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Heterogeneous amphibolite facies deformation of a granulite facies layered protolith: Matches Island shear system, Parry Sound domain, Grenville Province, Ontario, Canada

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ABSTRACT

Amphibolite facies transposition of granulite facies gneiss resulted in the formation of a nappe-bounding km-scale shear zone at the margin of the Parry Sound domain, Grenville Province. The Matches Island shear system illustrates the earlier stages of transposition in which heterogenous retrogression of the well layered (mafic–felsic) granulite facies gneiss along pegmatites orthogonal to layering controlled the location of shear zones and ensured that unretrogressed granulite persisted as strong elements. Shear zones curve anticlockwise from their original orientation accompanied by rigid rotation of wall rock layering which remains orthogonal to the shear zones. This relationship is modified so that wall rock layering form sigmoidal mafic 'fish' where shear zone linkage occurs via: (i) merging of established parallel shear zones by wall rock 'collapse'; (ii) merging of an established shear zone with a new shear zone formed within preexisting wall rock or; (iii) linking of two established zones by an oblique new shear zone. All of these wall rock – shear zone relations are displayed in the maximally transposed nappe-bounding shear zone but contrast with those at the boundary of other nappes where uniform amphibolite facies protolith is transposed with a buckle-and-shear style.

1. Introduction

The relevance of the study stems from the supposition that shear zone systems may accommodate a significant fraction of strain in deep orogenic crust as exemplified by the Central Gneiss Belt (CGB) of the Grenville Province. Further, the Matches Island shear system represents a small-scale sampling of the early stages of formation of a nappe-bounding, regional shear zone and thus provides insights into the evolution of major, large scale, deep-crustal structure.

The particular focus of the study is the geometry and kinematics of processes in the early stages of ductile deformation, shearing and reorientation of one class of compositionally layered gneiss found in the CGB: granulite facies gneiss in which shear zones nucleate on hydrated and often pegmatite-filled corridors (Marsh et al., 2011; Culshaw et al., 2010). Also we contrast the style present in this outcrop with the distinct style shown by ductile deformation and reorientation of a second, regionally common, species of layered gneiss: homogeneously amphibolized compositionally layered gneiss which had never reached granulite facies before shearing. Such gneissic products of reworking during progressive deformation may comprise structural styles generic to deep orogenic crust.

2. Geologic setting

2.1. Regional geology

The CGB is a major component of the Grenville Province, a ca. 1160–1000 Ma collisional orogen (Fig. 1). The Matches Island shear system lies at the periphery of the Twelve Mile Bay shear zone (TMBSZ) along the southern margin of the Parry Sound domain (PSD), a lithotectonic domain within the CGB. The present erosion surface of the CGB represents the deep levels of a thick orogen, comprising upper amphibolite to granulite facies gneisses and migmatites recording peak metamorphic temperatures in excess of 750 °C and pressures as high as 10–13 kb. The PSD, consisting of mainly granulite facies gneiss, lies within a stack of upper amphibolite facies domains in the CGB (Fig. 1) formed by either: (1) stacking

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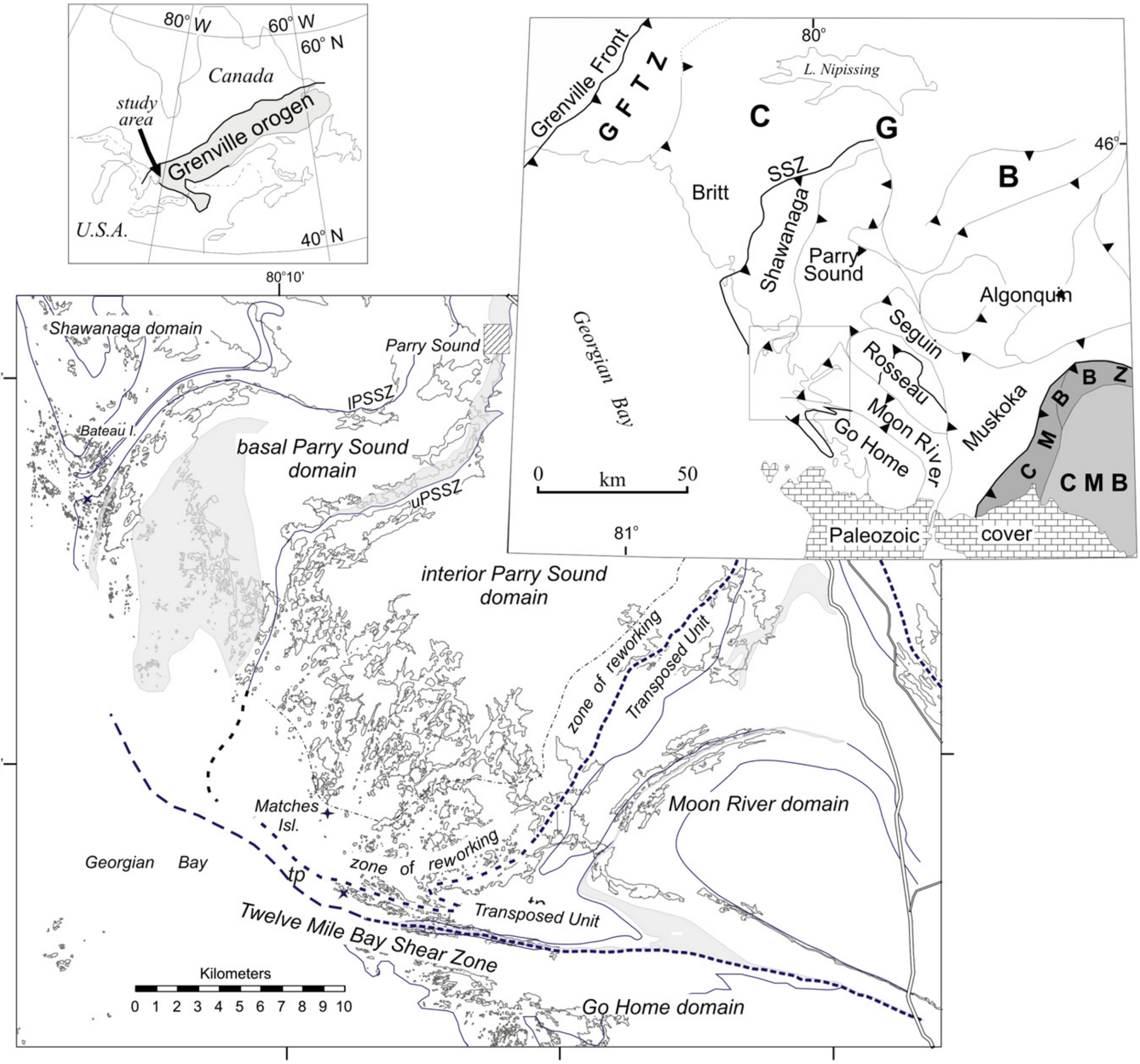

Fig. 1. Upper panels: location and maps of Central Gneiss Belt (CGB) in Ontario showing location & names of principal domains. GFTZ, Grenville Front Tectonic Zone; SSZ, Shawanaga shear zone; CMBBZ, Central Metasedimentary Belt Boundary Zone; CMB, Central Metasedimentary Belt. Domain boundaries internal to CGB are interpreted as ductile thrusts. Lower panel: study area (Matches Island) location & regional geology. Principal domains identified; Transposed Unit, transposed PSD lithology. Structure: lPSSZ, lithological boundary within lower strand of Parry Sound shear zone; uPSSZ, lithological boundary at upper margin of upper strand of Parry Sound shear zone; also shown is the proposed extension of Twelve Mile Bay shear zone into Georgian Bay inferred from bathymetry & geophysics; zone of reworking, area of retrogression & reworking of Parry Sound domain granulites transitional to Transposed Unit. Anorthosite and related units shaded. Location of Fig. 14a–c shown by star on Twelve Mile Bay shear zone & below Bateau Island, respectively.

of thrust sheets emplaced in a fashion analogous to a foreland thrust belt (Davidson, 1984), or (2) juxtaposition of lower crustal nappes and midcrustal material by lower crustal flow after crustal thickening (Culshaw et al., 2004; Jamieson et al., 2007). In cross section the PSD appears as a lozenge-like resistant block isolated within a softer flowing matrix of gently inclined amphibolite facies gneiss sheets (White et al., 1994; Culshaw et al., 1997). The PSD is itself a stack of thrust sheets constructed at or shortly after 1160 Ma and subsequently transported (Wodicka et al., 2000). A sheath of polyphase amphibolite facies transposed PSD gneiss truncates the internal PSD stacking structures and is related to the transport phase (Transposed Unit, Fig. 1) (Culshaw et al., 2010). The age of transposition is constrained by emplacement of ca. 1100 Ma age of syn-tectonic pegmatite dykes (Marsh et al. in review) at the start of ductile deformation. The ductile sheath, of which the TMBSZ is part, represents the softening margins of the PSD at its interface with the enveloping matrix of softer amphibolite facies domains.

2.2. Outline of the structure of the western PSD

Much of the western PSD interior consists of strongly deformed layered granulite facies gneiss of igneous origin, striking northeast, and with a down-dip lineation formed during the building of the internal nappe stack of the domain. The Matches Island shear zone system is situated north of TMBSZ proper, but is part of a wide zone in which granulites of the interior PSD are reworked (zone of reworking; Fig. 1) at the periphery of the zone of more advanced ductile deformation that defines the TMBSZ (Fig. 1). In the zone of reworking, trends of unsheared granulite gneissosity and shear zones appear irregular at map scale but cylindrical viewed in stereographic projection (Hanmer, 1984). To the south, in the TMBSZ segment of the Transposed Unit, PSD-derived and other upper amphibolite facies gneisses in various states of shearing and reorientation and retrogression dip north-northeast beneath the PSD interior. The boundary between the zone of reworking and the TMBSZ is gradational; they are clearly genetically linked, as indicated by the geometric and lithologic similarity of sheared rocks and the presence of pegmatite dykes or their deformed equivalents (Culshaw et al., 2010).

The role of fractures, fluid and, in some cases, pegmatite dykes, in shear zone formation has been noted in several studies (e.g., Pennacchioni, 2005; Pennacchioni and Mancktelow 2007; Mancktelow and Pennacchioni, 2005; Fusseis et al., 2006; Jamtveit et al., 2000; Jolivet et al., 2005). In the zone of reworking and the Transposed Unit (TMBSZ) their role is crucial (Marsh et al., 2011; Culshaw et al., 2010). Pegmatite- and granitoid-filled dykes within granulite are associated with a hydration and retrogression halo in the adjacent wall rock. Field relations show this hydration is tantamount to a necessary condition of shear zone formation with the pegmatite dykes as the source of the fluid that engendered softening, consistent with syn-tectonic pegmatite emplacement in fractures caused by underlying over-pressured fluid-rich magma. Metamorphic conditions for formation of the shear zones were in the amphibolite facies at ca. 6.5 kbar and ca. 700 °C (Marsh et al., 2011).

2.3. Geology of Matches Island

Matches Island contains a superbly exposed example of an amphibolite facies retrograde shear zone system representative of the zone of reworking (Fig. 2). Less complete examples are found on islands to the south and southeast, towards the TMBSZ. A half-kilometre of open water separates Matches Island from the closest retrogressed but minimally reworked granulites to the north, and granulites with retrograde shear zones lie a kilometre to the northwest; farther north and northeast, granulites are predominant (Fig. 1).

Matches Island itself consists of two lithological units, with a third cropping out on an islet lying to the southeast (Fig. 2). Unit 1, the focus of this study, underlies most of the island and is formed from

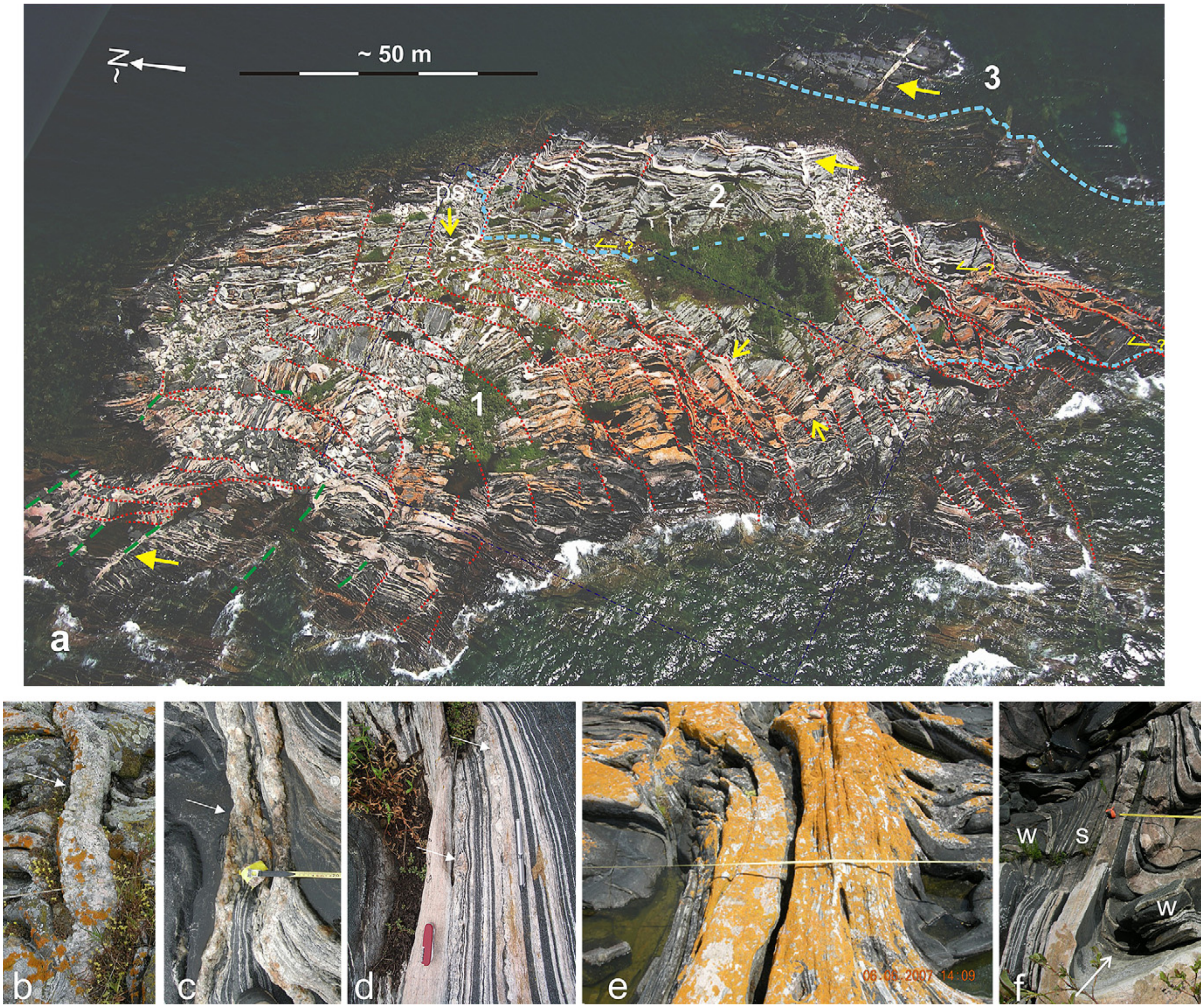

Fig. 2. a). Oblique aerial photograph of Matches Island. Unit boundaries, heavy dashed line; dextral shear zones, red; sinistral shear zones, green; sinistral shear zones, solid head arrows; intrusive granite, open head arrows unlabelled; pegmatite 'spider', open headed arrow 'ps' (see text for explanation). Scale & north arrow are approximate. Box, location of Fig. 3. Photos b–e, images of shear zones at locations indicated; visible pegmatites, or augenized remains, arrowed. f. Hinge of shear zone (arrow), at join of wall rock (w) & shear zone (s). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

a protolith common in the granulites to the north and northeast. The gneiss has decimetre to metre-scale layering of felsic (granitic) and mafic components. In and outside of the shear zones the felsic layers contain an assemblage of plagioclase-K feldspar-quartz-hornblende-biotite. Whereas the mafic layer assemblage within the shear zone is hornblende-plagioclase ± biotite ± quartz ± titanite, wall rock may retain coarser plagioclase-clinopyroxene-orthopyroxene-hornblende mantled by symplectic garnet, hornblende and biotite. Wall rocks have a cm-scale mineralogical layering and a planar-linear mineral aggregate shape fabric (e.g., quartz blades in felsic gneiss), typical of the granulites regionally, but no strong mineralogical fissility (e.g., mica schistosity).

Unit 2 is grey plagioclase-quartz-hornblende-biotite gneiss with scattered pink granite leucosomes, a uniform amphibolite facies mineral assemblage and no mafic layers. Pink leucocratic granite forms concordant layers within the grey gneiss but are more widely and irregularly spaced than similar layers in Unit 1. As in Unit 1 there are pegmatite-cored shear zones, but in Unit 2, mineralogical differences across these shear zones are absent and displacement relatively low. Unit 3, underlying the adjacent islet, is a uniform amphibolite but with textural features (leucosome patches containing retrogressed pyroxene) suggesting granulite facies heritage.

Pegmatite dykes with different degrees of structural overprint are present in many of the shear zones on the island (Fig. 2 a–d; see Supplementary data for mapped pegmatite in shear zones). Their structural state varies from parallel-sided (in shear zones of lowest displacement) through pinch and swell structure to completely disaggregation with increasing shear zone strain (for petrological details see Marsh et al., 2011). In the areas least affected by shear zones, e.g. Unit 3 and northwest part of Unit 1, where foliation attitudes are similar to those within the PSD interior, northwest-striking crack-filling pegmatite dykes are undeformed, with some wall-displacement across them appropriate for mixed mode fractures. These and other details are similar to features showing an earlier stage of shear zone and retrogression development that underlie outcrops north of the island (Culshaw et al., 2010).

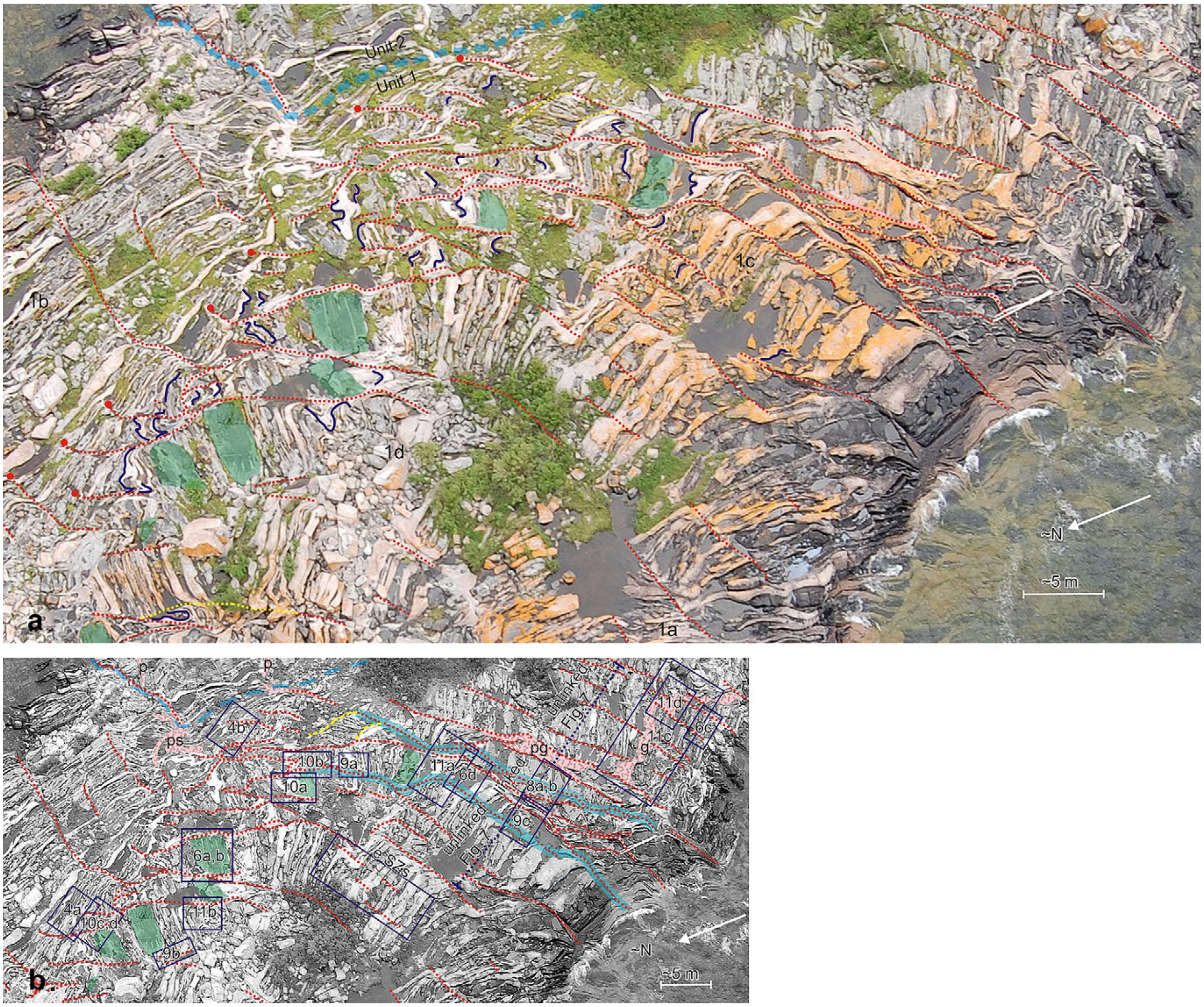

Fig. 3. Aerial photograph of parts of Units 1 and 2. (a) Top left, gneissic layering in Unit 2 strikes close to 'regional'; layering within wall rocks of Unit 1 shear zones rotate away from 'regional' as shear zones curve anticlockwise (from Unit 1c to Unit 1d); note continuity of layering into shear zones. Folded wall rock layering, bold lines; shear zones, dashed line (red, dextral; yellow, sinistral); shear zone tips close to Units 1–2 and 1d–1b boundary, solid circles. (b) Boxes, locations of figures; line, location of section line illustrated in Fig. 7 (locations of linked and unlinked shear zones indicated); eSZs, en echelon shear zones; thick transparent blue lines, boundaries of high strain zone of Unit 1c. p, pegmatite; pg, pegmatitic granite; ps, 'pegmatite spider' (see text for explanation); g, granite. See Fig. 2a and 5 for location of aerial photograph. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The orthogonal orientation of wall rock layering relative to shear zones, common at all stages of development (Figs. 2 and 3), was determined by this original orientation of the fluid and pegmatite bearing fractures which guided initial shear zone orientation (Marsh et al., 2011; Culshaw et al., 2010). There is some evidence for a minor later, syn-shear zone magmatic component. This includes the spider-like group of pegmatites situated at the tip of the northern Unit 1–2 boundary shear (ps, Fig. 3) which may have absorbed extension at the tip of a propagating shear zone. Some pegmatites may be syntectonic such as the large, pegmatitic granite lying within a shear zone (pg, Fig. 3) which contains inclusions with gneissosity parallel to the shear zone and small pegmatites at shear zone tips, arguably emplaced during shear zone propagation (Fig. 4a, b).

3. Methods

Much of the analysis presented below derives from cm-scale mapping of structures across the island. We used three complementary methods to generate the maps: low-altitude aerial photographs, DGPS (Differential GPS), and photographs from a pole-mounted camera (6 m pole). Photographs taken during low-altitude flight (ca. 150 m altitude) are slightly oblique, giving a foreshortened down-plunge view of the DGPS map, but provide a unique perspective of the structural character and nature of the units. The map made with DGPS (Fig. 5) gives a more accurate plan view of the island than the air photograph. The DGPS map shows most of the shear zones on the island but the map is necessarily incomplete with respect to comprehensively depicting the densely spaced layering. The DGPS data also allow calculation of quantitative information such as density of shear zones (per unit area), frequency of shear zone intersections (per unit length) or strain estimates via displacement of marker layers across shear zones. Large-scale structural features gleaned from the air photographs have in many cases been ground-truthed with photographs taken with the pole-mounted camera which gives excellent images of structures exposed on sub horizontal surfaces of low relief.

3.1. Map-scale structure of Matches Island

Summarising the structure at the scale of all dry land and visible submerged rock, Unit 3 is a competent mafic layer with incipient boudinage shown by a fold of Unit 2 layering infilling a boudin neck (below ‘3’ in Fig. 2a). As indicated by the undeformed pegmatite (arrowed, Fig. 2a), Unit 3 has little internal syn/post-pegmatite deformation. Based on density of shear zones, Unit 2 is divided into northern (Unit 2a, fewer shear zones) and southern (Unit 2b, more shear zones) parts (Fig. 5). The northern and southern segments of the boundary of Unit 2 with Unit 1 are bounded by dextral shear zones but the segment between the sheared parts of Unit 2a and 2b boundaries is partially obscured by vegetation and its nature is unclear.

Unit 1 has northwestern and northeastern lobes that are poor in shear zones and show an orientation of the granulite layering similar to the regional one (Fig. 5, Units 1a, b). In contrast, the central part of Unit 1 has densely developed shear zones curving anticlockwise ENE to NNE and forming a core zone to the island (Fig. 5, Units 1c, d).

Pole figures of gneissic layering in shear zone walls, shear zone-poor segments and shear zone cores show a dispersion around an axis plunging 50–65° eastward. This axis corresponds both to the drag fold axis of the granulite layering close to the shear zones (shear zone hinge) and, at a broader scale, to the curvature of the shear zones. It is also parallel to the fold axes within gneisses of Unit 2 (see below; Fig. 5). The magnitude of the plunge implies that the map plane is inclined about 30° to the XZ plane of the shear zone system but is not a great distortion of that plane.

3.2. Shear zones and wall rock

At outcrop scale, the shear zones consist of moderately grain size refined, thinned wall rock gneiss layers and pegmatite dykes within the shear zones (arrows; Fig. 2b–d) are progressively deformed in sympathy with shear zone strain (increasing: b–d; Fig. 2). Most shear zones are dextral. Sinistral shear zones are relatively rare and are concentrated in the northwest of the island in Unit 1a and contiguous parts of 1d (Fig. 2a) and there are two minor sinistral shear zones in Unit 1c (long dashes, Fig. 3). In many shear zone walls there is a lack of syn-shear zone deformation and shear zone walls preserve the regional pre-shear planar-linear fabrics, layering, and folds (Fig. 6b; bottom right arrow). In mafic layers melt-related textures (Fig. 6b; top right and left arrows) imposed during granulite facies metamorphism may be unaltered and accompany variably preserved granulite assemblages in the host (Marsh et al., 2011). The lack of syn-shear deformation in the wall rocks and of evidence for transpression-related extrusion from the shear zones, implies simple shear for tabular shear zone segments. Although there is no observed lineation in the shear zone, offset markers indicate that movement was perpendicular to the steeply plunging ‘shear zone hinges’ formed where layering curves sharply into the shear zones.

The measured shear zones underlie about 18 percent of the total area of the island with an aggregate length of more than a kilometre. In the shear zone-rich core of Unit 1 (1c, d, Fig. 5), where 80%

Fig. 4. Details of shear zone terminations with syn-tectonic pegmatites (arrows). (a). Shear zone is one of a pair forming a bifurcation close to termination at a prominent granite layer; note decrease of displacement along shear zone. (b). Detail of termination in Unit 1d close to boundary with Unit 2; p, pegmatite; sense of curvature suggests shear may continue parallel to layer and unit boundary. Horizontal field of view in both ca. 5 m (see Fig. 3 for location).

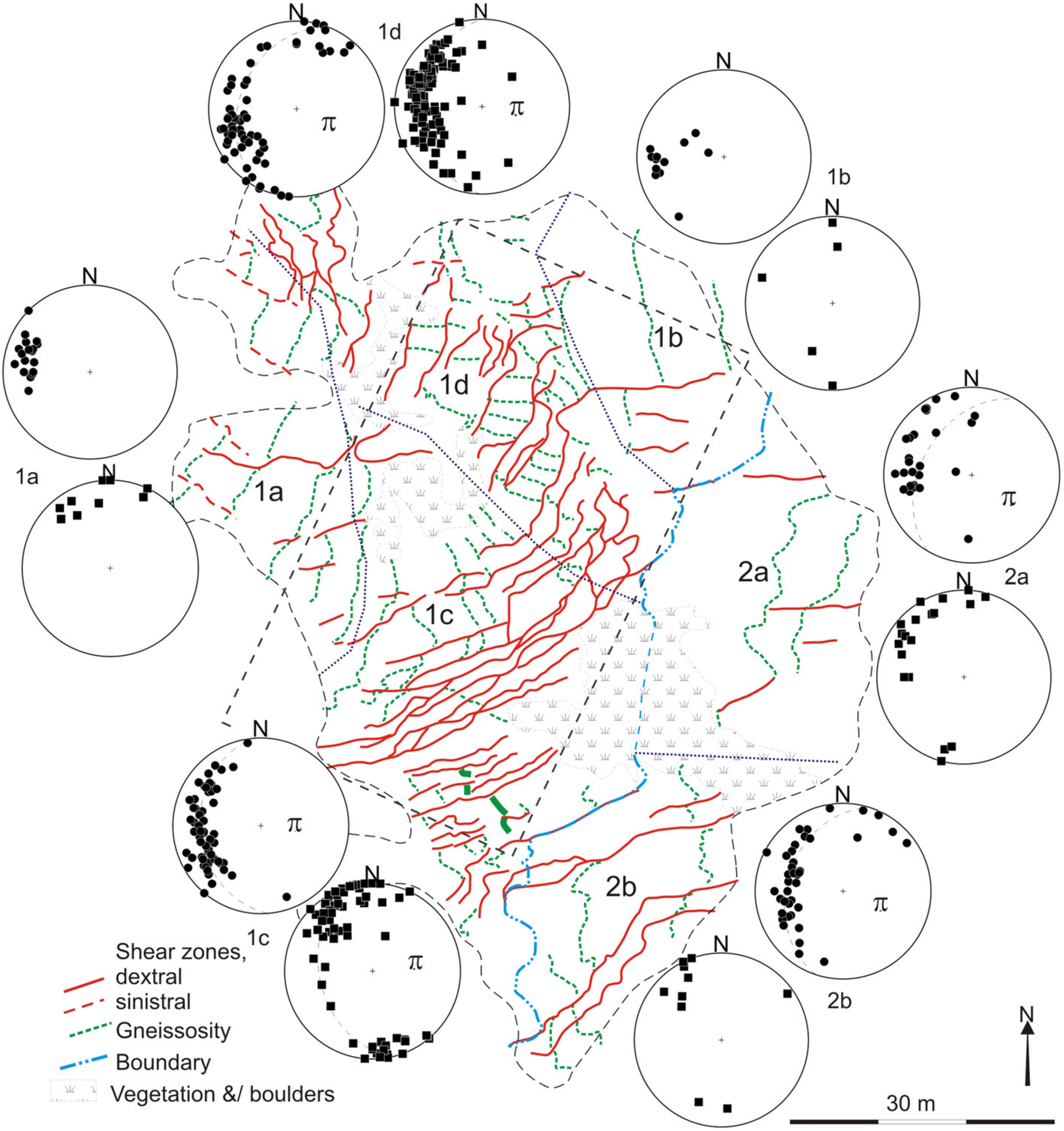

Fig. 5. Structural summary map shows structural domains for Units 1 and 2; continuous lines, shear zones; close spaced dashes, wall rock layering; wide spaced dashes, boundary Units 1 & 2; thick line in SW, concordant granite. Lower hemisphere equal area projections showing poles to unsheared gneissosity, circles, and gneissosity from within shear zones, squares; pole to best fit great circle (p, hinge or inflection point of shear zones) shown where appropriate. Box, Fig. 3.

of the total length and more than 90% of shear zone intersections are concentrated, the area increases to near 30%. Within this core shear zone spacing is constant but with higher variation where linkage is less common. Unit 2 comprises only 8 percent shear zones with a concentration in the southern portion (2b) where their areal percentage is closer to double the bulk Unit 2 value (i.e. comparable to Unit 1 core) (Table and figures, Supplementary data).

The southern arm of the core of the shear zone system (1c, Fig. 5) is characterised by northeast-striking shear zones and wall rock gneissosity that strikes anticlockwise from the regional trend (1a, Fig. 5). In the northern arm, wall rock is at an even higher angle to regional orientation and shear zones strike NNE (1d, Fig. 5). In the northwest tip of Unit 1d (close to the boundary with 1a), shear zones, locally deflected around mafic blocks, have an overall strike just west

Fig. 6. Details of wall rock panels flanked by shear zones. (a). Partially retrograde mafic granulite gneiss forming shear zone wall rock (w). (b). Oblique view of a, showing note pre-shear isoclinal fold (bottom right arrow) & partially retrogressed orthopyroxene-plagioclase patches (other arrows), textural features typical of mafic granulites. (c & d). Shear zones reworking layered gneiss wall rock panels (W) formed of varying proportions of granitoid (light) & mafic (dark) layers. Horizontal field of view: (a & d) ca. 6 m; b, ca. 4 m. See Fig. 3 for locations.

of north. The shear zones trace a large-scale sigmoidal pattern from Unit 1c, through 1d to 1b (Fig. 5). Both aerial and pole-camera views emphasise the preservation of the original orthogonal relationship between most wall rock gneissosity and shear zones despite rotation of the latter (compare the orientation of layering close to regional strike, top left of Fig. 5, with that below it; also Figs. 2 and 6).

Besides in the shear zone rich corridor (Unit 1c and southern Unit 1d; Fig. 5), linked shear zones are also common in a NNE trending area close to where Unit 1d shear zones terminate against Unit 1b (Fig. 3). Where shear zones are sparse in Units 1a and 1b they are unlinked as in both flanks of the shear zone rich corridor of Unit 1c (Fig. 7).

There are two distinct modes of shear zone linkage: (i) minor, new shears (cutting established wall rock) link with major established shear zones; (ii) established shears merge and form a thicker single shear. The first type of linkage has two varieties both of which affect established wall rock panels and contain minor pegmatitic material, of indeterminate relative age (e.g., Fig. 8a–b, Fig. 9a) which potentially assisted shear zone nucleation within a hydration zone probably related to nearby established zones. In the first-sub-type, oblique minor shear zones link separate established shear zones (Figs. 2e, 3 and 7). Such linking transverse shear zones have low displacements, similar to minor unlinked zones (e.g. Fig. 7), and consistent with their relative narrowness compared to the high displacement zone to which they link. Linkage of this type results in a locally dense network of shear zones that increases the local bulk displacement and alters the original orthogonal wall rock – shear zone relationship producing sigmoidal wall rock ‘fish’ between linking and established shear zones (e.g., Fig. 8b).

In the second sub-type, linkage results where a new shear zone (embryonic SZ$_2$, Fig. 9a) ‘slices’ off the edge of a preexisting wall rock panel, beginning and ending in the single established shear zone that bounded one side of the original panel of wall rock. As in the first-sub-type, because the proportion of curved relative to straight layering increases with decrease in the size of wall rock panel the process isolates a sigmoidal ‘fish’ of wall rock between the new and old shear zones (Fig. 9b). Examples of one or more such ‘fish’ lie within a single thick shear zone (Fig. 9c), may have been produced by the first or second sub-type of the first mode.

The second mode, merging of established shear zones, occurs where the entire wall rock between parallel shear zones effectively collapses, uniting shear zones formerly lying on opposite sides of wall rock panels. The beginning of this process is displayed where folded intervals appear in felsic layer-rich wall rock (Fig. 3; Fig. 10a, shear zones to left and right of deformed wall rock, dw, in process of merging) and a more advanced stage is evident where merged shear zones (Fig. 10b, msz, shear zones merge from left to right) contain relics of collapsed wall rock (dw, Fig. 10b). The entire process is displayed at a smaller scale near the tips of curving shear zones which merge in response to increased displacement (Figs. 3 and 10c, d). This is accompanied by wall rock folding (Fig. 10c) with open folds amplified to isoclinal with progressive shear zone merging (Fig. 10b–d). The relative strength of mafic wall rock compare to the more readily folded layered gneiss results in the formation of a second species of mafic ‘fish’ (Fig. 10b).

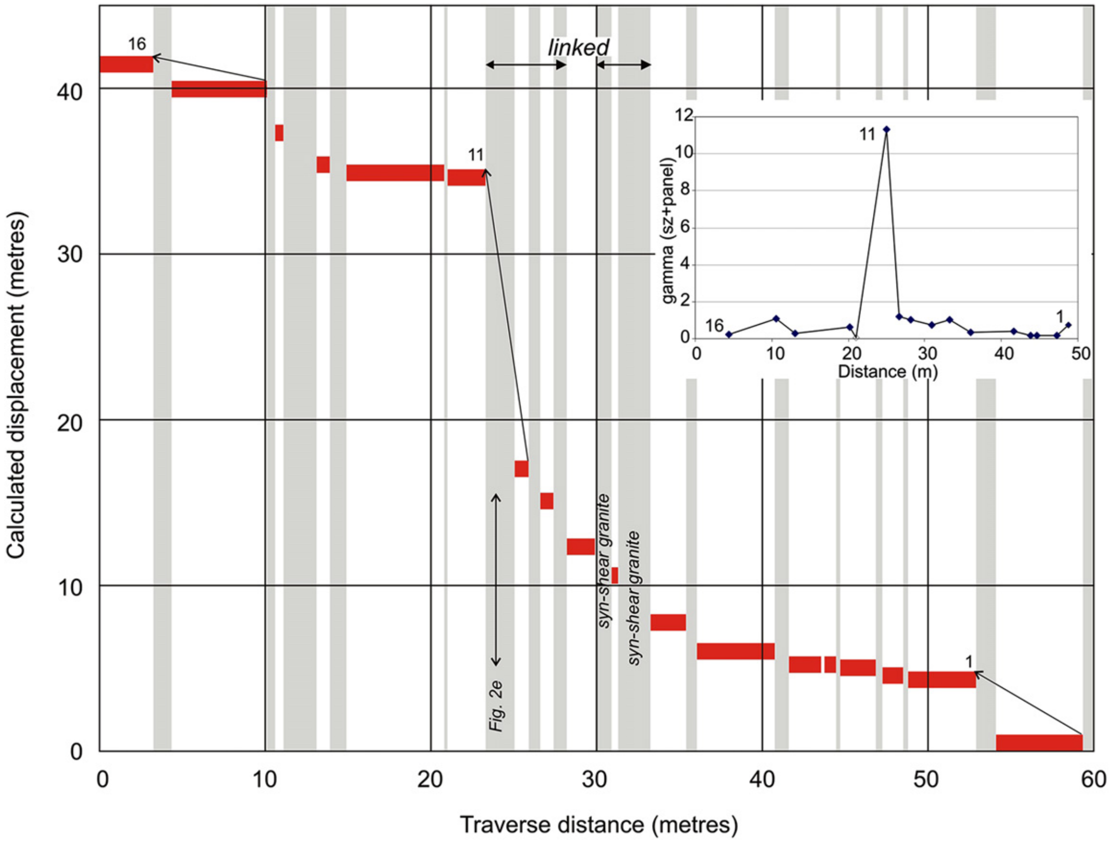

Fig. 7. Cumulative displacement across shear zones along traverse shown in Fig. 3. Shear zones with measured widths, shaded vertical bars; shear zone walls, plain and containing displacement markers. Displacement across shear zones calculated from average shear strain–distance plots, with average shear strains calculated using α–α' method (see text). Inset shows total shear strains calculated from displacement across shear zone – shear zone wall pairs (maximum average shear strain is ∼8).

Unusual structures include those located at points of abrupt curvature of corridors of parallel shear zones, a triangular zone of asymmetric wall rock deformation (Figs. 3 and 11a) and en echelon shears lie within broader zones of curvature (Fig. 3). In Unit 1c, an irregular concordant granite sheet separates domains of different layer rotation and shear zone displacements (Fig. 11c). One segment of the granite fills an extensional zone mediating a change in displacement and strike along the shear zones (Fig. 11d). Enigmatic folds with sheared margins lie within wall rock but away from such bends in shear zone – wall rock corridors. The sheared margins of the folds link with the main shear flanking the wall rock (Fig. 3; dsz, Fig. 11b).

Displacement along the shear zone terminations in Unit 1d, (close to the boundary with Unit 1b; filled circles at shear zone tips, Fig. 3), decreases with curvature (evident from variation of offset of layering; Fig. 4a). Rotation (clockwise for dextral zones) from high to lower displacement segments is characteristic of the terminations. Although pegmatite is emplaced close to the shear zone tips, this geometry is consistent with shear zone propagation without nucleation along pegmatite (Fig. 4). In most cases the termination is abrupt close to a thick felsic layer that presumably formed a barrier to propagation (Figs. 3 and 4a), but one shear zone in the same area penetrates the barrier and persists eastward across the island into

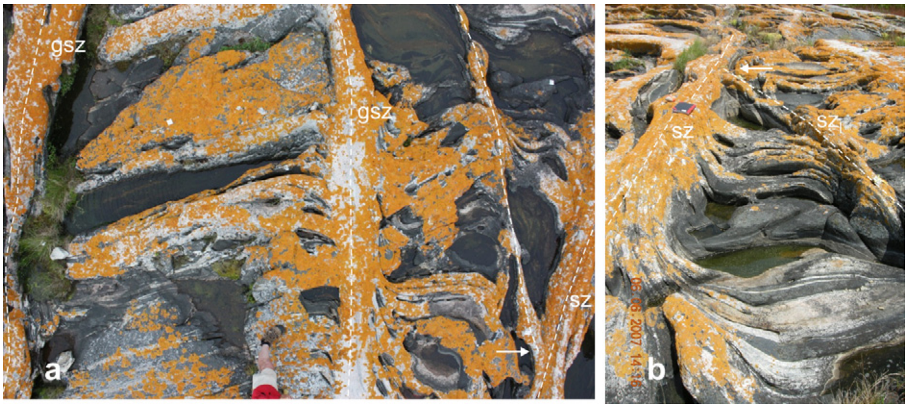

Fig. 8. a, b). Partial views of granite-cored (gSZ) & high strain (SZ) shear zones with separating wall rock traversed by shear zone (SZl) which links the larger zones and deforms the wall rock. a & b are views form opposite directions, arrow gives common reference. Horizontal field of view: a, ca. 6 m. Location shown in Fig. 3.

Fig. 9. Structures accompanying widening of shear zones. (a). Development of new shear zone (SZ2) within a wall rock panel (w); SZ2 is parallel an existing shear zone (SZ1), the two shear zones which isolate a deformed embryonic 'fish' (fnew) derived from the wall rock merge along strike. (b). A 'fish' derived as in a, flanked by shear zones which merge along strike. (c). Two 'fish' (f1 and f2) in one shear zone (SZ1); the shear zone is interpreted to have widened by two episodes of the process shown in a. Horizontal field of view: a, ca. 4.5 m; b, ca. 3 m; c, ca. 4 m. Locations shown in Fig. 3.

the shear zone poor Unit 1b. In contrast, curving shear zones in the southeast of Unit 1d appear to terminate at the layer-concordant boundary with Unit 2a (open circle, Fig. 3). The curvature of the discordant, dextral shear zone into the layer parallel segment is anticlockwise opposite to the previous examples (Fig. 4b).

3.3. Displacement and strains in the shear zone system

For individual shear zones we use several methods to estimate the displacement and average shear strain (defined as strain calculated from total displacement across a zone of known thickness (Fusseis et al., 2006)). We also estimate the maximum shear strain (γ_{max}) within some shear zones, which together with the average shear strain (γ_{mean}) allows calculation of the strain localisation intensity factor I_{loc} (Schrank et al., 2008):

$$I_{loc} = 1 - (\gamma_{mean}/\gamma_{max})$$

The closer this factor is to unity the more abrupt and angular is the shear zone profile, the closer to zero, the more smoothly curved (Schrank et al., 2008).

Because the gneiss is layered, the α–α' method (Ramsay and Huber, 1987) was the preferred method to measure shear strain. Plots of shear strain vs. distance across the shear zone permitted displacement calculations (e.g. Fusseis et al., 2006; Ramsay and Graham 1970). In many cases individual layers traceable across shear zones of known width allowed an independent estimate of displacement and thus average shear strain (see Supplementary material for examples of shear strain measurement, comparison of results by different methods and data). Maximum shear strains are difficult to measure accurately because of uncertainties measuring local strike where there is extreme rotation of layering at highest strains. Pegmatite forms a significant proportion of the width of low displacement zones but any shear strain taken up within them was unaccounted for due to the absence of strain markers. These calculations show that average shear strain values (as defined above) can be high (mean of values on Fig. 12 is 6.15; for compilation from all shear zones measured by all methods see Supplementary data). There is a tendency for the NNE-striking zones (e.g., Unit 1d, Fig. 12) to have higher values than those striking northeast (e.g., Unit 1c, Fig. 12). Maximum shear strains found within zones are in several cases in excess of 20. The average strain intensity localisation factor is 0.72 (range 0.53–0.86) reflecting relatively abrupt, subangular profiles seen in shear zone images (Figs. 3 and 6).

Within the least rotated part of the core zone, Unit 1c, there are significant variations in displacement and strain of individual shear zones. As noted, Unit 1c has areas of predominantly unlinked shear

Fig. 10. Structures accompanying merging shear zones. (a). Folds in predominantly granitoid wall rock (dw), mafic wall rock (w) remains undeformed except lobe (L) close to dw (L and w in a and b are same). (b). Merged shear zone (msw) containing predominantly mafic deformed wall rock 'fish' (dw). (c). Shear zones merge to form single thicker zone (msz), layered wall rock fold (dw) and open fold is amplified to isoclinal fold i, indicated also on d at point of merging. (d). Lobe of mafic wall rock (L, indicated also on c). Horizontal field of view: a, ca. 3 m; b and c, ca. 5 m; d, ca. 1 m (knife, 8 cm). Locations shown in Fig. 3.

zones separated by a swath of linked shear zones that differ both in appearance and displacement from the unlinked shear zones (Fig. 3). A traverse across the linked and unlinked portions of Unit 1c shows aggregate displacement summed across zones increases where zones are linked (Fig. 7). The increase in displacement is in part related to the closer spacing of the linked shear zones (relative to unlinked zones with similar displacement) and in part to high strain in one zone. The overall heterogeneity of 'bulk strain' (strain across specified section of rock including wall rock and shear zones) in this part of the system is also illustrated by shear strain calculated from displacement across shear zone-wall rock pairs along the traverse (inset Fig. 7).

Displacement across two or three parallel shear zones and intervening wall rock was measured where a continuous traceable layer could be followed from one shear zone to another to estimate 'bulk strain', as defined above (Fig. 13b). Following the method of Horsman and Tikoff (2005), this permitted calculation of bulk strain integrated over a wider area than that depicted in Fig. 7 and shows how the several components of the shear zone system together contribute to the deformation of the larger rock volume. The strains, as expected (given that wall rocks are included in the measurement), are much less (lower strain ratios; Fig. 13a) than average shear strains of individual zones, and may decrease with length of traverse along which bulk strain is measured (Fig. 13b, compare result from long traverse of Fig. 7 with others nearby). Overall the bulk strain shows a predominant NNE extension of the total rock volume with a swing to a northwesterly direction in the north of the island as shear zones curve towards that direction (Fig. 13a).

3.4. Shear zones in Unit 2

Unit 2 contrasts with Unit 1 in composition, character of layering, style of deformation, total area and spacing of shear zones (Figs. 2a and 5), further, gneissosity between shear zones in Unit 2 is folded. The discordant shears along the Unit 1–2 boundary have a net effect of extending the units parallel to the regional gneissosity (NNE) (Fig. 2a). Shear zones are more pervasively developed in Unit 2b (and parallel those in Unit 1c) than Unit 2a, and shear linkage is apparent close to the high displacement layering-discordant dextral shear along the unit boundary. There is local evidence for layer parallel sinistral shear in Unit 2, including offset and boudinaged pegmatite, winged feldspar and a metre-scale shear band. Weak folding of many Unit 2a discordant pegmatite dykes (Fig. 2a) indicates a unique element in the deformation path of Unit 2 involving shortening across the layering following back-rotation of domains between the boundary-parallel shear zones.

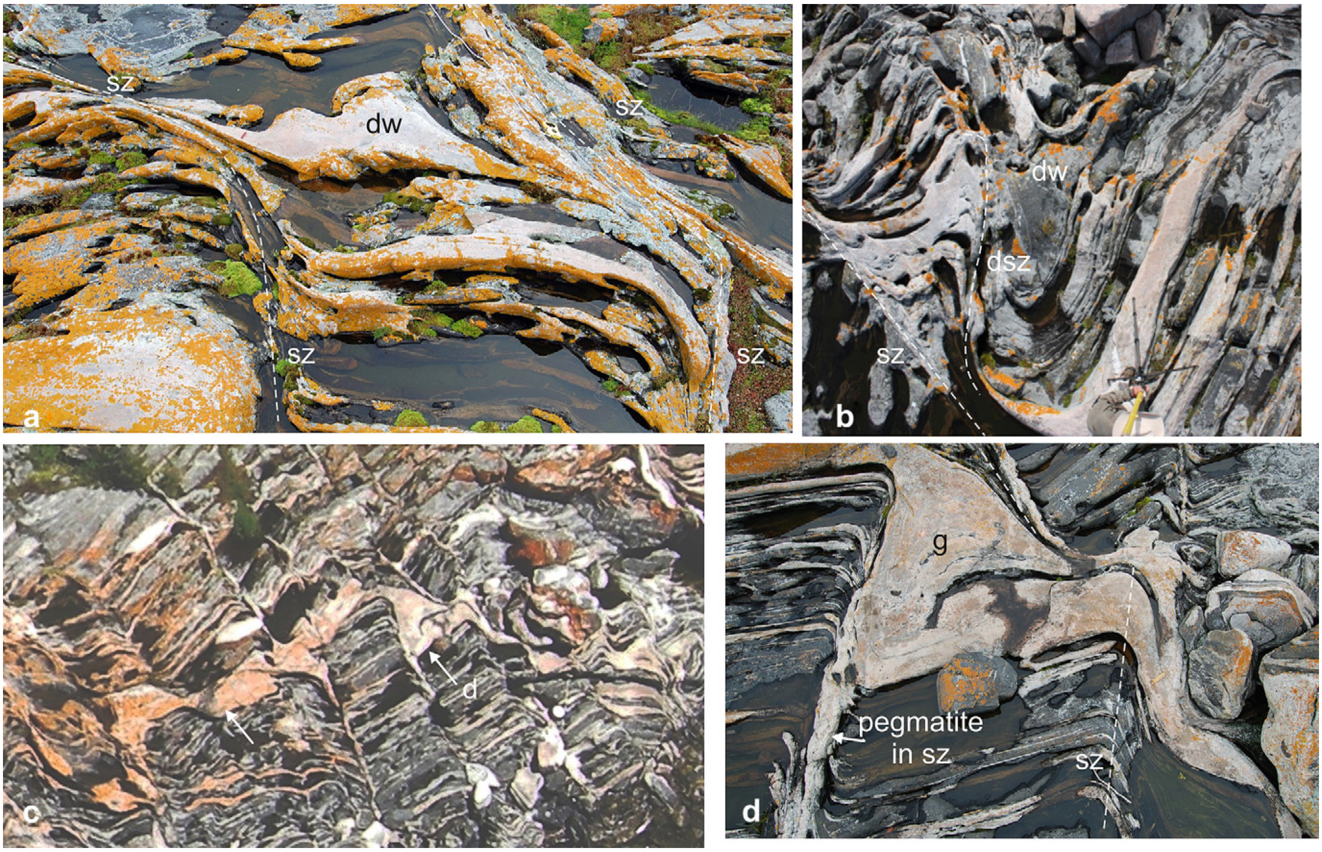

Fig. 11. Structures accompanying (a, c, d) and following (b) shear zone curvature. (a). Asymmetrically deformed wall rock at point of maximum curvature of shear zone pair; horizontal field of view ca. 5 m. (b). Deformed (?) shear zone (dsz) within a panel of wall rock (dw) flanked by a through going shear zone (sz); this deformed shear zone may have evolved from a compatibility maintaining zone; horizontal field of view ca. 4 m (c). Granite (arrows) separating shear zones of different strike; left arrow, compatibility maintained by tapering shape of granite segment; right arrow and d, change in amount of displacement managed and compatibility maintained by filling of extensional zone by triangular granite segment (g); horizontal field of view in c ca. 25 m; in d, ca. 2 m. Locations shown in Fig. 3.

4. Discussion

4.1. *Shear zone curvature*

The longest shear zones are curved and the Unit 1 array displays a sigmoidal pattern on the island scale. Several features may be relevant to explaining the curvature, and assessing whether the curvature was passive, imposed on preexisting shear zones, or an active feature inherent in the process of propagation. Noteworthy at island scale is the tendency for shear zone orientation to correlate with apparent strain judged from field appearance and measurements showing shear zones with highest and lowest average shear strains strike, respectively, NNE and east–west (Fig. 12). At outcrop scale the correlation of average shear strain and orientation is evident at shear zone tips (Fig. 4a). Anomalous anticlockwise curved termination of the dextral shear zone in the south of Unit 1d (Fig. 4b) may imply dextral displacement transitions to sinistral along the concordant segment (note sinistral shears a few metres to west are sub-parallel the Unit 1–2 boundary (Fig. 3a)) or shear zone termination was parallel the layering anisotropy (Fusseis et al., 2006).

A second distinctive feature of the curved shear zones is the common preservation, whatever the shear zone orientation, of the original orthogonal relationship between undeformed wall rock gneissosity and shear zone. This is explained by the tendency of mafic wall rock (in contrast to compositionally layered felsic–mafic intervals, e.g. Fig. 10a) to partially retain strong granulite facies mineralogy thus restricting syn-shear zone deformation of the wall rock (e.g. Fig. 6a–b). The relevance of this behaviour is that some structures located where wall rock – shear zone corridors curve may be accounted for by compatibility requirements imposed by rotation of such strong wall rock. Thus, where strong (undeformed) wall rock segments are differently rotated there must be localised wall rock deformation to avoid triangular gaps or overlaps. Structures formed to satisfy the compatibility requirements likely include the triangular zone of asymmetric wall rock deformation (Figs. 3 and 11a) and structures along the concordant granite sheet separating and detaching domains of different layer rotation and shear zone displacements (Fig. 11c, d). The en echelon shear zones with minor displacements may serve the same purpose within a wide, curving wall rock – shear zone corridor (Fig. 3). We further speculate that when corridors containing such en echelon zones rotate, the isolated elbow-like ‘en echelon’ zones may evolve into the folds with sheared margins that penetrate into wall rock in places (Fig. 3; Fig. 11b).

‘Bulk strain’ measurements across several segments of shear zones and wall rock indicate an overall NNE, varying to northwest in the north, extension of the rock volume. A similar bulk extension direction is inferred from orientation of sinistral and dextral shear zones in Unit 1 and from dextral boundary shears and layer parallel sinistral shear in Unit 2. This extension direction is compatible with that inferred from the mega-boudinage of Unit 3 (Fig. 2) and is consistent with extension direction inferred from orientation of precursor fractures and pegmatite dykes in shear zone free granulite to the north.

Taken together, the occurrence of curvature at different scales and of shear zones formed to accommodate curvature, for example the en echelon shears (Fig. 2) or in the ‘triangle zone’ (top left Fig. 11 a),

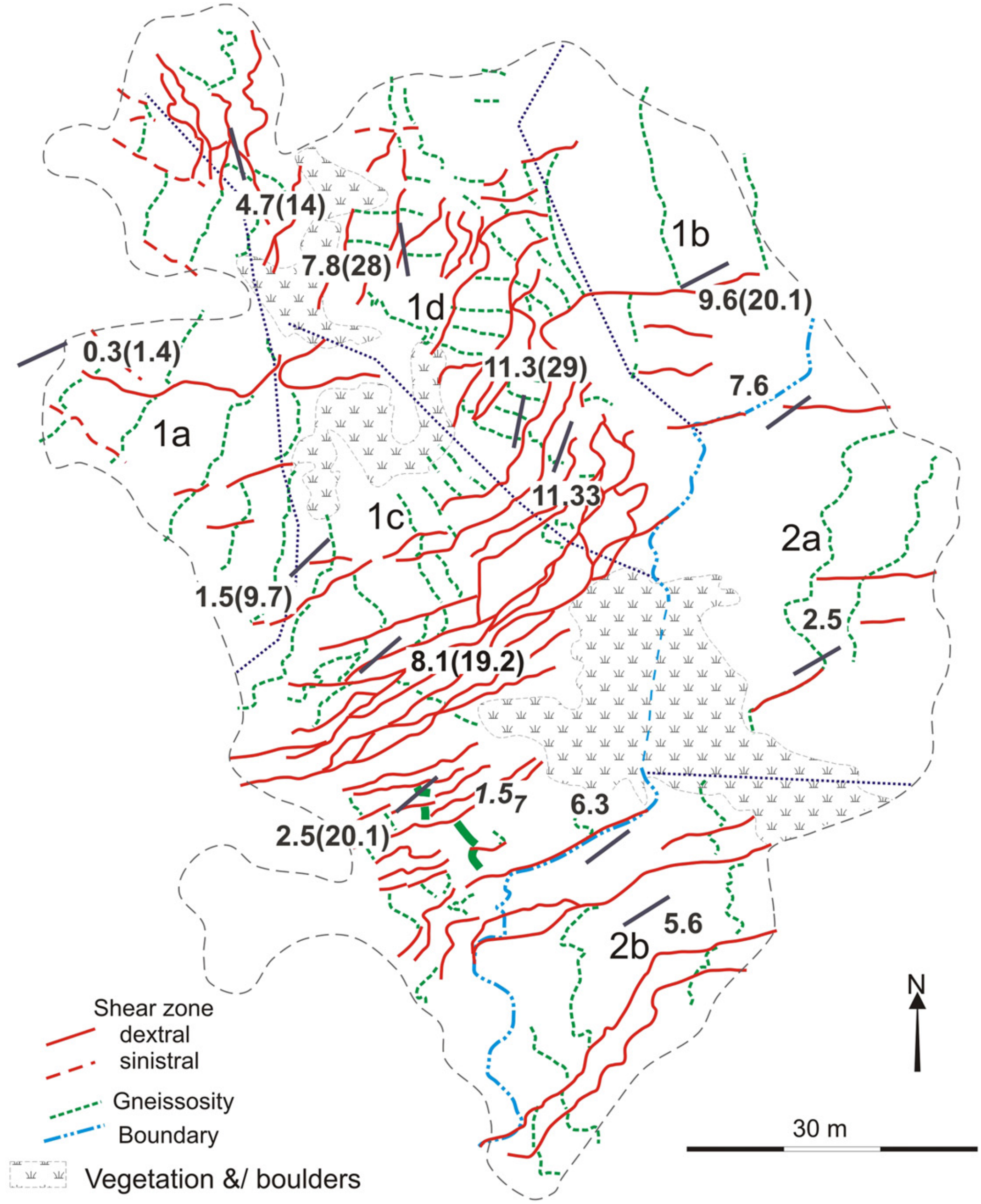

Fig. 12. Map showing values of average shear strain calculated using α–α'-based method (maximum shear strain in brackets) or displacement vs. shear zone thickness method (no maximum shear strain); see text for further explanation of 'average'. Italicised values (bottom left), arithmetic means of shear strains from several shear zones (subscript, number of shear zones). Granite layer, thick green line; short straight line, long axis of strain ellipse. Map symbols as Fig. 5. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

favour an active element in generation of curvature. However the swing to the northwest in the bulk extension direction may result from the influence of the irregular edge of a mostly unexposed undeformed block (e.g. Unit 1a).

4.2. *Shear zone networking*

For a small-scale system such as Matches Island to evolve into a component of a large-scale, high strain, nappe-bounding system, such as Twelve Mile Bay shear zone, isolated shear zones must develop into a linked network (Handy, 1994; Handy and Stunitz, 2002; Fusseis et al., 2006; Schrank et al., 2008).

The scarcity of linkage in Unit 1a, where shear strains are low, when contrasted with parts of Units 1c and most of Unit 1d where linkage is much more common and shear strains higher, is prima facie evidence for progressive occurrence of network development (Fig. 13). A directly comparable case can be made for the contrast between Units 2a and 2b. At a local scale within Unit 1c, low displacement unlinked shear zones give way to aggregate high displacements where shear zones are linked (Fig. 7). Increased displacement is clearly related to linkage where merging of two shear zones accompanies increased displacement in curving segments near shear zone tips (Figs. 4a and 10c).

From the above we infer that shear zone linkage is progressive and the linking and networking present in Unit 1c–1d corridor

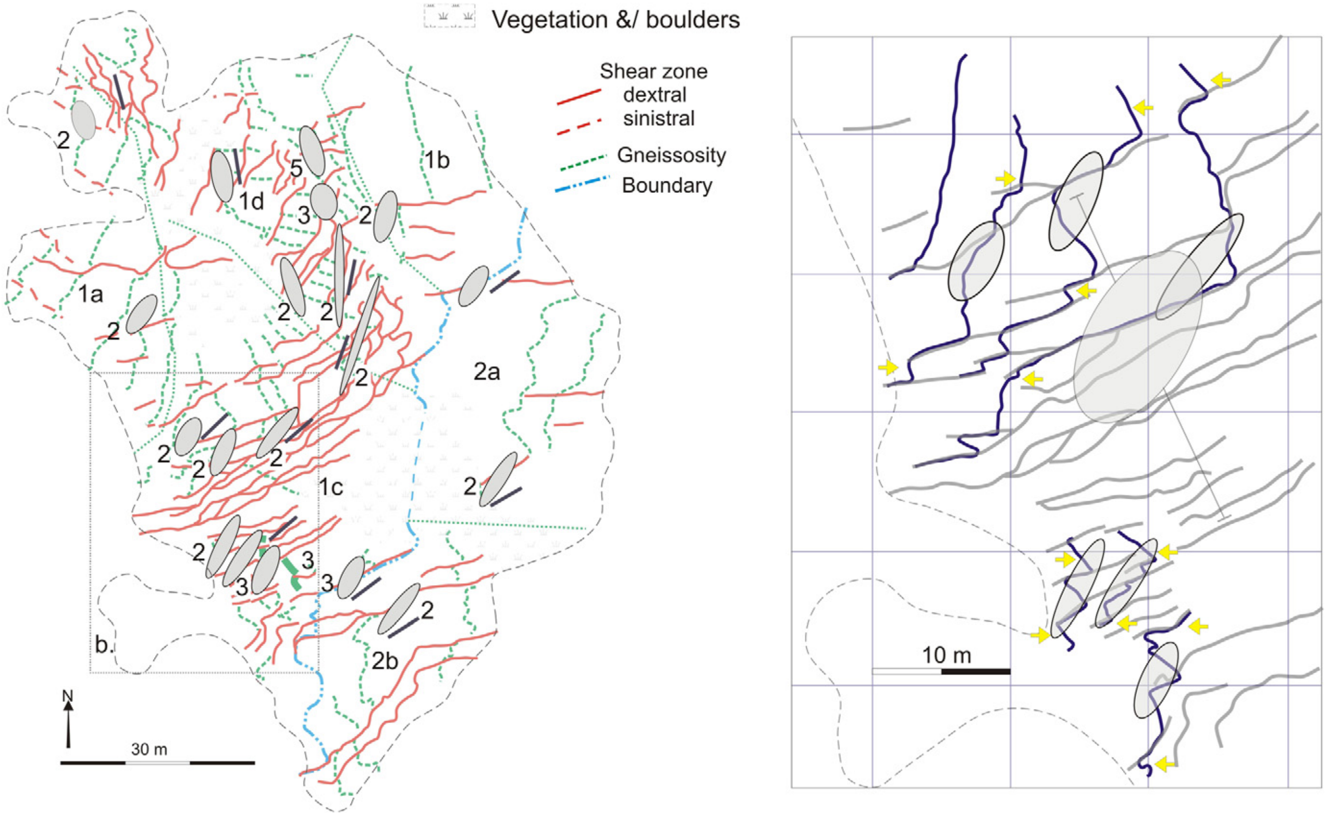

Fig. 13. a). Map showing bulk strains across shear zones & wall rock (see text for explanation); number of shear zones traversed indicated; line by strain ellipse is long axis (from average shear strain) of a component individual shear zone. (b) Detail of map showing marker horizons (arrowed) used to derive distance-displacement data for deriving strain (see text & Supplementary data for further information).

mark a large scale softening and an important milestone in transposition of the margin of the Parry Sound domain. Initially the shear zones, narrowly restricted to within hydrated and retrogressed zones focused on early pegmatite dykes, were isolated and unconnected to their neighbours (e.g., the unlinked pegmatite bearing shear zones in south of Fig. 7; also Unit 1a, Fig. 5). Networking was related to the inability of the isolated active shear zones to accommodate imposed strains within already fluid-softened, but volumetrically restricted, rock rather than to the spread of retrogression. The result was the linked parts of the system became weaker than the unlinked parts (Handy, 1994) and characteristic relict structures were generated, e.g. sigmoidal gneissic 'fish' (i.e., rotated wall rock relicts), unrotated mafic wall rock blocks and isoclinal folds.

Comparable features are present within the thicker shear zone segments of the Twelve Mile Bay shear zone for which there is ample independent evidence of granulite facies protolith (Marsh et al., 2011). In the Twelve Mile Bay shear zone individual shear zones are proportionately wider (Fig. 14a), undeformed wall rock may have a Matches-like orthogonal relationship to shear zone (Fig. 14a) and deformed wall rock may be subtly preserved and represented by asymmetric folds within shear zones (dw, Fig. 14a) or quite plainly preserved (e.g., dw, Fig. 14b; note too examples of 'fish', f). The occurrence of a suite of comparable features within incipient and advanced zones of transposition demonstrates the regional significance of the transposition processes inferred from Matches Island for multilayers with granulite facies protoliths. Underlining the significance of these features, Gerbi et al. (2010) calculated that Matches Island underwent approximately 30% bulk weakening due to the formation of the shear zone network.

4.3. Control of deformation geometry and sequence by layer mineralogy

Matches Island displays the response of two different types of layered units to similar kinematic boundary conditions. Of these, Unit 1 formed a widespread linked shear system and has a completely distinct structural style compared to Unit 2 (hornblende-biotite-bearing gneiss), which displays significant folds between variably developed shear zones.

The Unit 1 multi-layer did not buckle prior to shear because strength was maintained where hydration of mafic granulite facies mineralogy was incomplete. The incomplete retrogression of mafic wall rock, as well as orientation of pegmatite-related fractures, the source of softening fluid, accounts for the distinctive style of the deformed Matches Island multi-layer.

Unlike Unit 1, Unit 2 is pervasively retrogressed, the underlying reason for this is most likely the absence of Unit 1-type mafic layers capable of locally retaining dry granulite vestiges. The absence of such mafic layers with their inherent strength (relative to quartz-feldspar rich rocks) is also responsible for the lack of the characteristic wall rock – shear zone geometry of Unit 1 although all Unit 2 shear zones are localised on pegmatites (as in Unit 1). The shear zone displacements are predominantly lower than in Unit 1 suggesting bulk strains are accounted for by layer parallel shear in the pervasively retrogressed matrix and/or buckling of the multi-layer.

The style of Unit 2 is comparable to that documented where layered gneisses of the Parry Sound shear zone are buckle folded then sheared at the edge of the Shawanaga shear zone (Culshaw, 2005), a style which may be widespread in polydeformed layered gneisses of the Central Gneiss Belt (Culshaw et al., 2010). There are

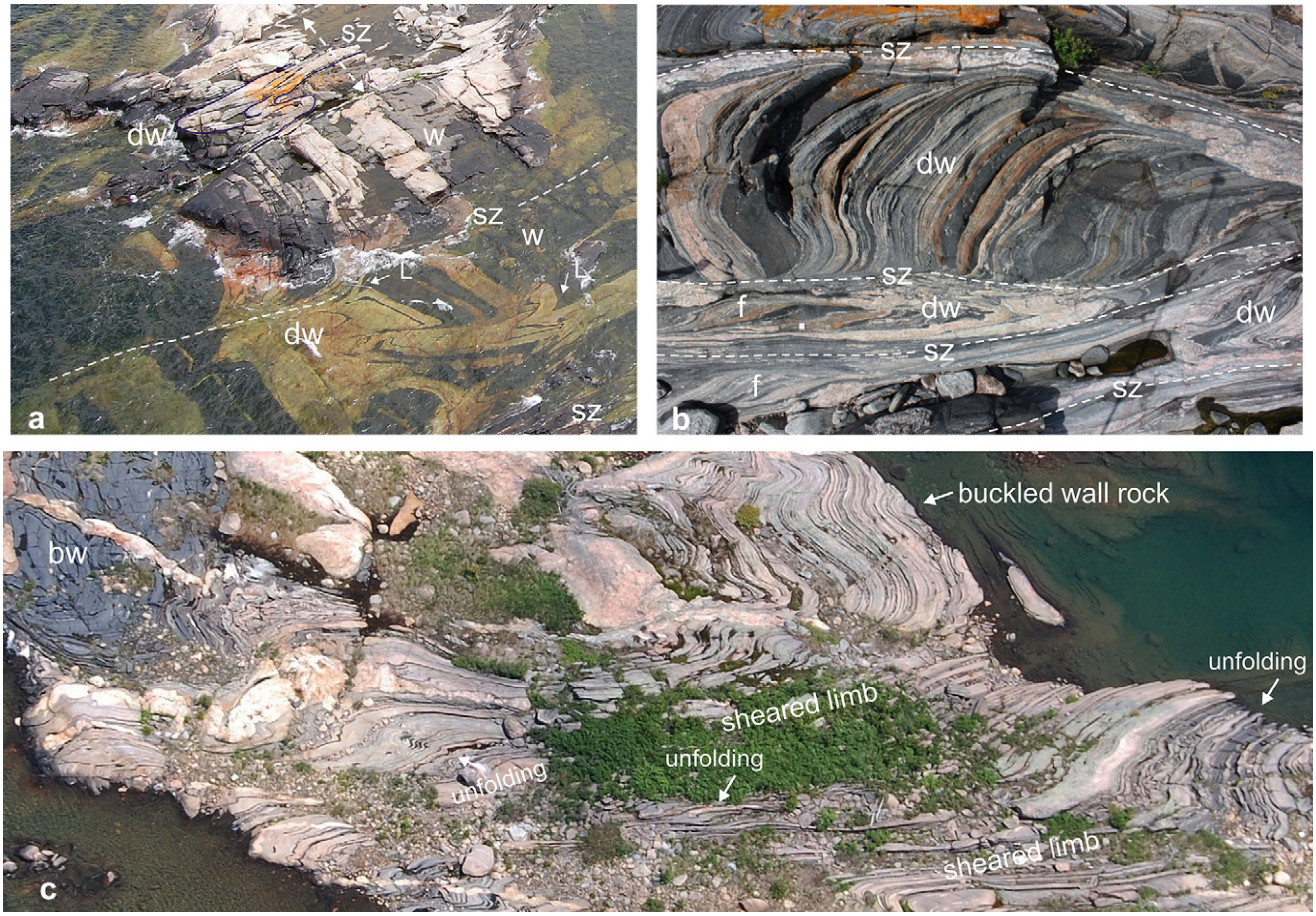

Fig. 14. a) and (b) show shear zone structures from TMBSZ (location, Fig. 1) similar to those on Matches Island. (a). Thick shear zones in tonalitic gneiss (arrow ca. 5 m) displaying asymmetric layering (dw) interpreted to be relict wall rock panel transposed during shear zone merging; w, wall rock panels with orthogonal angle to shear zone; L, lobes developing to isoclines. (b). Well preserved wall rock panel (same location as a) showing merging of three shear zones (SZ) & related development of 'fish' (f) & deformed wall rock (dw); note absence of thickness related fold wavelengths (no buckling); field of view, ca. 5m. (c). Aerial view (location, Fig. 1) shows style of shearing- and-reorientation related structures in layered granitoid-mafic gneiss with amphibolite facies protolith; pre-shear buckles are evident in 'buckled wall rock', some of these are part unfolded in sheared limb; field of view ca. 45–50 m.

thus at least two contrasting modes of deformation in response to shear of gneissic multilayers in the CGB. The type exemplified by Unit 1 preserves wall rock structure and displays the distinctive features described above. The second type includes gneissic multilayers (e.g., Unit 2) which buckle before or during shearing (Culshaw, 2005). The key difference between these types is the localisation (in granulite facies protolith e.g., Unit 1) or ubiquity (in buckle-and-shear multilayers, e.g., Unit 2) of amphibolite facies mineralogy (especially mica) present within layers at the beginning of deformation. Pervasive amphibolite facies mineralogy before deformation (e.g., Unit 2) may engender a significant competence contrast that allows multi-layer buckling as a first response to deformation. In the granulite protolith buckling cannot occur before shearing because a strength anisotropy (the incompletely retrogressed granulite) runs transverse to the compositional layering. Folding may occur much later, after formation of shear zones (e.g., bold form lines, Fig. 3).

The contrasting transposition structures that result from these differences are easily distinguished. The amphibolite protoliths buckle first then shear resulting in wall rocks displaying buckle folds and shear zones containing folds that are unfolding or tightening, depending on their asymmetry and the sense of shear imposed on the buckles (Fig. 14c; Culshaw, 2005). In contrast, in the zonally retrogressed granulite protolith gneiss, curving or non-orthogonal (to shear zone) gneissic layering may result within relict wall rock (e.g., 'fish' Fig. 14b), but periodic folding with layer thickness controlled wavelength, characteristic of buckle folding, has not been observed.

4.4. Origin and development of the Matches Island shear zone system

If we accept the northwestern corner of Matches Island as unrotated from NNE regional strike (Fig. 5, Unit 1a), the original fracture orientation is orthogonal to the regional layering as observed in mostly unsheared rock on the periphery of the reworked granulites. Shearing is then restricted to the hydrated and softened zones peripheral to the pegmatite dykes (whether filling purely extensional- or extensional shear fractures) cutting the granulite layering.

We offer two models for the further evolution of the shear system. In the first the regional layering is simply extended parallel to its strike (Fig. 15a). Progressive extension in the same direction rotates shear zones and wall rocks as average shear strain accumulates on the shear zones and bulk strain of the whole rock volume increases (left to right, Fig. 15a). On Matches Island such extension would have been heterogeneous (i.e. a mix of the three panels of Fig. 15a) and can explain rotation of shear zones, shear zones along the boundary between Units 1 and 2, layer parallel shear within Unit 2 and boudinage of Unit 3.

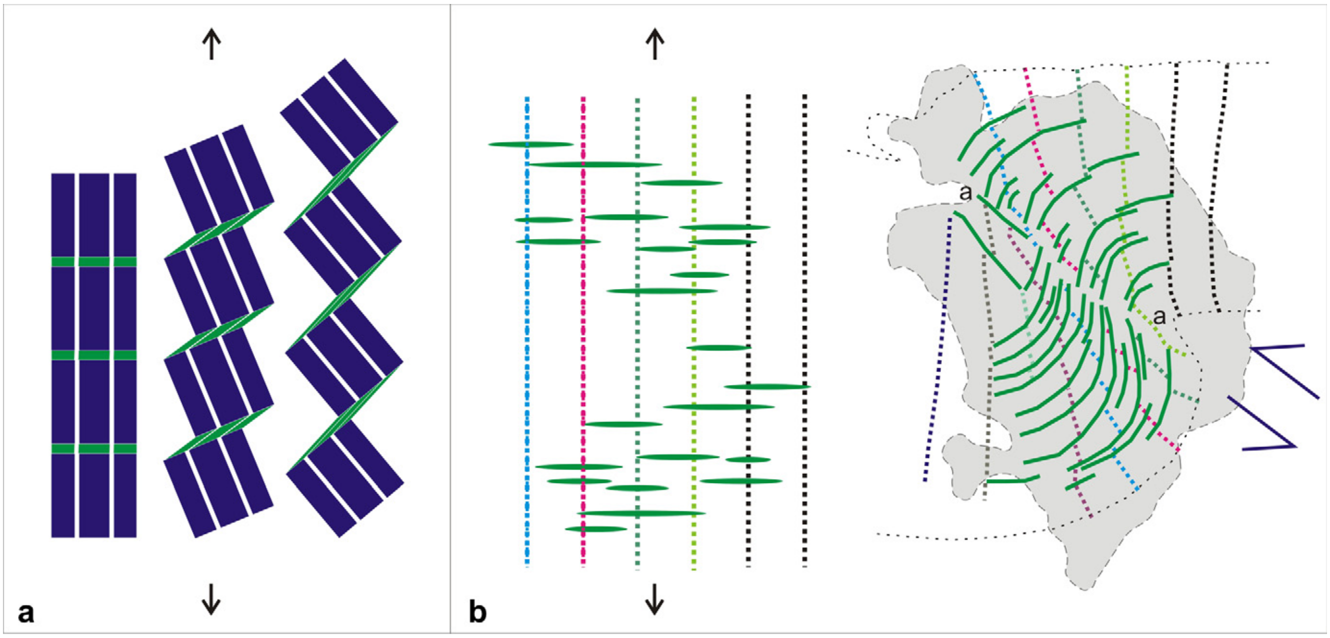

Fig. 15. a). Left: pegmatites fill extending regional gneissosity (vertical) hydrating & weakening thin zone in wall rock which evolve to shear zones as extension continues (to right) & progressively rotates shear zones. (b). Left: extending regional gneissosity cut by cracks which, as in (a), evolve to shear zones (modelled by faults in figure to right) Right: adaptation of figure (mirror image) of Kuenen and de Sitter (1938) showing deformation of clay slab with initially vertical markers (dashed) along curved faults superimposed on outline of Matches Island. Most faults/shear zones are antithetic to sinistral TMBSZ parallel shear; they are analogous to flexural slip surfaces.

The second model is adapted from an analogue model of Kuenen and de Sitter (1938; in Ramsay, 1967, Figs. 7–60). In this model flexural slip in shortened clay slabs is expressed predominantly as curved faults with sense of shear opposite to that imposed – producing a fault pattern quite similar to Unit 1 shear zones (Fig. 15b). Model and natural sigmoidal shear zones have the same shear sense and vary displacement along their length. Marker offsets and fault spacing in the model are appropriate to produce comparable bulk strains (across two or more zones) to Matches Island. Also, model and reality have in common relatively minor shear zones synthetic to the master (long-dash shear zones, Fig. 2a; location a), Fig. 15b. The model implies that early syn-shear veins and fractures should have slip parallel to their walls, as observed in the embryonic structures north of Matches Island. In the analogue model some boundary-parallel shear of wall rock took place comparable to that on Matches Island where wall rock layering at a high angle to shear zones may be deformed (in Units 1d and 2). In the analogue model, the clay between the faults is much closer in strength to the fault surfaces, more like Unit 2 than the partially retrogressed (hydrated) Unit 1 granulite gneiss possibly explaining fold proliferation there. In contrast, Gerbi et al. (2010) estimate the Unit 1 shear zones to be at least an order of magnitude weaker than wall rock thus Unit 1 gneiss initially partitioned strain into the fully retrogressed shear zones, with resulting strain incompatibility accommodated in part by rotation of the stiff wall rock (Lister and Williams, 1983).

5. Conclusions

The Matches Island shear system displays the early stages of transposition of granulite layered gneiss to amphibolite facies layered gneiss during formation of a major nappe-bounding shear zone. The Matches Shear system is not to be viewed solely as an isolated set of shear zones but as an illustration of an early stage in the development of a major crustal structure. The component shear zones nucleated within retrogressed zones around early extension fracture-filling pegmatites at high angle to layering, subsequently propagated, increased displacement, linked and rotated towards the local extension direction (deduced from bulk strain and initial pegmatite orientation). The resulting style of transposition, which contrasts with the buckle-and-fold mode of amphibolite layered gneiss, may be typical of partially retrogressed, layered granulite protoliths.

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Appendix. Supplementary material

Supplementary data related to this article can be found online at doi:10.1016/j.jsg.2011.03.005.

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