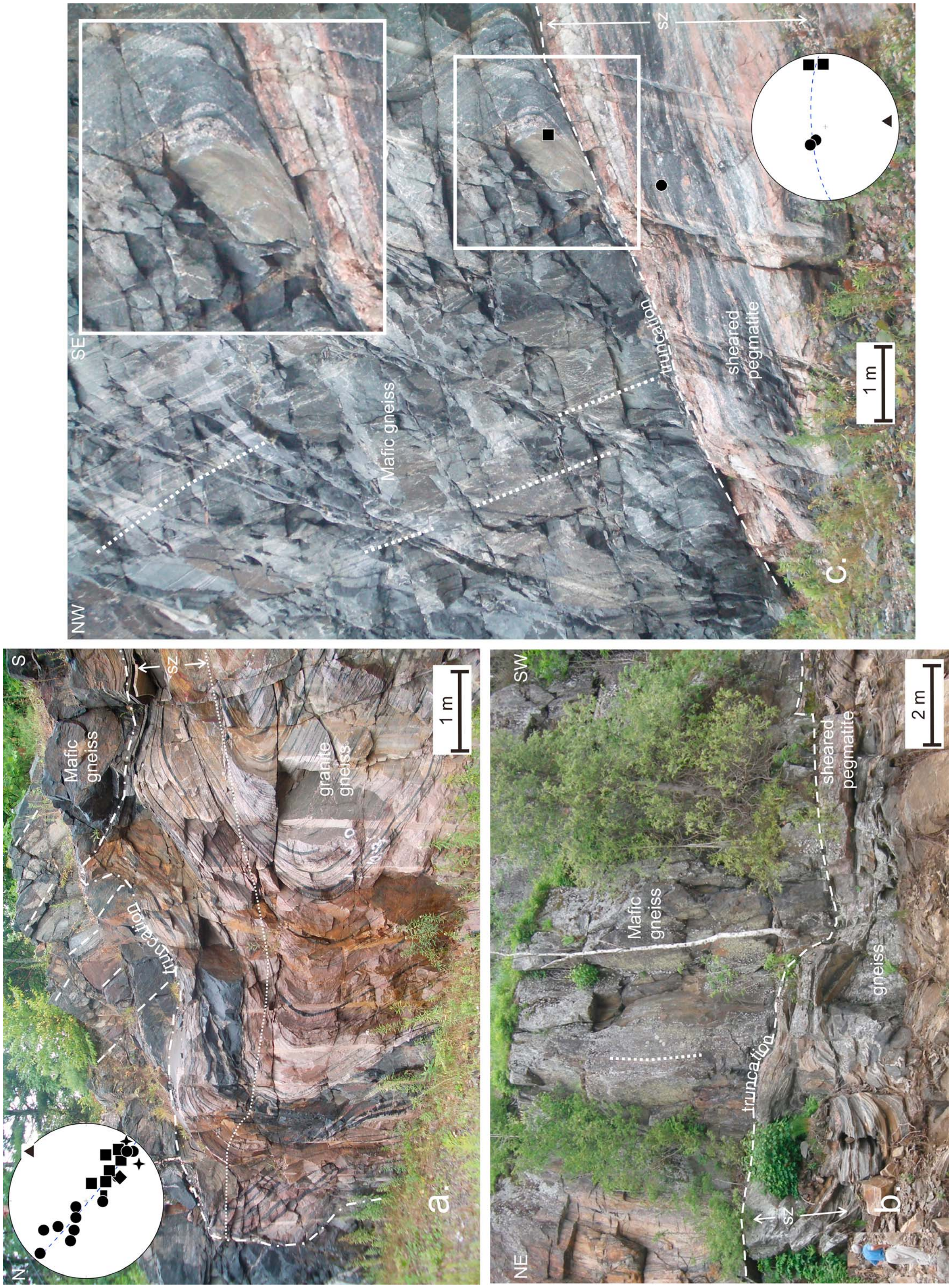

NW
SE
Mafic gneiss
truncation
sheared pegmatite
sz
1 m
c.
N
S
Mafic gneiss
truncation
sz
granite gneiss
1 m
a.
NE
SW
Mafic gneiss
gneiss
truncation
sz
sheared pegmatite
2 m
b

Figure 14

which a cylindrical gently dipping thrust shear zone in the upper PSSZ is imposed on steep Parry Sound domain retrograde foliation (amphibolite facies) and a amphibolite-granodiorite contact. Attenuated granodiorite gneiss defines most of the gently inclined shear zone. In contrast, on the upper side of the shear zone in the boudinaged mafic gneiss, new foliation oriented parallel the shear zone is confined to a very narrow interval, and old steep foliation is preserved close to the shear zone.

[32] Minor amphibolite facies thrust shear zones associated with pegmatites are also located well within the Parry Sound domain interior, although potentially close to its eroded roof and thus possibly within the zone of reworking. The shear zones may be responsible for some gneissosity trends discordant to regional fabric (Figure 14c and Figure 3, zone 9). In all cases the shear zones, in contrast to the surrounding gneiss, are retrogressed to amphibolite facies (Table 1), contain pegmatite and display the characteristic abrupt change of curvature of wall rock layering entering the shear zone. In the Figured example, which strongly resembles another example from the PSSZ (Figure 14b), a gently dipping thrust shear displays the familiar profile (Figure 14c). The hanging wall has steep gneissosity that is reoriented ("truncated") over a few centimeters (Figure 14c). The shear zone (more than a meter wide), which contains a thoroughly recrystallised pegmatite, diminishes in width to only 10–20 cm over a distance of seventy meters along strike, attesting to a lateral limited, dislocation-like planform.

5.7. Reworking of Amphibolite Facies Layering in the Moon River Domain

[33] The open synform and asymmetric antiform at the western side of the Moon River domain display a contrasting style of reworking (zones 1 and 2, Figure 3) contrasting with that displayed by shear zones within the Parry Sound domain. Form lines which trace gneissosity-parallel topographic ridges reflect the penetratively layered nature of the interior Moon River domain gneissosity (Figure 15a). Although there is evidence for origin of this layering by transposition comparable to that in Parry Sound domain (Figure 15b), its later reworking is heralded by open buckle folds within the Moon River synform (crinkled form lines, Figure 15a; at outcrop scale, Figure 15c) that, on approaching the Twelve Mile Bay shear zone, develop to folds with east trending rodded hinges. This type of sequence (buckle folds grading to deformed buckle folds then to transposed gneiss), in contrast to the direct formation of shear zones without initial folding of wall rock layering (as in formation of transposed gneiss from Parry Sound granulite protolith), is comparable to that at Bateau Island to the northwest (Figure 2) where strongly layered amphibolite facies gneisses of the lower PSSZ enter the tip of the Shawanaga shear zone (Figure 16b) [*Culshaw*, 2005]. This style of deformation is illustrated further at map scale where folds with northwest trending hinges in the southern Shawanaga domain flank the Shawanaga shear zone (Figure 16a). It remains moot whether these Shawanaga shear zone-related folds are coeval with other regional northwest trending folds such as the Moon River synform, as claimed by *Culshaw et al.* [1994, 1997] and *Culshaw* [2005]. Nevertheless the latter (and the related marginal buckling and shearing) deforms and thus postdates the initial formation of the transposed gneiss unit and thus contributes to the latter part of the polyphase history of the Twelve Mile Bay shear zone. Coeval or not, these locations have in common a deformation mode contrasting with that associated with retrogression of Parry Sound domain granulites: formation of folds in well layered amphibolite facies gneisses, which are progressively tightened and sheared on approaching a major shear zone.

6. Discussion

6.1. Development of Ductile Sheath

[34] The newly recognized transposed gneiss unit is continuous from northeast of the Moon River domain, where it overlies the Parry Sound domain, to Twelve Mile Bay where it underlies the Parry Sound domain. As thus far mapped it forms part of a sheath enveloping the interior Parry Sound domain (Figures 4 and 17). The open synform at the west side of the Moon River domain refolds the overturned antiform, defined by the Twelve Mile Bay assemblage and anorthosite, the core of which contains the point where upper and lower surfaces of the Parry Sound domain meet. It is not known if the transposed gneiss is folded by- or axial planar to this nappe-like fold [cf., *Gower*, 1992]. From Twelve Mile Bay, the transposed gneiss and the Parry Sound domain–upper Go Home boundary are extrapolated parallel to magnetic anomalies and bathymetric ridges northwest toward the basal Parry

Figure 14. Illustration of typical morphology of pegmatite-associated and related shear zones within PSSZ and Parry Sound domain interior. (a) Thrust sense shear zone reorients steeply dipping (left) granitoid-mafic contact (dash-dotted line). Apparently truncated layering in mafic hanging wall (dashed line); shear zone fabric is wide in granitoid , but narrow in mafic hanging wall (close to gently inclined segment of dash-dotted line); scar fold of granitoid gneiss projects into extending mafic gneiss (to right of "truncation") demonstrating shear-related extension of mafic hanging wall. Lower hemisphere equal area stereographic projection: poles to granitoid gneissosity within shear zone, circles; out of shear zone, squares; lineation, stars; layering in mafic hanging wall, diamond. Location approximately 300 m west of outcrop in Figure 13. (b) High-angle "truncation" of retrogressed granulite layering (vertical dotted line) by shear zone; location, west side of town of Parry Sound. (c) Thrust sense shear zone in the central part of the western Parry Sound domain. Hanging wall is layered gneiss (retrogressed mafic granulite and tonalite, steep white dashed lines); inset shows detail of "truncation" (change of orientation of layering over short distance) at margin of shear zone (filled with sheared pegmatite). Poles to foliation in and out of shear zone shown on stereo net and keyed on photo. Location, Figure 2.

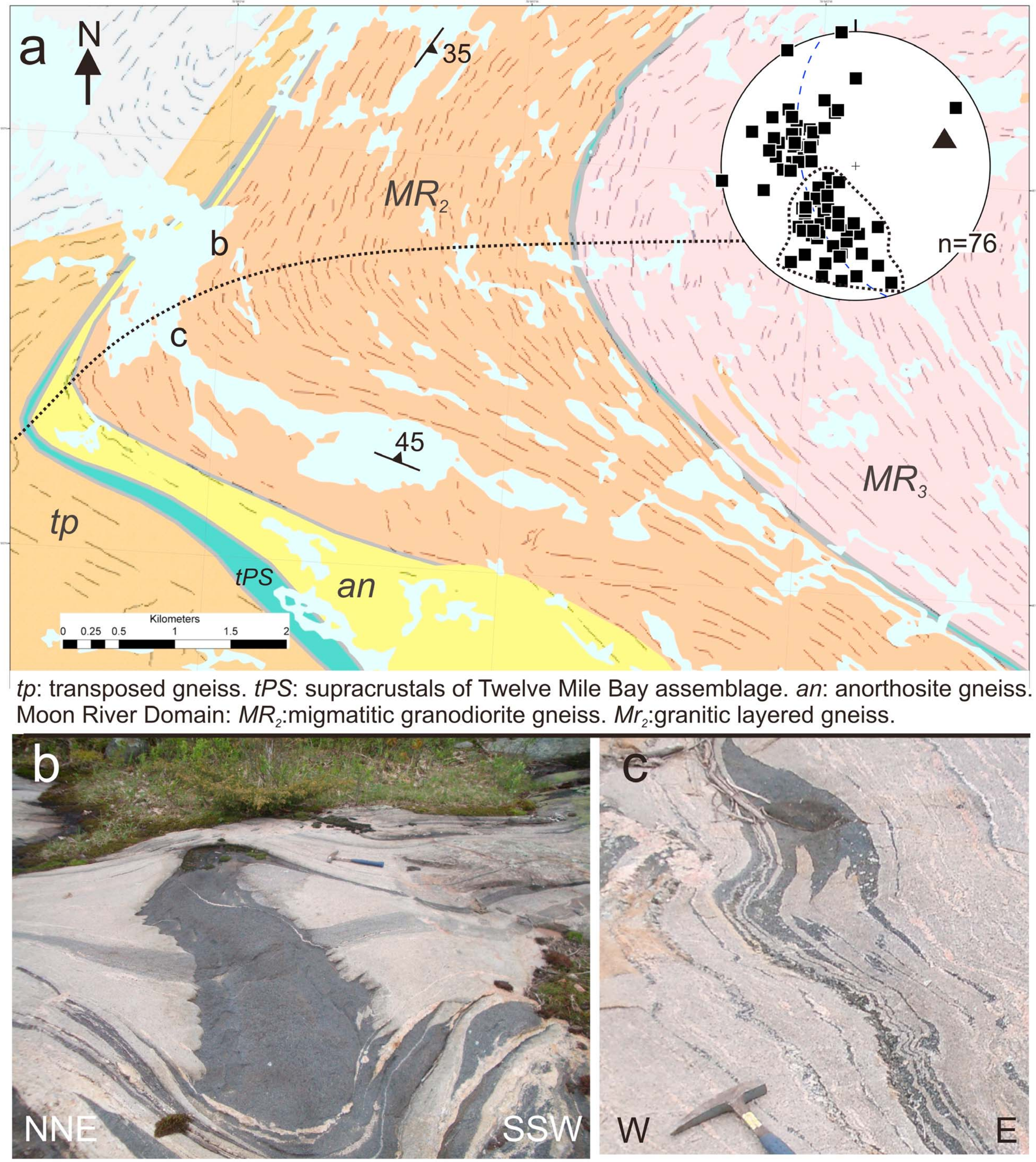
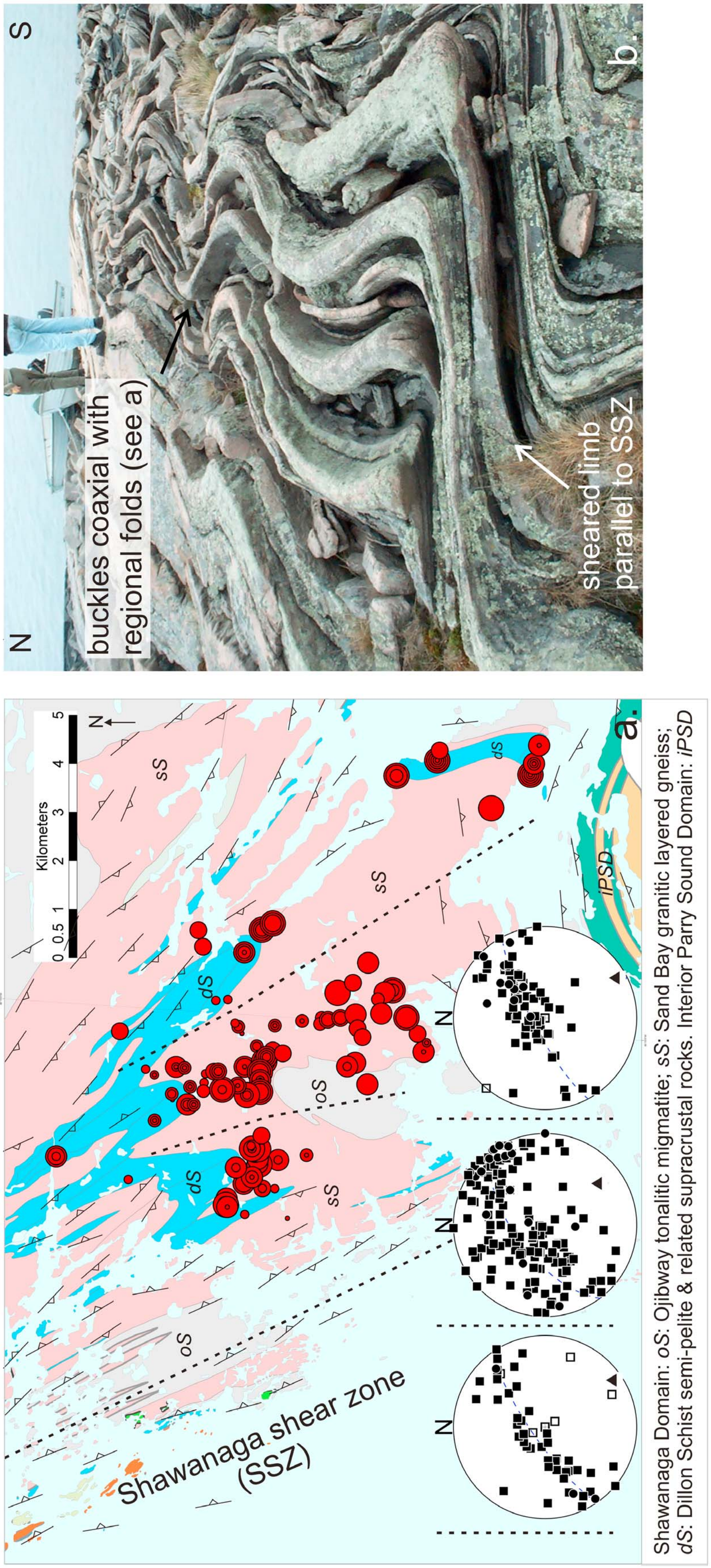


Figure 15. (a) Form line map of western synform of Moon River domain close to contact with Parry Sound domain–derived transposed gneiss. Units as in Figures 2 and 4. Poles to gneissosity shown on lower hemisphere equal area stereo net, southern limb poles are outlined; triangle is calculated fold hinge. (b, c). Moon River gneiss, showing some steps from (b) early transposition, on way to (c) retransposition, shearing and concomitant stretching of hinges via buckling. (b) Details of early transposed cross-cutting metadiabase dyke (location shown on Figure 15a). (c) Isocline of the transposed gneissosity buckle-folded in the transition to retransposition. Locations shown in Figure 2.



Shawanaga Domain: *oS*: Ojibway tonalitic migmatite; *sS*: Sand Bay granitic layered gneiss; *dS*: Dillon Schist semi-pelite & related supracrustal rocks. Interior Parry Sound Domain: *iPSD*

Figure 16

Sound domain where it may truncate or, more likely, merge with the lower PSSZ (Figure 17b). The ductile sheath around the interior Parry Sound domain (Figure 17b) was made by transposition of an interior Parry Sound domain parent, as demonstrated by relations north of Twelve Mile Bay (which represents the base of the sheath), and in the eastern part (top) of the sheath where outcrops illustrate steps in the transposition process (compare Figures 6 and 7 with Figures 10 and 11). Such a ductile carapace might be thought of as developing dynamically around a moving granulite facies nappe as predicted by numerical models [*Jamieson et al.*, 2007, Figure 5b] of long distance tectonic transport of the preassembled Parry Sound domain thrust stack [*Wodicka et al.*, 1996; *Culshaw et al.*, 1997]. The minimum age for initiation of the ductile sheath is estimated at approximately 1100 Ma, based on the similarity of deformation ages obtained by *Krogh and Kwok* [2005] and *van Breeman and Davidson* [1990] along Twelve Mile Bay and in the northeast of the ductile horizon, respectively. Because the Parry Sound domain is believed to have been transported as a preassembled nappe, we suggest the lower PSSZ is part of the ductile sheath, the upper PSSZ relating to early internal stacking of the domain. This is supported by the across-domain matching metamorphic age data of *Krogh and Kwok* [2005]. However, the composition and presheath metamorphic state of lower PSSZ protolith contrasts with that of the ductile sheath formed on the interior Parry Sound domain and although we cannot comment at this point on the lower PSSZ's modes of deformation, we suspect significant compositionally controlled differences.

[35] The transposed gneiss may extend for a significant distance to the southeast along the northeast margin of the Moon River domain as suggested by occurrence of several large relicts of Parry Sound domain lithologies along this margin and topographic and magnetic trends that constrain the potential extent of this material (Figure 17a). This part of the transposed gneiss would overlie or envelop, but be more extensive than, the wedge of dense, presumably partly granulite facies, and untransposed material shown geophysically to lie beneath the northwest of the Moon River domain [*Lindia et al.*, 1983]. This northeastern margin of the transposed gneiss would also in all likelihood incorporate part of the subjacent domains given that map scale "truncations," and consequently transposition, of older gneissosity occur in several places along the margin of this horizon (e.g., triple point where the internal Rosseau domain boundary meets the transposed gneiss boundary; Figure 17a). Field evidence permits an antiform-synform pair in the transposed gneiss-interior Parry Sound domain boundary in the northeast comparable to that in the west (Figure 17a). This structure would replace a Parry Sound domain–transposed gneiss–upper Rosseau triple point and suggests the ductile sheath continues northeast.

[36] The early deformation along Twelve Mile Bay dated at or before 1100 Ma and was followed by "extension" (top to east shear) at approximately 1050 Ma [*Krogh and Kwok*, 2005]. We suggest that the older event corresponds to the initiation of the ductile sheath during early Ottawan transport of the Parry Sound domain nappe northwestward [cf., *Davidson*, 1984]. The anticlockwise curvature of magnetic and bathymetric patterns into the ductile sheath northwest of the Twelve Mile Bay shear zone (Figure 4), in this scenario would have resulted from left handed strike slip shear at the southwest tip of the Parry Sound domain. Folding of transposed gneiss and layered gneiss in an open synform in the western part of the Moon River domain demonstrates an episode of deformation younger than formation of the ductile sheath (Figure 3, zones 1, 2 and Figure 15; Figures 15a and 17b). As noted previously, this large synform, associated with minor folds, is part of a set of structures comparable in style to the buckle-and-shear pattern documented at the intersection of the lower strand of the PSSZ and the younger Shawanaga shear zone (Figure 2). Features indicating top side to east shear along Twelve Mile Bay (dextral winged feldspar and shear bands) likely complement the buckle-and-shear structure set and may be correlative with the late Ottawan top-to-southeast shear which occurred within the Shawanaga shear zone [*Ketchum et al.*, 1998; *Culshaw et al.*, 1994] accompanied by similar structures [*Culshaw*, 2005].

[37] In summary, we postulate the initial assembly of the Parry Sound domain thrust stack before approximately 1100 Ma [*Krogh and Kwok*, 2005; *Wodicka et al.*, 2000], with ductile sheath formation during northwest displacement of the Parry Sound domain thrust stack, probably beginning in early Ottawan times (approximately 1100 Ma) and continuing through pegmatite and granite formation in Shawanaga domain at approximately 1090 Ma [*Slagstad et al.*, 2004b] and into the period of migmatite formation and related metamorphism in Shawanaga and Moon River domain that occurred in the range 1050–1036 Ma [*Slagstad et al.*, 2004b; *Bussy et al.*, 1995; *Krogh and Kwok*, 2005]. Reworking in the range approximately 1050–1020 Ma [*Krogh and Kwok*, 2005; *Ketchum et al.*, 1998] during the event forming the top-to-southeast shear structures is consistent with the "buckle and shear" style deformation of the transposed gneisses of the ductile sheath across the western synform of Moon River domain (zone 1, Figure 3) and of the lower strand of the PSSZ at Bateau Island along the Shawanaga shear zone during flow of units beneath the Shawanaga domain [*Culshaw*, 2005]. The younger event was the prime contributor to formation of the regional northwest trending folds [*Schwerdtner*, 1987; *Culshaw et al.*,

Figure 16. Buckling at map and outcrop scale adjacent to Shawanaga shear zone. (a). Map scale buckling displayed by marker horizon (Dillon schist): coeval outcrop scale buckling; concentric circles show variation of dip at individual outcrops (diameter increases with decreasing dip) indicating importance of small scale buckles, lower hemisphere equal area stereo nets show same data; triangles are calculated fold hinges. (b) Outcrop photo showing transition from buckling of PSSZ gneiss to shearing at transition into Shawanaga shear zone. Locations shown in Figure 2.

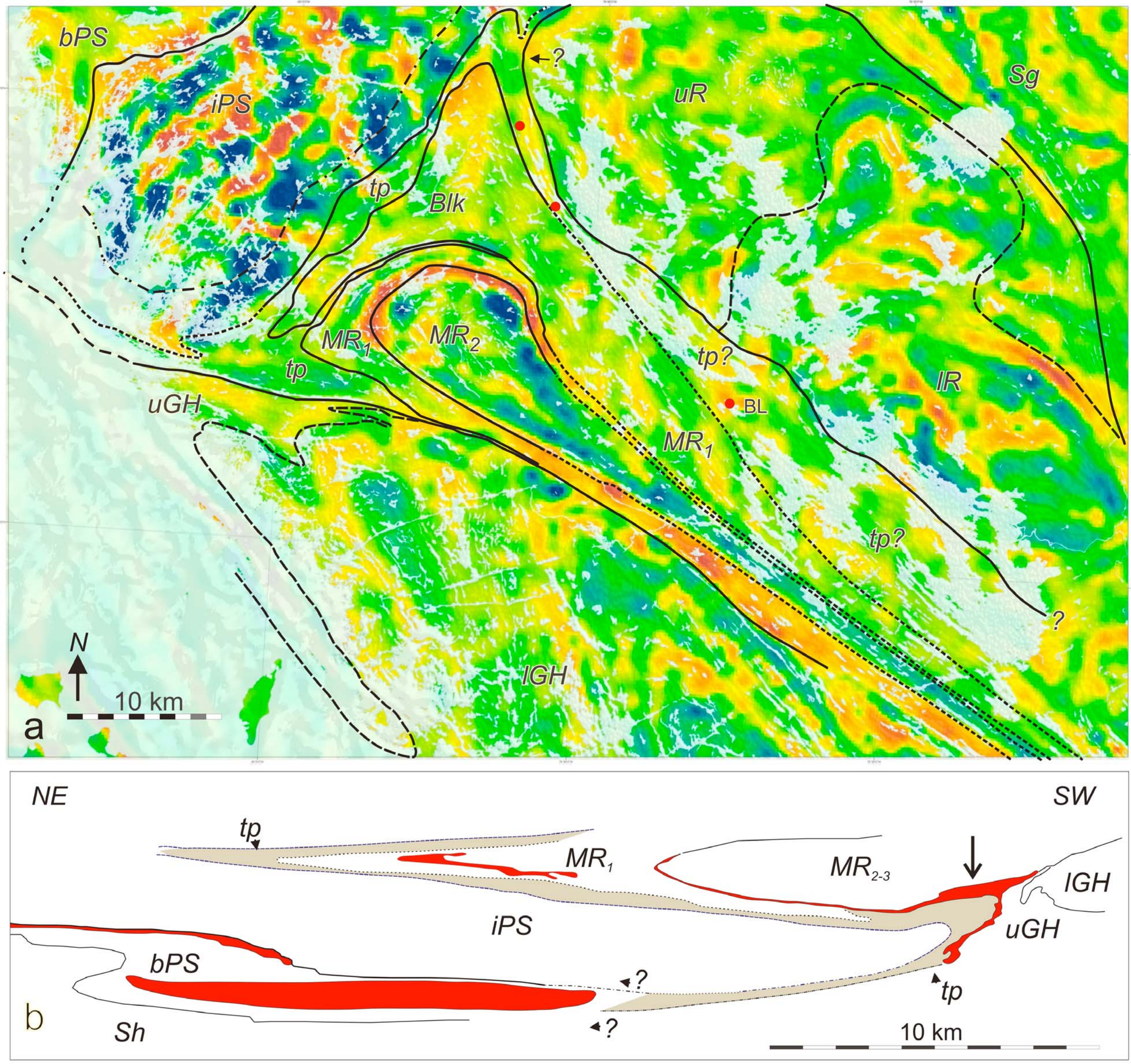


Figure 17. (a). Map of SW Parry Sound and adjacent domains showing how known and proposed boundaries follow topographic and magnetic features (first vertical derivative of total magnetic field draped on shaded relief; same labels and magnetic scaling as Figure 4). Map: Extrapolation of boundaries between Parry Sound domain and transposed gneiss (tp), and uGH, dashed; zone of heterogeneous reworking and retrogression of Parry Sound domain gneiss peripheral transposed gneiss, dash-dotted. Proposed extensions of the boundaries tp-Blk, Blk-MR$_1$, and MR$_1$-MR$_2$ based on topography and geophysics are shown. Dots, Parry Sound domain relicts (BL is hectare scale relict at Butterfly Lake). Question mark with arrow indicates boundary triple point where presence/absence of transposed unit (tp) to NE along uR-iPS boundary is uncertain. *tp*? indicates some transposed unit likely present here (based on magnetics, topography and presence of Parry Sound domain relicts). (b) Down plunge views of the Parry Sound domain and Moon River domains based on trend and plunge of antiform (arrow) just north of Twelve Mile Bay. Principal boundaries and anorthosites (red) are shown; unit codes as in Figure 2; the apparent recumbent, tight closure on the left of unit tp is an effect of the angle of projection on an open upright fold.

1994], a key requirement for such regional fold formation being the presence of "hard lumps" (e.g., the unretrogressed interior Parry Sound domain) needed to generate lateral shear parallel the direction of transport.

6.2. Rheology of Sheath Development

[38] Pegmatites and amphibolite facies retrogression of host rock consistently accompany shear zones along the east and southwest reworked margin of the Parry Sound domain

and in many other late shear zones within the Parry Sound domain. For the southwest Parry Sound domain, we have shown field evidence for a sequence of fracturing, fracture wall hydration, and fracture filling by fine granite and pegmatite; in this sequence, fractures may be formed in en echelon arrays consistent with dominant dextral and sinistral brittle displacement demonstrated across fracture walls, dextral ductile shear in amphibolized fracture margins and veins, and, ultimately, dextral ductile shear in meter-scale shear zones containing veins and pegmatites. We emphasize the pegmatites lie precisely within the shear zones, do not cross cut them, and are always deformed; further, the few examples of undeformed pegmatites (no foliation or pinch-and-swell) lack ductile shear in their wall rock margins. After emplacement, the pegmatites and shear zones rotate with increasing shear strain.

[39] We hypothesize that the pegmatites and/or related fluids controlled the formation of the shear zones rather than vice versa as observed at somewhat higher levels of some orogens [e.g., *Tourigny and Tremblay*, 1997; *Pennacchioni and Mancktelow*, 2007]. On the basis of, for example, the amphibolization of the granulite walls of healed fractures and the ubiquitous more widespread amhibolization within and marginal to shear zones, it appears that introduction of fluid (coeval with and related to the pegmatite) played a necessary softening role in shear zone formation. Validation of this hypothesis is the focus of a separate petrologic study (J. H. Marsh et al., Initiation and development of the Twelve Mile Bay Shear Zone: The low viscosity sole of a Grenvillian thrust sheet, submitted to *Journal of Metamorphic Geology*, 2110). Regardless of the exact mechanism, the presence of shear zones implies the granulites underwent up to an order of magnitude syntectonic weakening [*Gerbi et al.*, 2010]. All or parts of the shear zone development sequence are present elsewhere in shear zones of Parry Sound domain, e.g., in the conjugate fractures with opposite senses of marginal ductile shear at Parry Sound (Figure 13). The morphology of veins and pegmatites suggest fracturing was an integral dynamic feature of the development of the amphibolite facies shear systems affecting this part of the Parry Sound domain; their earliest phase was brittle [cf., *Mancktelow*, 2006]. This leads us to conclude that the location and orientation of the shear zones was controlled by fracture mechanics responding ultimately to regional stress, thus shear zones may have initiated at high angles to the regional shear plane and rotated toward it with progressive deformation. The source of the hydrous melt that generated the fluid and pegmatites cannot have been internal to the dry Parry Sound domain but may have originated within migmatites now or formerly beneath the Parry Sound domain comparable to those of the Shawanaga domain that were producing melt shortly before activity in the Shawanaga shear zone or the approximately 1090 Ma pegmatites in the same domain. *Slagstad et al.* [2004b] show that the composition of leucosomes in migmatites of Shawanaga and Muskoka domains (i.e., above and below Parry Sound domain) most likely represent cumulates, the complementary hydrous melt being expelled upward. We infer that the formation of migmatites such as these was intimately related to the formation of the transposed gneiss and softening of the Parry Sound domain granulites via expelled hydrous melt.

6.3. Contrasting Modes of Transposition

[40] A subset of the rocks of the Parry Sound domain affected by the shear zones are layered on decimeter to submeter scale with alternations of granitoid and mafic compositions (Figure 6b); in this respect, the geometry of the layering differs little from the younger layering of the interior Moon River (Figure 15a) or Shawanaga domains (Figure 16b). However, the modes of deformation of the two penetratively layered gneisses differ in important respects. Where the preretrogression mineralogy of mafic layers included pyroxenes and plagioclase (e.g., unit 3, Figure 6), the walls of the shear zones appear minimally deformed (scattered open folds in wall rock panels occur after shear zone formation). And, as illustrated by the zone of reworking north of Twelve Mile Bay, these rocks may exhibit a high density of shear zones forming recognizable hectare-scale networks (Figure 6) [*Hanmer*, 1984]. In the layered gneiss of the interior Moon River (Figure 15), in the transition into the Shawanaga shear zone, in the southern Shawanaga domain (Figures 16a and 16b) [*Culshaw*, 2005], the picture is contrasting: layering formed buckle folds at several scales in the walls before incorporation into the major shear zone and networking of shear zones is unrecognized. The differences in behavior of the two environments correlate with the metamorphic grade before shearing. In contrast to the Moon River and Shawanaga amphibolite facies layered gneisses, the Parry Sound domain granulites have insignificant biotite before shear zone deformation and must undergo localized hydrous retrogression to deform. The reason for occurrence of buckling before shearing in the amphibolite facies multilayers is likely because the preexisting uniform grade and mineralogy ensured an appropriate competence contrast was present throughout the multilayer.

6.4. Transposition and "Truncation"

[41] All the pegmatite-related shear zones of the Parry Sound domain have abrupt profiles in which the transition from shear zone walls to shear zone occurs over a relatively narrow space ("truncation"; Figures 6–11). Although outcrop scale profiles are rare at Bateau Island, some have a comparable geometry to the Parry Sound domain shear zones (Figure 16b) and a map scale profile shows the transition to the Shawanaga shear zone is similarly abrupt [*Culshaw*, 2005]. The same geometry of profile is present in the transposed gneisses of northeast Moon River domain (Figures 10 and 11). The abrupt profile is geometrically similar to that expected for a shear zone in a material deforming by power law flow with a relatively elevated value for the exponent [*Talbot*, 1999; *Mulchrone*, 2001] and compares to those shown by high-grade rocks inferred to have deformed in a viscous plastic manner [*Puelles et al.*, 2005]. The analogy is somewhat imperfect, however, because in transposition of the retrogressed granulites the hydrated region closest to the pegmatite probably had a different rheology than the undeformed rocks (dry granulites) away from the shear zones. A conclusion is that once

Parry Sound domain–derived material contained amphibolite facies assemblages, as Moon River and Shawanaga did from the start, deformation modes with respect to accommodating shear in the three domains were similar, presumably an effect of similar upper amphibolite facies mineralogy in granitoid compositions.

[42] The transposed gneiss or ductile sheath around the interior Parry Sound domain formed from a Parry Sound domain protolith (Figure 17, tp), as demonstrated by the presence of small windows of untransposed gneiss with Parry Sound domain textural features and structural relations (e.g., Figure 11). Together with the evidence that at least some of the gneiss from the interior Moon River domain is transposed gneiss (Figure 15), this implies a large volume of gneiss was derived in a comparable fashion. A feature of the windows that capture the transposition process is the abrupt nature of the transition from old to transposed gneiss (Figures 7b, 11, and 15b). The transition has the same character as that noted above for the shear zone profiles, the difference being the relationship between transposed rock and older gneiss is reversed: the windows are embedded within straight gneiss. The transposition process can almost be followed "frame by frame" in the northeastern part of the Moon River structure (zones 4–6, Figure 3; Figures 10 and 11) and also across the zone of reworking north of Twelve Mile Bay into the shear zone (Figures 5–7). Derivation of what is in essence a single large shear zone from a shear zone system composed of many smaller zones is an extension of conceptual models [*Fusseis et al.*, 2006] that predict the strength of a shear zone system should become stable at a given density of linked shear zones.

[43] Comparable extensive units of transposed gneiss may define parts of the boundaries of Central Gneiss Belt domains along which apparent map scale "truncations" of other boundaries and older structures have long been noted (see form line maps in the work of *Davidson* [1984]) (Figure 17a). Such "truncations" may well be sites of transposition, implying that the "truncated" unit is incorporated into the margin of a transposed unit bounding an allochthonous domain. This scenario explains why fragments of anorthosite gneiss are found along the Moon River boundary southeast of its intersection with subjacent boundaries decorated with map scale anorthosite bodies (e.g., Upper and Lower Go Home and Rosseau boundaries; Figure 17a).

[44] **Acknowledgments.** We thank Jacques Martignole and an anonymous reviewer for insightful comments on an early draft. N.C. was supported by an NSERC discovery grant. C.G. received support from NSF EAR-0837922. We acknowledge provision of aeromagnetic data by Canadian Aeromagnetic Data Base, Geoscience Data Repository, Geological Survey of Canada, Earth Sciences Sector, Natural Resources Canada, Government of Canada.

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