Photo-mapping and Structural Geology of Matches Island, Central Gneiss Belt, Grenville Province, SW Ontario

Peter Regan

A thesis submitted to the Department of Earth Sciences, Dalhousie University in partial fulfillment of BSc Honours requirements

April 2012

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DALHOUSIE UNIVERSITY
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Department of Earth Sciences
Halifax, Nova Scotia
Canada B3H 4R2
(902) 494-2358
FAX (902) 494-6889

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AUTHOR: Peter J Regan

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Abstract

The Parry Sound domain (PSD), a granulite nappe in the Central Gneiss Belt of the ca 1.1 Ga Grenville Province gives insight into structural processes in mid-crust of a doubly-thickened orogen. The Twelve Mile Bay Shear Zone forms a boundary of the PSD along which interior granulite facies PSD structures are transposed at amphibolite facies. The focus of the study is to create a quantitative map and to make measurements from the map for further structural analysis, for a better understanding of how the lower crust deforms. In the summer of 2011 a Dalhousie team set about creating this unique map by using a camera on a pole to shoot very low aerial photos of a few islands. The islands were selected being transitional from foliated granulite facies rocks to transposed sheared amhibolite facies rocks of the same composition, with the intention of understanding how these shear zones form and propagate. Leica DGPS system was used to set up a grid of points in combination with the pole-camera to shoot the grid systematically. Photos were merged together to create the map by experimenting with several different photo software suites. Now that the map is complete, data such as change in thickness of a layer as it enters a shear zone and layer displacement across a shear zone can be collected. This data can be used to quantify the shear strain and tell us how the islands have changed shape over time.

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Acknowledgements

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Last but not least I would like to thank my family, for their support as well. I would like to give a special mention to my father, John Regan who continues to be an inspiration to me.

Chapter 1: Introduction

1.1 General Statement

The Grenville Province of eastern Canada (Fig. 1.1) is a vast area extending from Labrador to southeastern Ontario. The exposures are predominantly amphibolite to granulite facies assemblages which give a unique window into the middle-lower section of a doubly thickened crust. The Grenville Province is a Mesoproterozoic (ca. 1190 to 980 Ma) (Hynes and Rivers, 2010) lithotectonic assemblage originating from the Grenville Orogeny that extends along the margin of eastern North America, with exposures in eastern Canada, and the southern United States. The Grenville Province is a result of continent-continent collision and coeval accreting of terranes to the Laurentian continent (Culshaw et al, 1997). The other continent involved in the collision with Laurentia is the Amazonia supercontinent at ca. 1100 Ma (Hynes and Rivers, 2010). The Grenville orogeny is one of the largest mountain building events in earth's history, spanning a significant part of eastern North America. The mountain belt extends from Labrador to Mexico.

Matches Island and Pseudo Bartram's East (PBE) are two islands on Georgian Bay that have been interpreted as being part of an allochthonous nappe, the Parry Sound domain, in a thrust sheet system of the Grenville Orogeny. These two islands display highly strained rocks that sit in a transitional zone from competent granulite facies rocks of the Parry Sound domain (PSD), which are gradually reworked by shear zones to amphibolite facies due to the softening of the PSD during its travel as a nappe. While both islands are within a gradient of

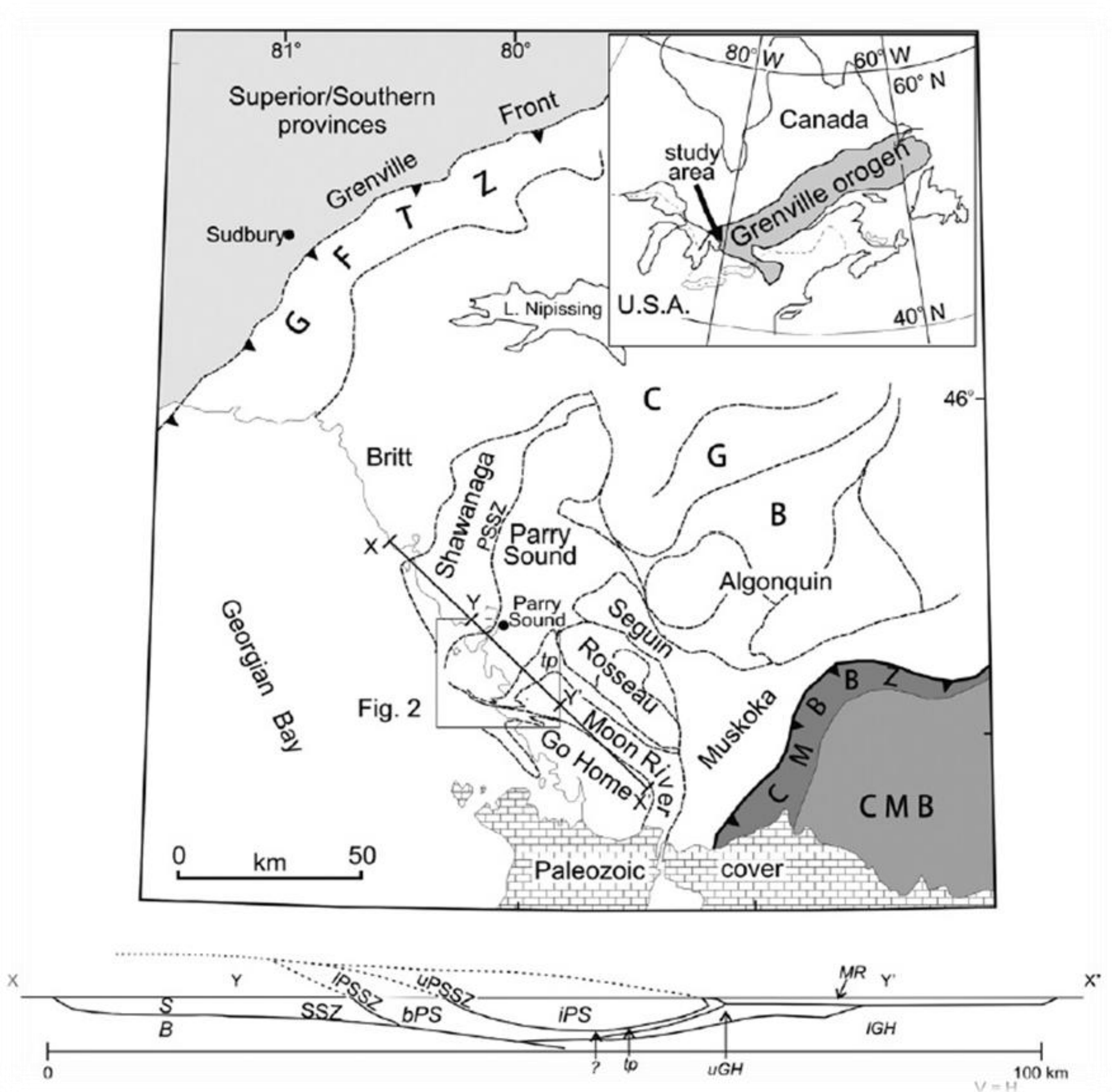


Figure 1.1: Geologic map of the Grenville Province of southeastern Ontario Lithotectonic subdivisions. GFTZ, Grenville Front Tectonic Zone; CMBBZ, Central Metasedimentary Belt Boundary Zone; CMB, Central Metasedimentary Belt; CGB, other domains of the southwestern Central Gneiss Belt. Central Gneiss belt domains on crosssection 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, lowerParry Sound shear zone; uPSSZ, upper Parry Sound shear zone; SSZ, Shawanaga shear zone; tp, transposed gneiss) (Culshaw et al., 2010)

transposition, Matches Island is in a mid-transitional stage, showing shear zones with undeformed wall rocks (Fig. 1.2). PBE shows a late-transitional stage of transposition, as the rocks are further along the softening process, subjected to higher strains, and are nearly transposed (Culshaw et al., 2012; Culshaw et al., 2010; Gerbi et al., 2010).

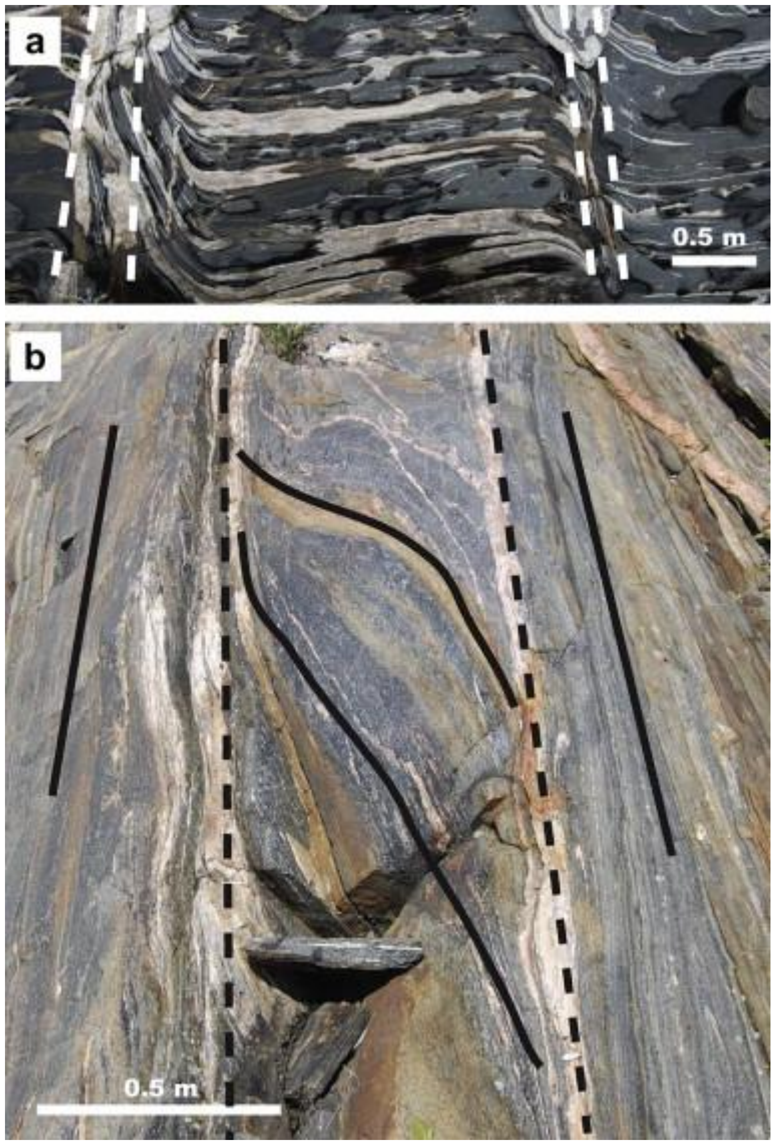


Figure 1.2: Examples of panel types. (a) Undeformed panels separated by shear zones on Matches Island, (b) deforming panels between shear zones. Shear zones are represented by dashed lines (Gerbi et al., 2010)

The focus of this study is to develop a method for creating a highly detailed map of Matches Island, by using low altitude, spatially referenced, aerial photographs to capture the intricate structure. The eventual outcome is to be able to use the photo map for quantitative structural analysis of the shear zone networks focussing on particular examples of structural complexity. The structural analysis may lead to further understanding of how a lower-mid crustal nappe such as the PSD softens along its margins during transport.

The ductile behavior of the zone of reworking around the margins of the PSD is evidenced by the existence of a network of shear zones on Matches Island (Fig 1.3). How the Matches Island shear zone networks change with strain when they are compared to the higher strain shear zones on PBE Island is an important aspect to this study - PBE being further along in the softening process, displaying nearly complete transposition is closely proximate to the entirely transposed Twelve Mile Bay shear zone (TMBSZ).

The structure of the exposure at Matches Island is a complex shear zone network with shear zones being at a high angle to the foliation of the wall rock, and while there is a general north-easterly trend of the shear zones, there is significant variation of the orientation due to the anticlockwise curvature of the shear zones (Culshaw et al., 2012). The shear zones appear to become increasingly complex in the southern portion of the map, where shear zones begin to become progressively denser. With this increase in shear zone density the degree of linkage of shear zones increases as the shear zone network is developed. The curvature of the shear zones reflect a change in shear strain along them, which could be due to linkage and network development.

Figure 1.3: An aerial photograph of Matches Island taken from a low flying plane, with north end of the island being the top of the photo. Photo by Culshaw.

Because of the cover of lichen, close spacing, and curving nature of the shear zones a large scale detailed map is necessary in order to truly begin to understand and interpret the structure. The map will allow quantitative measurements to be made. Examples include measurements of shear strain within shear zones and bulk shear strain integrated across several zones. Details of these methods will be further discussed in chapter two.

Using the data from these measurements, we can quantify shear strain across shear zones in an attempt to see how volumes of rock on Matches and PBE islands have changed shape in time with increasing strain. This is to be done in parallel with studying how these shear zones form networks, widen, and how shear strain is accommodated along the shear zone. We will also look at variations in the degree of shear zone linkage, something that is useful for understanding the relationship between shear zone linkage and strength (Fussesis et al., 2006).

1.2 Geologic Setting

The Grenville Province's multifaceted tectonic evolution is responsible for the complex crustal structure of thrust sheets and crustal nappes observed in the field relations and in map pattern. The accretion and subsequent stacking of micro continents and arc related terranes with the Laurentian continent formed the Grenville Orogen during the building of the supercontinent Rodinia by ca. 1.1 Ga and culminating with the collision of Amazonia with Laurentia (Hynes and Rivers, 2010).

The Grenville Province in southeastern Ontario is divided into three distinct units; the Grenville Front Tectonic Zone (GFTZ), the Central Gneiss Belt (CGB), and the Central Metasedimentary Belt (CMB) (Wynne-Edwards 1972) (Fig. 1.4).

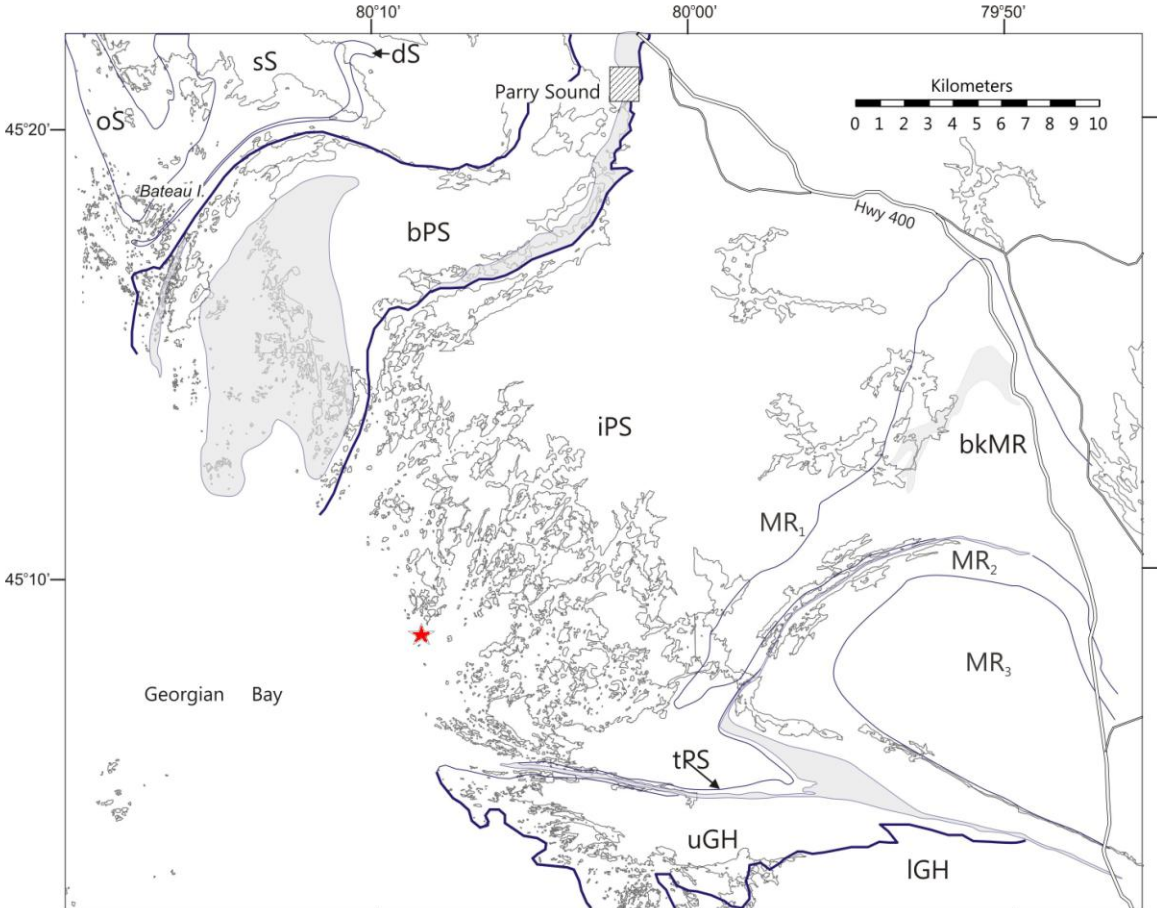


Figure 1.4: Southwest end of Parry Sound domain and parts of contiguous domains between Highway 400 and Georgian Bay. Shawanaga domain: oS, Ojibway; sS, Sand Bay gneiss associations; dS, Dillon Schist. Parry Sound domain: bPS, basal Parry Sound; iPS, interior Parry Sound; tPS, Twelve Mile Bay assemblage; tp, transposed gneiss unit. Moon River domain: MR1–2, 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 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. Matches Island is marked by the red star (Culshaw et al., 2010).

The CGB, within which the study area is situated, is made up of several lithotectonic domains, interpreted as thrust sheets (Hynes and Rivers, 2010; Carr et al., 2000; Culshaw et al., 1997) that are separate based on shear zone boundaries and their respective tectonic histories. The lithologies of the CGB are predominantly granitoid gneisses metamorphosed at upper amphibolite and granulite facies, some of which are migmatic with peak metamorphic temperatures in excess of 750 degrees C and pressures as high as 10-13 Kbar (Culshaw et al., 2010), which represent the mid to lower crust of a thickened orogen. The Georgian Bay section of the CGB is characterized by gneissic fabric with structures such as shear zone networks that indicate high strains originating by ductile flow over ca 70 Ma of tectonic activity (Culshaw et al., 2005).

The Parry Sound domain (PSD) is the lithotectonic domain that contains the study area of Matches and PBE islands. The PSD as a unit is an allochthonous nappe that has major shear zones that define its boundaries, being the Parry Sound shear zone (PSSZ) to the north and the Twelve Mile Bay shear zone (TMBSZ) which underlies the PSD (Culshaw et al., 1997). The PSD is one of several thrust sheets within the CGB. The PSD consists of mainly granulite facies gneiss which were derived from 1400-1330 Ma plutonic rocks, most likely arc related (Culshaw et al., 2005). There are large outcrop scale shear zones along the domain margins (Gerbi et al., 2010). The PSD is made up of metasediments, arc-related mafic through felsic orthogneisses and anorthosite originally formed ca.1400-1160 Ma (Marsh el al., 2011).

The field work for this project is in the southwest margin of the PSD, approximately 20km south of Parry Sound, Ontario on Georgian Bay (Fig 1.4).

1.3 Definition of a shear zone

During orogenic events rocks are subject to large amounts of deformation as the crust is shortened and thickened. For rocks that have been subject to deformation by orogenic processes it is common that finite strain state varies from locality to locality. In some rocks that have suffered these processes localized belts of high strain states will accumulate within a planar zone which we know as shear zones. These form when large scale rock deformation has occurred by the mechanism of ductile flow generally at medium to high metamorphic grade in the deeper levels of orogenic crust (Ramsay and Graham, 1970).

Angular shear strain is defined as angular changes for any direction is defined by measuring the change in angle between the line in that direction and another that was originally perpendicular to it. Shear strain is derived from angular shear zone by taking the tangent of angular shear strain, and is referred to by the Greek letter 'gamma' (γ)

$\gamma = \tan(\psi)$ (Ramsay and Huber, 1983).

Shear zones characteristically deform a body of rock under very high strains under ductile conditions, where displacement is a by-product of the strain. To describe these drastic changes in shape, an initial position of (x, y), of any point within an undeformed volume of rock is defined. The final position of the original position is written as (x', y'), and relates to the post deformation phase under Cartesian coordinates. The vector between the initial position and the corresponding post deformation position is known as the displacement vector and represents the shortest distance between the initial and final positions. The displacement vector can be broken down into components of x and y, so equations can be derived with a dependence on either component (Ramsay and Huber, 1970). By understanding this relationship (Fig. 1.5), numerous equations have been created to calculate change in shape, rotation and displacement with a given finite strain. The simplest pair of transformation equations is as follows:

$x' = x + A$, and

$y' = y + B$

where A and B are constants. (Ramsay and Huber, 1970).

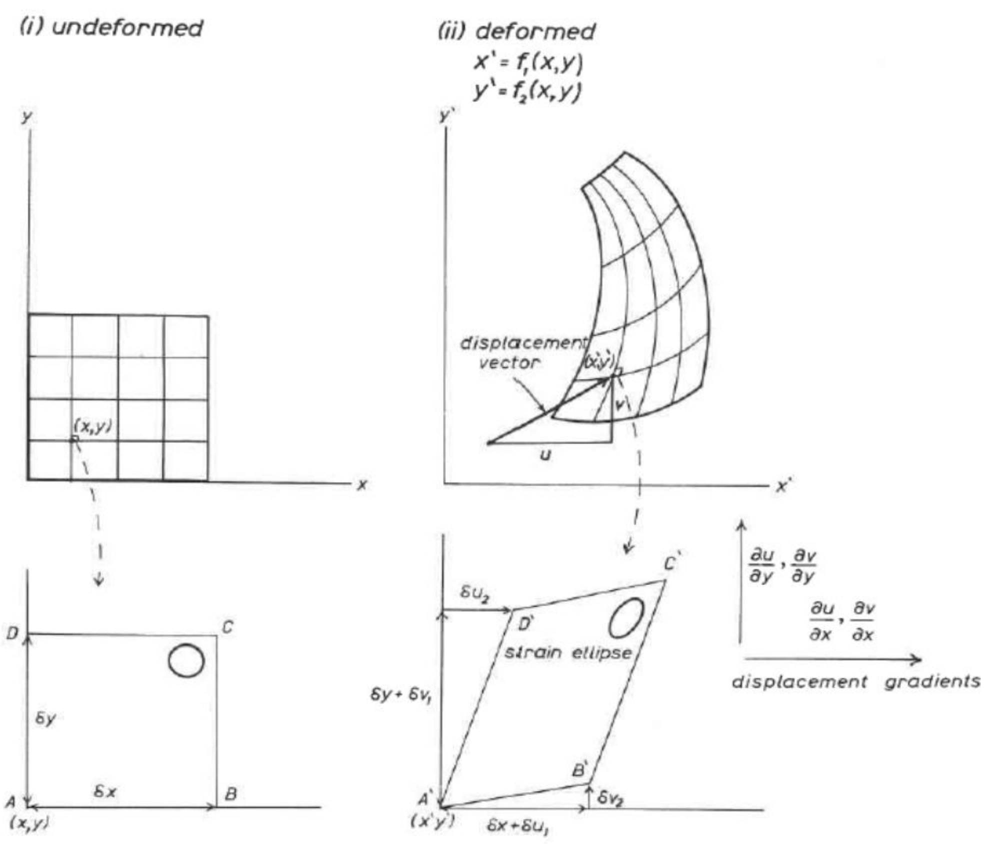


Figure 1.5: i) an undeformed body, and ii) the deformed body, with strain ellipses shown below to demonstrate shear strain (Ramsay and Graham, 1970)

1.4 Study Area

The two islands that were selected for study area, Matches Island and PBE Islands, are approximately 10km apart, to the north of Twelve Mile Bay on Georgian Bay. The islands were selected because they had excellent exposures of the rocks showing lower to mid crustal process of the progressive development of ductile shear zones at work. The process observed was shear zone network development by the softening of a competent block and transposing original layering to create a new fabric. From these two islands we see a transition from foliated granulite facies rocks of the PSD to transposed sheared amphibolite facies rocks of the same composition.

Matches Island has a network of shear zones that rework an early Grenvillian foliated granulite into the TMBSZ, which is key structural evidence for ductile deformation in the mid-lower crust of this region. North of Matches Island is found to have pre-Grenville granulite facies packages. To the south of Matches Island, we enter the same granulites that have been almost fully reworked and retrogressed to amphibolite facies gneisses by the TMBSZ. These two differing packages of rock represent both ends of the spectrum. Matches Island therefore represents a transitional zone between the unsheared granulites and the retrograde amphibolite gneisses of the TMBSZ; this transition represents a gradient of weakening of the deformed rock.

Chapter 2: Regional Geology

The lithotectonic units that make up the Grenville Province of southeastern Ontario have alternatively been termed as being the ‘pre-Grenvillian Laurentia’ terrnanes L1, L2 and L3. L1 and its margins include ca. 1740-1450 Ma continental arc plutons with associated supracrustal rocks, while L2 consists of mainly pre-ca. 1450 Ma rocks penetratively deformed and variably transported northwest. L3 includes post-ca. 1450 Ma margin of Laurentian crust, which is strongly deformed and transported northwest. ‘Composite Arc Belt’ of allochthonous ca. 1300-1250 Ma volcanic arcs and sedimentary rocks, and the Frontenac-Adirondack Belt’ containing supracrustal and granitoid rocks, and anorthosites which represents an offshore composite arc belt that amalgamated at 1160 Ma, and thrust over Laurentia by ca. 1080-1035 Ma (Carr et al., 2000).

The Carr et al terminology translates to L2 and L3 making up the CGB with most belts being described as parautochthounous belts, with the exception of the PSD and Muskoka domain, with are termed as allochthonous polycyclic belts. The Composite Arc Belt relates to being the CMB, as well as the Frontenac terrane of the Frontenac-Adirondack Belt. These terranes are termed allochthounous monocyclic belts (Carr et al., 2000).

The end product of the Grenville Province's tectonic evolution is the stacking of thrust sheets (Davidson 1982; Carr et al., 2000; Culshaw et al., 1997; Culshaw et al., 2010) which is shown in cross-section in Figure 2.1 (Culshaw et al., 1997).

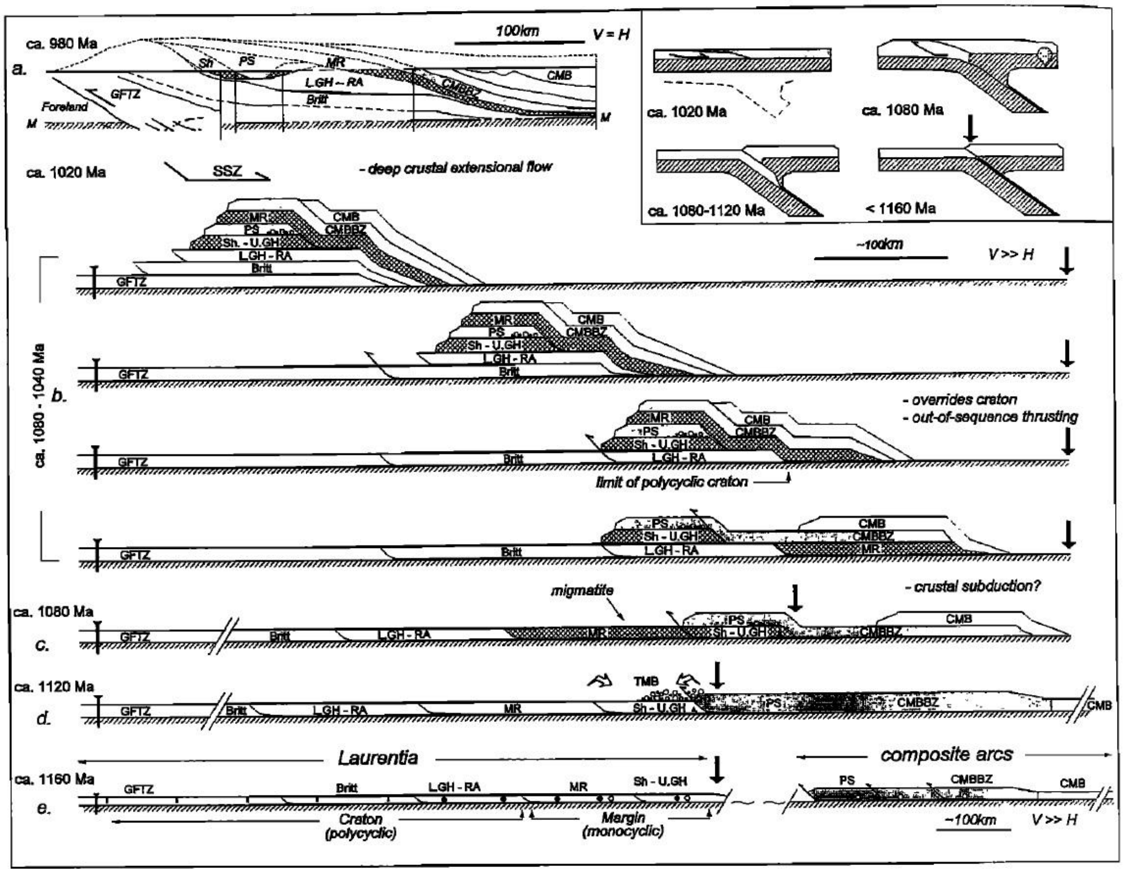


Figure 2.1: A cross-section of the collision and accretion of terranes during the Grenville Orogeny. Domains are Grenville Front Tectonic Zone (GFTZ); Britt; Lower Go Home (LGH); (Moon River (MR); Shawanaga (Sh); Upper Go Home (UGH); Parry Sound (PS); Central Metasedimentary Belt (CMB) (Culshaw et al., 1997).

2.1 Tectonic Evolution

The Grenvillian Orogeny has been recognized as having two distinct orogenic phases, the Ottawan orogenic phase from ca. 1090-1020 Ma, and the Rigolet orogenic phase from ca. 1005-980 Ma, with portions of the Ottawan phase being overprinted by the Rigolet phase (Hynes and Rivers, 2010).

Early tectonic activity related to the Grenville Orogen included the intrusion of coronitic gabbro at ca. 1160 Ma within the Laurentian craton (Culshaw et al, 1997; Ketchum and Davidson, 2000). The earliest metamorphism of the CGB is the upper amphibolite to granulite facies metamorphism of the PSD between ca. 1160-1120 Ma with peak metamorphism occurring at a temperature between 800-900^{o}C, and 10-13 kbars of pressure (Culshaw et al., 1997). By ca. 1120 Ma the Laurentian craton had collided with the composite arc terranes (Fig. 2.1) and began the metamorphism, deformation, exhumation and cooling of the basal PSD assemblage. At ca. 1080 Ma the entire transect is subjected to high grade metamorphism, with the exception of the GFTZ and the PSD corresponding to the Ottawan orogeny phase. This metamorphic event is interpreted to include the thrusting and transport of the PSD over the Laurentian craton (Culshaw et al., 1997). The shear zones of Matches Island have been dated to ca. 1.1 Ga (Marsh et al., 2011), which would put the formation of the shear zones within the thrusting and transport time set for the PSD.

In the CGB a more pervasive Grenvillian metamorphism takes place between ca. 1065-1045 Ma with migmatites and amphibolite facies assemblages present in both the Britt and Shawanaga domains. This metamorphism is at a lower grade than the early Grenvillian metamorphism with peak temperatures and pressures being 700-800^{o}C and 10-12 kbar (Culshaw et al., 1997). Between ca. 1080 and 1040 Ma thrusting continued with several of the other units of the CGB being thrusted upon the PSD. The Moon River domain (MR) is an out of sequence thrust that gets thrusted upon the PSD. The final stage of the Grenvillian metamorphism was the exhumation of the GFTZ at 1000-980Ma (Culshaw et al, 1997, Jamieson et al., 2007).

The CGB is made up of reworked high grade upper amphibolites to granulite facies packages of the Laurentian Craton with protolith ages older than

1450 Ma, and allochthonous rocks (above the Allochthon boundary thrust) are greater than ca. 1450Ma. The CMB represents units with formation ages less than ca. 1300 Ma and deformation ages that are post 1160 Ma which consist of a system of accreted magmatic arcs and a marginal basin during the Grenville Orogeny (Culshaw et al., 1997; Windley, 1989; Easton, 1992).

The study will largely focus on the CGB, in particular the allochthonous Parry Sound domain (PSD) and the periphery of the Twelve Mile Bay Shear Zone (TMBSZ), where the field work has been conducted.

2.2 Domains

2.2.1 Central Gneiss Belt

The tectonic domains that make up the CGB are interpreted as being thrust sheets (Carr, 2000; Culshaw 2010; Culshaw 1997; Davidson 1982) and have been classified by their metamorphic histories as either being monocyclic or polycyclic. The polycyclic domains are units affected by both Grenvillian and mid-Proterozoic metamorphism which, stratigraphically lie at the lowest structural level of the CGB.

The polycyclic domains of the CGB along Georgian Bay are the Britt domain, which is comprised of ortho- and paragneisses in the north, with the lower Go Home and lower Rosseau domains to the south that are made up of amphibolite facies orthogneisses and migmatites (Culshaw et al., 2010). The Shawanaga shear zone is the boundary which separates the polycyclic domains from the hanging wall allochthonous monocyclic domains that have experienced only Grenvillian metamorphism. The Shawanaga shear zone an extensional shear zone that reworks the Allochthon Boundary Thrust (ABT), a major thrust within the Grenville Province that separates the Laurentian crust with deformations pre-ca. 1450 Ma (Culshaw et al., 1994; Ketchum and Davidson, 2000) of the GFTZ and Laurentian crust rocks with deformations post-ca. 1450; although along the Shawanaga shear zone the ABT is overprinted by normal sense shear (Culshaw et al., 1994; Ketchum and Davidson, 2000). The ABT has been active from ca. 1090-1020 Ma (Ketchum and Davidson, 2000; Carr et al., 2000).

The monocyclic domains consist of the Parry Sound domain, which will be discussed in more detail in the next section, as well as the Moon River domain (MR), the Shawanaga domain (Sh) and the upper Go Home domain (uGH). The MR contains uniform pink and gray gneisses that are commonly layered and have abundant leucosomes. The lower contact of the MR with the PSD is along the TMBSZ assemblage and associated anorthosites. The TMBSZ assemblage shows no signs of a granulite facies heritage. The associated Blackstone Lake gneiss is also gray gneiss of granodiorite composition with pink leucocratic lenses, is considered to be of possible PSD heritage (Culshaw et al., 2010).

2.2.2 Parry Sound Domain

Based on the similarity of igneous protolith ages and lithologies, the PSD is interpreted as having originated within the CMB, and consequently it must have travelled up to 100km to its current position (Wodicka et al., 1996).

The PSD is a monocyclic domain within the CGB with lithologies of mafic granulites. The PSD is an allochthon comprised of three assemblages in the west separated by ductile shear zones, the basal PSD, the upper PSD (sometimes referred to as the interior PSD), and the TMBSZ (Culshaw et al., 1997). The structure of the PSD reflects a competent block within a lower crustal flow of hot ductile material (Marsh et al., 2011; Culshaw et al., 2010). (The interior PSD retains its structure and fabric while along its extremities there is a zone of reworking by retrogression of granulite facies to amphibolite facies, with the introduction of fluids, and transposition of the gneissosity. The fluid emplacement (primarily focussed in linear corridors cored by pegmatite) allowed initiation of a shear zone network by which the gneissosity was transposed at a high angle to the original fabric trend. This reworking behaves as a shell to the interior PSD which is unaffected by the reworking processes (Culshaw et al., 2012).

The basal PSD is made up of a combination of orthogneiss, anorthosite, and supracrustal rocks with widespread retrograde amphibolite facies mineralogy which overprint the earlier granulite facies fabric and mineralogy (Culshaw et al., 2010). The basal PSD is separated from the Shawanaga domain by the lower Parry Sound shear zone (PSSZ), where the basal Parry Sound rocks become reworked to the west by the Shawanaga shear zone, the extensional version of the ABT (Culshaw et al., 2010).

The basal PSD and the upper PSD are separated by the upper Parry Sound shear zone. The upper PSD is made up of mylonitic granulite gneisses of interior PSD protolith, as well as basal PSD derived amphibolites facies gneisses, and deformed anorthosite and granitoid orthogneiss sheets. The distinction between the upper and lower PSDs is the protolith, where the interior PSD is composed of granulite facies orthogneisses (Fig. 1.4) (Culshaw et al., 2010).

A thermobarometric summary for the interior PSD, zone of reworking, and TMBSZ can be seen in Table 2.1 (Marsh et al., 2011).

Location	Type	Assemblage	T (oC)	P (kbar)
S. iPSD	Granulite	Pl-Grt-Cpx-FeOx	862	10
S. iPSD	Granulite	Pl-Grt-Opx-Bt-FeOx	831	10.2
S. iPSD	Granulite	Pl-Opx-Qtz-FeOx-Kfs-Grt-Hbl	847	11.8
S. iPSD	Granulite	Pl-Cpx-Qtz-FeOx-Grt-Hbl	875	11.9
N. ZoR	Wall rock panel	Pl-Grt-Cpx-Hbl-Qtz-FeOx	832	10.5
S. ZoR	Wall rock panel	Pl-Grt-Cpx-Hbl-Qtz-FeOx	813	11.2
N. ZoR	Sheared Amphibolite	Pl-Hbl-Qtz-Bt-Ttn	695	6.4
S. ZoR	Sheared Amphibolite	Pl-Hbl-Qtz-FeOx	697	5.6
S. ZoR	Sheared Amphibolite	Pl-Hbl-Qtz-Bt-Ttn	708	6.2
TMBSZ	Sheared Amphibolite	Pl-Hbl-Qtz-Bt-Ttn	700	5.2
TMBSZ	Sheared Amphibolite	Pl-Hbl-Qtz-Bt-Kfs-Ttn	708	6.5
TMBSZ	Sheared Amphibolite	Pl-Hbl-Qtz-Grt-Bt-Ttn	731	6.9
TMBSZ	Sheared Amphibolite	Pl-Hbl-Qtz-Grt-Bt-Ttn	709	6

Table 2.1: A thermobarometric summary of south and north interior Parry Sound domain (iPSD); north and south zone of reworking (ZoR); and the Twelve Mile Bay shear zone (TMBSZ) (Marsh et al., 2011).

2.2.3 Zone of Reworking

Along the southwestern margin of the upper PSD there is a gradational change in the regional structural style due to reworking of the PSD from its interior. The regional foliation is gradually overprinted whereupon entering the Twelve Mile Bay shear zone the transposition of its original gneissic fabric is nearly complete.

The earliest stages of transposition begin with the appearance of thin granitoid filled fractures lying at a high angle to the granulite facies gneissosity (Fig. 2.2). The margins along these fractures become amphibolized primarily by the introduction of a hydrous fluid, hydrating the granulite facies pyroxenes to become amphiboles. These small brittle fractures show left handed en echelon step overs. Eventually the wall rock along the edge of the fractures begins to show signs of behaving ductiley, forming of a narrow band of shear foliation. The foliation of the upper PSD becomes more and more altered as these fractures become more common and as they begin to behave in a ductile fashion, until it is entirely transposed in the TMBSZ (Culshaw et al., 2010).

2.3 Matches Island

On Matches Island there is a higher degree of transposition-related strain as the pegmatite infilled veins have become the cores of shear zones (Marsh et al., 2011) (Fig. 2.3). To the north of Matches Island a half a kilometre of open water lies between Matches Island and the nearest retrogressed but minimally reworked granulites (Culshaw et al., 2012).

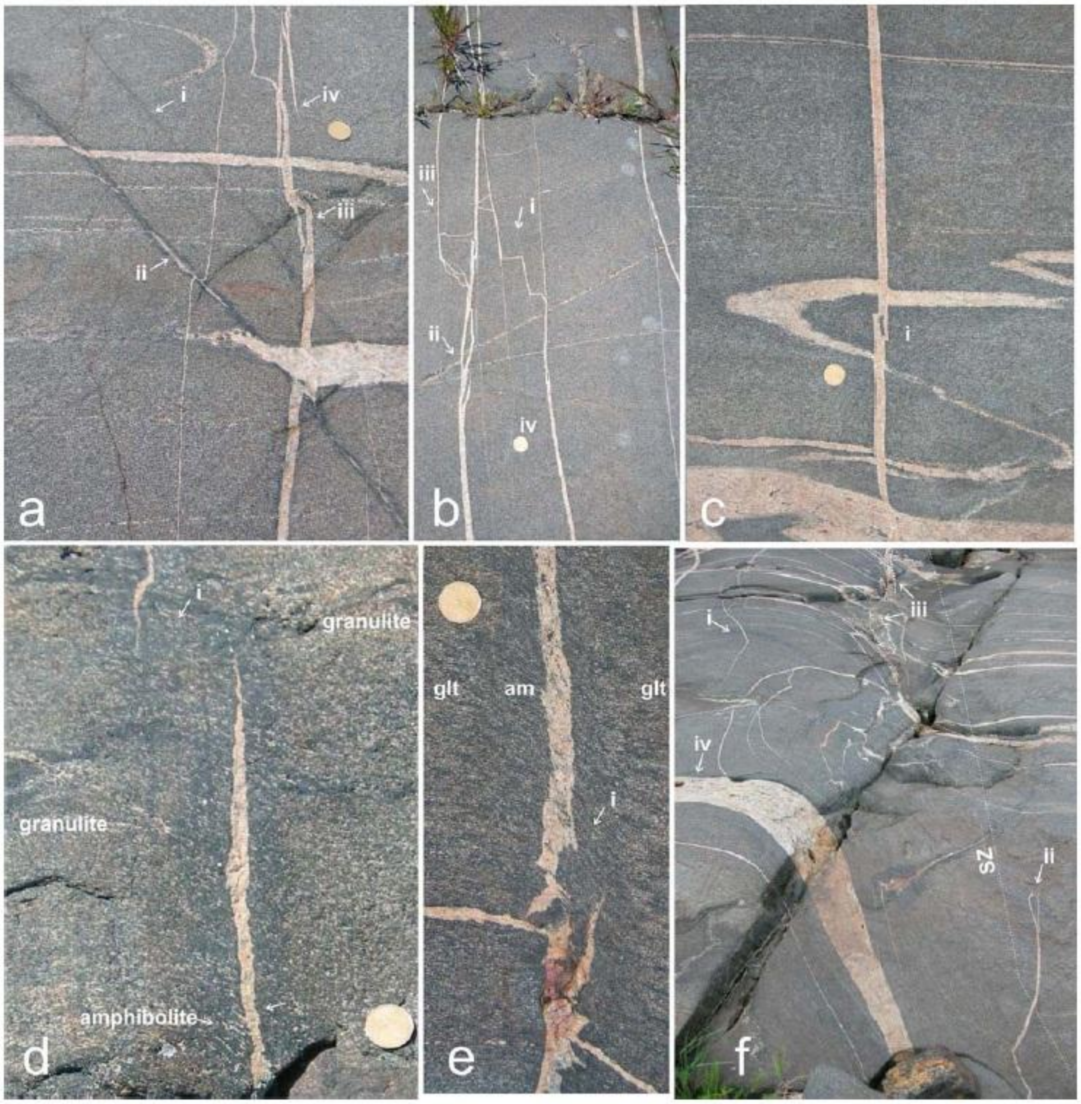


Figure 2.2: Granite-filled veins and dykes showing healed fractures with amphibolized margins. Fractures show left-handed step overs. Strain increases from (a) to (f), where there is a brittle/ductile transition (Culshaw et al., 2010

Figure 2.3: A shear zone on Matches Island, with a vein of pegmatite at its core. The shear zone is transposing the gneissic layering, showing the 'ladder and rung' structure, where the shear zone cuts the gneissic layering at high angles, leaving the wall rock undeformed.

Matches Island lies within the transitional zone between the TMBSZ and the granulite facies interior PSD rocks, previously described as the zone of reworking, while PBE Island sits in the TMBSZ, showing that transposition is never really complete. Matches Island is composed of two distinct lithologic units: a layered mafic and felsic orthogneiss, which is the dominant lithology, and intermediate gneiss with pink granitic layers (Gerbi et al., 2010; Culshaw et al., 2012). The shear zone network exhibits a 'ladder and rung' structure (Fig. 2.3). This structure is typical of Matches Island, where the shear zones are at high angle to the gneissic layering in undeformed wall rock. The alternating 0.1-1.5m thick mafic and felsic granulite layering of Matches island is cut at high angles by generally thin (~0.5m), closely spaced shear zones. The shear zones have been defined by the sharp (~90^{o}) deflection and ~80-95% thinning of both the mafic and felsic layers (Marsh et al., 2011).

The gneissic layers are intersected by a series of shear zones, initiated by pegmatites veins. This injection of fluid creates a plane of weakness for the shear zones, to deform the rock by ductile deformation accompanied by retrogression (e.g. the retrograde reaction of pyroxene to amphibole in mafic layers (Marsh et al., 2011; Gerbi et al., 2010)). Such reactions are part of a softening process in which pegmatites are the catalyst for the retrograde reaction of granulite to amphibolite facies by hydrating the granulite facies mineral phases, causing them to become unstable. It is due to this reaction that the PSD assemblage is weakened enough to allow shear zones to form. These shear zones range from centimeters to nearly half a meter in width, and begin to link up to form networks. Most of the shear zones on the islands are dextral (Gerbi et al., 2010).

The layering in the dominant layered gneiss maintains a uniform thickness along strike for several meters within undeformed sections, with decimetre to meter scale layering of felsic and mafic bands. There are mineralogical contrasts between the wall rock and shear zones particularly in the mafic layers, where there are pyroxenes in the wall rock while the mafic layers in the shear zone have amphibole instead of pyroxene. For the full mineral assemblages of mafic and felsic layers in both shear zones and wall rock, consider Table 2.2. In both the shear zones and wall rock the felsic layer mineralogy consists of plagioclase-K feldspar-quartz-hornblende-biotite. The mafic layering in the shear zones is made up of hornblende-plagioclase±biotite±quartz±titanite, in contrast to the mafic layering of the wall rock which is made up of coarser grained plagioclase-orthopyroxene-clinopyroxene (Culshaw et al., 2012; Marsh et al., 2012).

The second unit of making up Matches Island is a grey plagioclase-quartz-hornblende-biotite gneiss which is a typical amphibolites facies mineralogy. This unit lacks granulite facies mineralogy as well mafic layers, pink granitic leucosomes are less common then the first unit and more irregular in spacing (Culshaw et al., 2011).

2.3.1 Shear Zone System Development on Matches Island

The majority of the shear zones on Matches Island are dextral although there are the rare sinistral shear zones (Culshaw et al., 2011; Gerbi et al., 2010). The shear zones strike north easterly and form at a high angle to the granulite facies gneissic layering which transposes and thins the gneissic layering as the layering enters a shear zone. Gneissic layers ranging from meters to decameters in thickness are reduced to thicknesses of centimeters as they enter the shear zones.

Shear zones tend to locally deflect around competent mafic blocks. DGPS data from previous work shows that shear zones underlie approximately 14% of the total area of Matches Island, and have an aggregate length of more than a kilometer (Culshaw et al., 2011).

There are two styles of shear zones on Matches Island, straight and curved; the curved shear zones bend in an anticlockwise fashion in the northern part of the island. The curved-style shear zones show that the magnitude of strain increases along the shear zone, as can be seen by simply looking at the increasing displacement around the curve as seen in Fig. 2.4. It is known that straight shear zones also exhibit this behaviour, with lower strains being quantified at the tips of the shear zones (Pennachioni and Mancktelow, 2007) but whether the straight shear zones on Matches Island conform to this style remains to be seen.

The shear zone network on Matches Island shows several degrees of linkage, with the highest degree of connectivity seeming to be a corridor in the south west of the island (Fig. 2.5). As strain increases, the shear zones become progressively more linked with one another to form a semi-continuous network. This accompanies the rotation of panel layering from its original NNE orientation (Marsh et al., 2011).

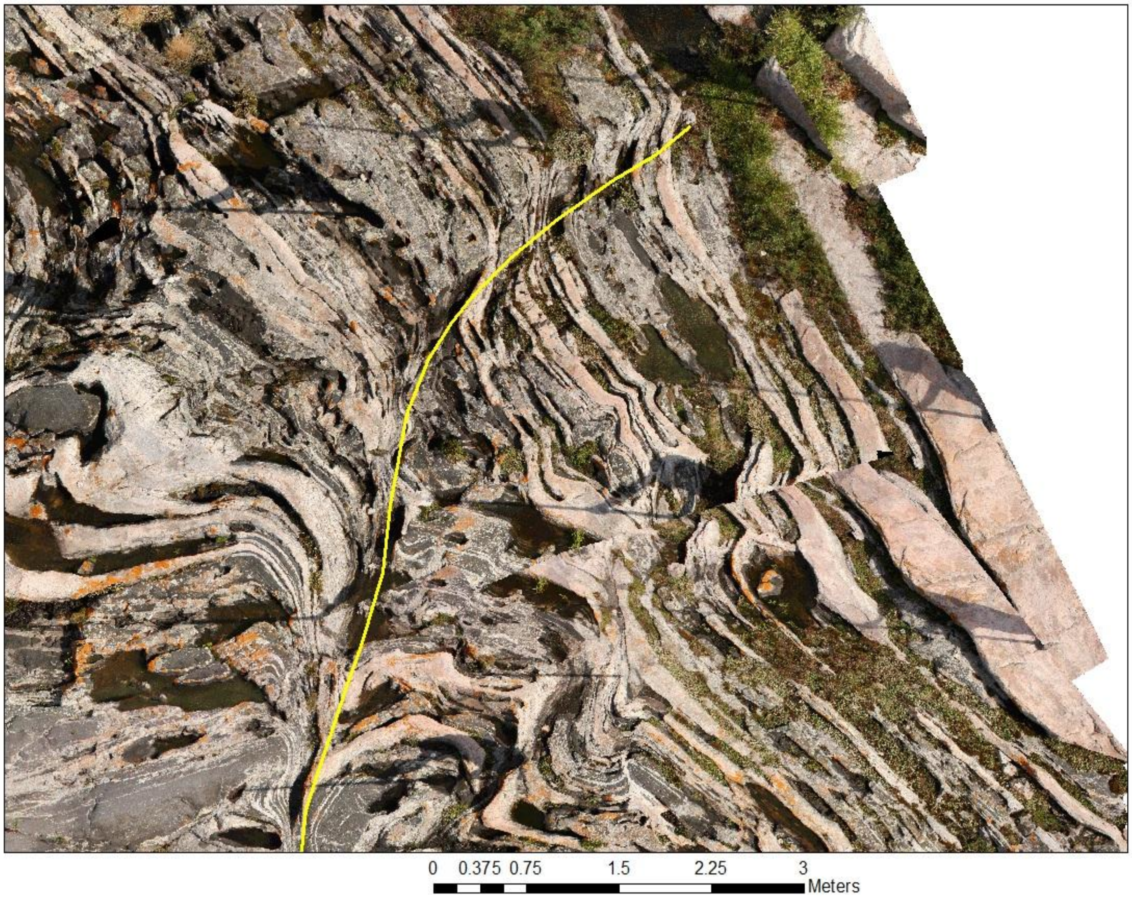


Figure 2.4: A curved shear zone, marked in yellow exhibits a change in shear strain as is begins to curve. The displacement in the straight part, in the top of the picture is low. As the shear zone curves, the displacement increases.

Figure 2.5: The shear zone traces displayed in ArcMap, with solid lines being known shear zones and dashed lines being inferred shear zones. This figure shows that most of the shear zone linkages occur on one corridor in particular.

The development of linkage and networking of shear zones occurs by increasing shear strain. The development of a shear zone network acts as a mechanism for shear zones to widen. It is thought that densely spaced shear zones will begin to be linked by smaller subparrallel shear zones that eventually will consume the entire section of wall rock between the larger older shear zones (Fig. 2.6). As a shear zone is widened, there is a rheological change as the volume of material behaving plastically increases. This development of the shear zone network is the principle softening mechanism, as the higher the degree of linkage, the softer the rock becomes (Fussesis et al., 2006).

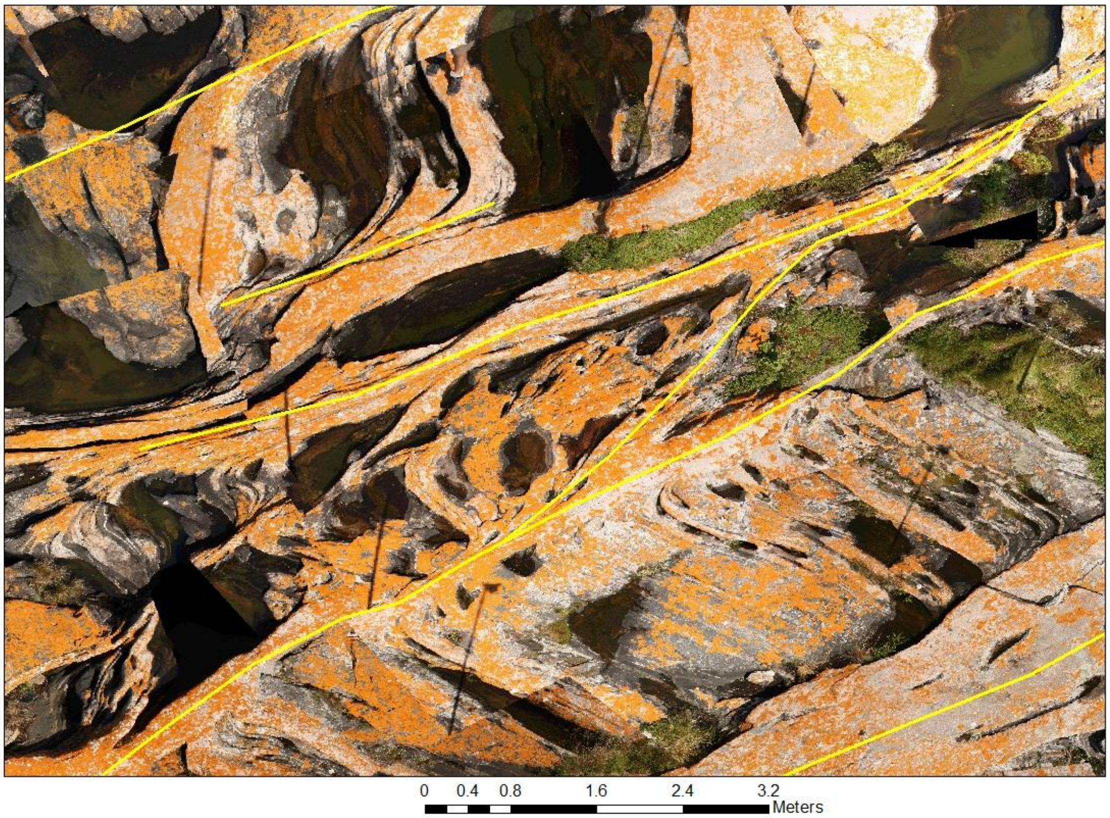


Figure 2.6: Shear zone traces are highlighted in yellow, where two large shear zones are being linked by smaller subparallel shear zones.

Chapter 3: Methods

3.1 Mapping Methods

The mapping of the structure of Matches and PBE islands began with identifying key areas for understanding the structure and which are well exposed. On Matches Island, a section was selected because it had a large area of well exposed rock with a high density of shear zones, with the intention of creating a highly detailed photomosaic map of ultra-low-level aerial photographs. The photographs would then be georeferenced to a grid so that an accurate map consisting of the photomerged low aerial photographs could be constructed. The map would be used to quantify various features of the shear zones, such as average length, width, areas, spacing, and shear strain.

3.1.1 Use of Tools

The grid on Matches Island serves two purposes.The first is to have four grid tiles that appear in the corners of the photos so that the photos can be organized based on where the photos appear on the grid. The second is to have these grid points georeferenced so the map will be able to have a single scale that is accurate across the entire map.

3.2 Mapping Tools

The DGPS was used to georeference the grid, and was done by having the rover visit each square of the grid and store the coordinate at that point with the corresponding grid number. By doing this, the digital grid would now correspond to the real grid on the ground captured by the photographs.

The photographs were taken using a camera on a pole, which was a two man job, one person holding the pole-camera rig, and a second person off to the side, lining up the lens with the middle of a grid square and using a remote to trigger the shutter. Every grid square was photographed at least twice, each image containing at least four tiles displaying a grid number to ensure overlap of the photos.

3.2.1 The Grid

The grid was set up to trace the major shear zones on Matches Island in order to georeference the ultra-low-level aerial photos. In the chosen section of Matches Island a grid was laid down marked out by 5 cm by 5 cm tiles numbered sequentially, with a total of 531 tiles laid down. The tiles were spaced 2 m apart along lines running 260^{o}, approximately parallel to the average shear zone orientation and 80^{o}, approximately parallel to the average orientation of wall rock layering. Three separate grids, totaling approximately 350 tiles were laid down on PBE Island.

3.2.2 The Pole Camera

In order to accurately map the shear zone networks upon Matches and PBW islands a ‘pole and camera’ method was applied. By using a camera mounted on a ~15 foot pole and a remote shutter release approximately vertical photos were taken of the structure. The ‘pole and camera’ method is illustrated in cross section in Figure 3.1 and in plan view in Figure 3.2. The camera mount at the top of the pole was constructed as a swivel so that the camera could swivel up and down, parallel to the pole. A weight on one side of the mount counterbalances that of the camera and lens so that the lens was point straight down.

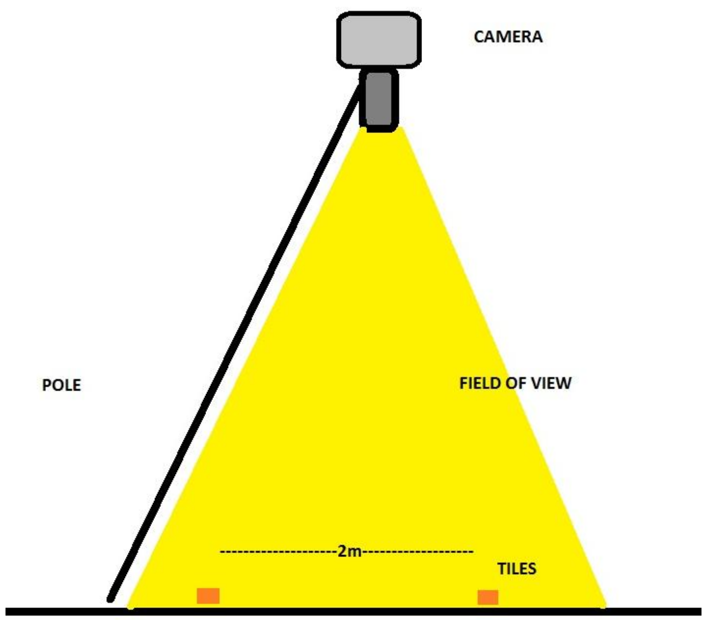


Figure 3.1: A cross section of the camera on a pole method. The camera, pole and grid tiles are labelled, and the yellow shading is the cameras field of view. The tiles are spaced at 2 m.

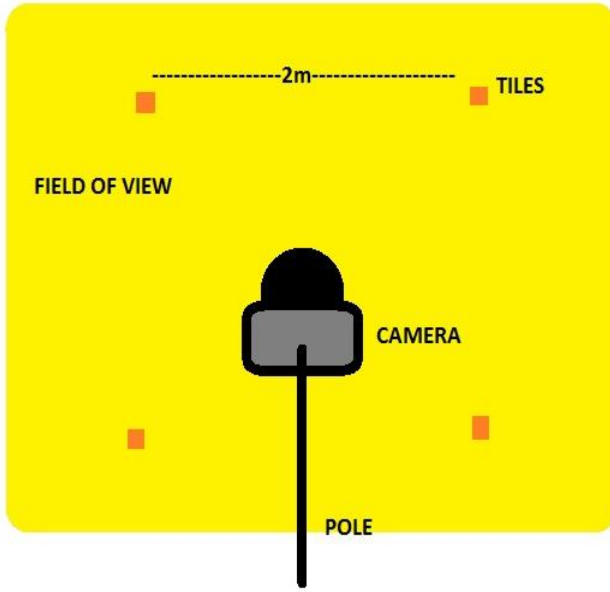


Figure 3.2: The plan view of the camera on a pole method. The camera, pole and grid tiles are all labelled, the yellow shading is the camera's field of view. The grid tiles are spaced 2 m in either direction.

The aim of this method is to have a series of ultra-low level aerial photos of the shear zone networks with the necessary detail to be able to pick out individual layers. For every square on the grid a vertical photo was taken with each of the four tiles visible within the shot, ensuring overlapping photos with no gaps between the photos. Each tile within the picture corresponds to a DGPS survey marker defining the grid.

3.2.3 Differential Global Positioning System (DGPS)

Both of the grids were then digitized using a Leica differential global positioning system (DGPS) to achieve georeferencing accuracies to the cm scale. The DGPS is made up of two components; a base station, and a mobile receiver unit termed a rover. The base station remains stationary in a fixed position while the DGPS survey was taking place. The initial coordinates of the base station's location is saved in its memory card. Immediately after storing these initial coordinates, the coordinates are subsequently recorded by the base station at one second intervals. These differ from the initial coordinates due to the wandering of satellites and eccentricities of their orbits. Since the base station had the initial coordinates stored, in a sense it 'knows' it is in the same position, despite the ongoing changes in coordinates being observed for the same location. This allows the base station to make corrections accounting for these wandering paths. These corrections are transmitted in real time to the rover allowing for the position of survey markers to be recorded within ± 1 cm horizontally and ± 2 cm vertically.

3.4 Data Organization

Upon arriving back to the lab with approximately 1200 photos, a system was needed to organize and merge the photos into a mosaic efficiently. Organizing the photos was achieved by using a sketch of the grid with labeled grid squares (each had a square with 4 numbered tiles at its corners, and assigned each grid square number to the matching photo. Once the photos were all assigned grid square numbers, it was simple to locate photos.

3.5 Development of Photo-Stitching

The next task at hand was to devise a way to combine the series of photographs with the DPGS data in order to have a detailed and accurate map.

The protocol followed was to orthorectify the photos and stitch the corrected photos together in a seamless manner with photo editing software and then georeference them to the DGPS data via ArcMap. The photos needed to be orthorectified to correct for any variations in the angle of the lens to the surface being photographed, an orthorectified photo being a true representation of the surface with minimal inaccuracies and distortions.

3.5.1 Orthorectification in Arcmap

There are many software suites that have orthorectification capabilities. However these suites commonly deal with air photos, which are much less detailed than the pole photos. Also these programs are very expensive. Fortunately ArcMap, an existing program available on Dalhousie campus, has orthorectification capabilities. By importing the grid data and photos into ArcMap, orthorectification of a photo was accomplished by opening up the georeferencing toolbox, selecting the layer of a photo and then selecting 'fit to display'. Tiles on the photos corresponding to DGPS control points were then matched to their digital counterpart derived from the DGPS data. Once the control points are georeferenced the photo can be saved as an orthorectified version by using the georeferencing pull-down and selecting 'rectify', and the last step is to select 'update georeferencing' to lock the orthorectified photo into the grid.

For the steps that were taken for the entire process of photomerging and georeferencing see the flow chart in Figure 3.3.

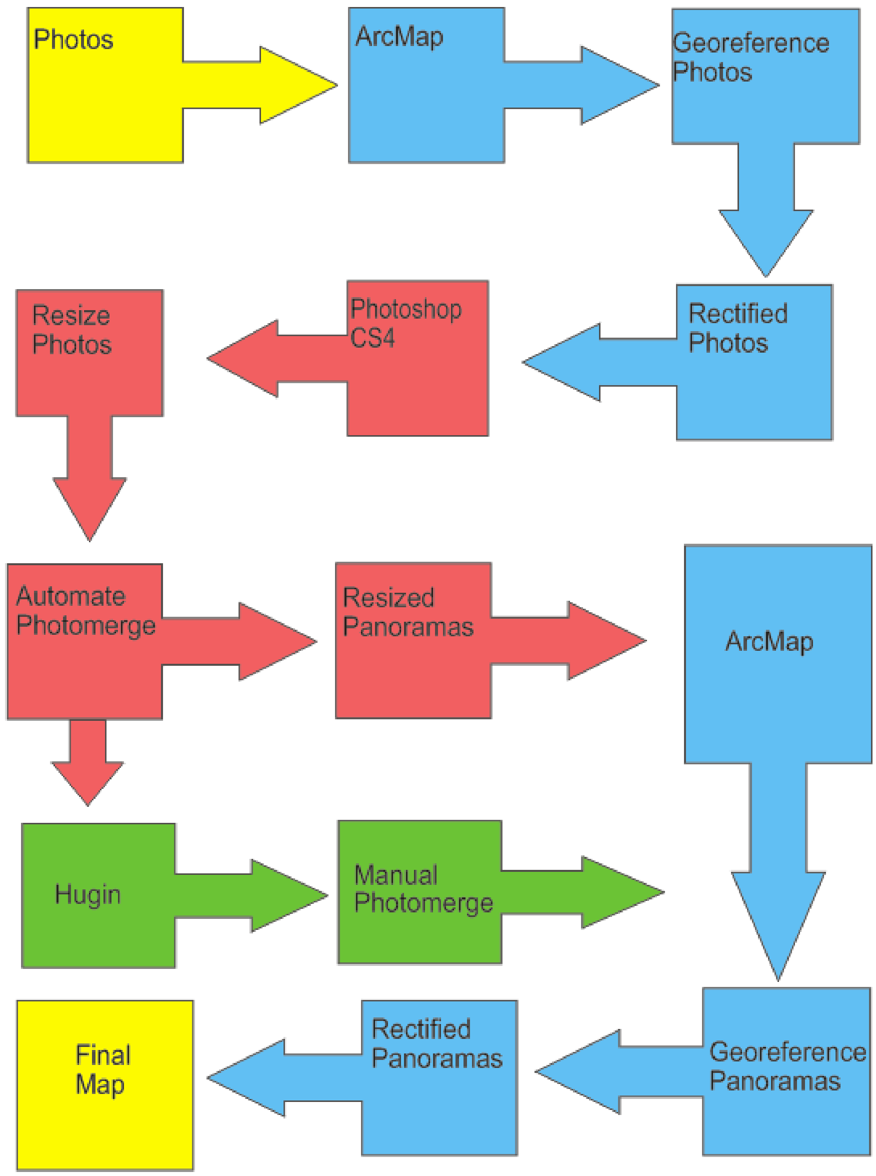


Figure 3.3: A flow chart of the steps that were taken to produce the photomerge map. The flow chart is color coded by programs or file types. Yellow steps are JPEGs, blue is a step in ArcMap, red are steps in Photoshop CS4, and green are steps in Hugin. Note at the 'automate photomerge' step in Photoshop CS4 that there are two routes. The route to Hugin was taken if the output of photoshop was not usable. If the Photoshop outputs were useable, the flow chart continues into ArcMap, without going through Hugin.

3.5.2 Photoshop CS4

Once the photos were orthorectified they were stitched together in blocks of 3x3 or 3x6 photos in Photoshop. These photomerges were then brought back into Arcmap and georeferenced to the grid a second time. Because of the distortions of the photographs involved with the photomerging process, the photomerges were georeferenced once more to the DGPS grid to ensure that they were indeed in their correct place.

Photoshop CS4 has a photomerging function that is fast and effective. By clicking the 'automate' tab under 'file' there is a photomerge option. The photomerge function enables the user to select photos to be stitched together, as well as to select a projection that will suit the user's liking. For the purposes of this study, all photomerges that were created in Photoshop CS4 used the automatic projection option for consistency.

Once the photos and projection have been selected, Photoshop will automatically create its own set of control points to merge the photos. A pitfall of the Photoshop photomerge is it does not have a manual option for selecting control points. There were times when Photoshop could not find similar control points, which were the same tiles within the photos selected for merging, causing the output to be less than adequate -- stacking the photos on top of one another or having small portions merged with blank gaps in between the merged portions. In most cases the outputs of Photoshop were good, where the photographs would be merged with either no blank spaces, or with an insignificant amount of blank space relative to the whole area of the merged mosaic. In the case of a sub-standard automatic output photomerge, a backup photomerging option was needed.

3.5.3 Hugin

Hugin is a cross platform open source panorama photo stitching and photo merging program that was used in experimenting to find the best way to merge the images together, and became the backup stitching method. Hugin creates photomerges by matching up manually selected control points with a range of projections to choose from. The photomerges turn out nicely but there are some artifacts as a byproduct of the photomerge process, such as tiles being duplicated. The manual selection of control points can be time consuming, but when the Photoshop CS4 photomerges do not work it is a good backup. Hugin was used for several photomerges used to create the photo mosaic map of Matches Island, when Photoshop CS4 photomerge outputs were not acceptable. Hugin played a minor but vital role in the eventual outcome, with four Hugin produced photomerges used in the final map.

Chapter 4: Structural Geology

4.1 Intro to Structural Analysis

The goal of the map discussed previously was so that observations and quantitative measurements can be gathered electronically. This was to be done to calculate shear strain for Matches Island, and identify structural features that form in high shear strain regimes and hypothesize their genesis.

4.2 Methods of Structural Analysis

For our shear strain calculations to be valid we have assumed that simple shear governs shear zone development on Matches Island. The evidence for this assumption is the localized nature of deformation within the shear zones with the wall rocksbeing commonly undeformed this is definitive for the case of simple shear (Fig. 1.2, Fig. 2.5). This assumption is made in spite of locations where wall rocks show signs of significant deformation.

By having a detailed and georeferenced photo-stitched map of Matches Island, it was possible able to make measurements of significant features in order to calculate local strain rates. There were two methods employed to calculate shear strain:

1. from the ratio of displacement of a gneissic layer across a shear zone, to the shear zone width, and (Fusseis et al., 2006)

2. from the change of the angle of the gneissic layering compared to layering in the wall rock at several points across a shear zone, the α - α'method (Fusseis et al., 2006).

Both of these methods were used to measure shear strain across the same shear zones. They were performed independently of one another in order to serve as a 'check' for the other method.

4.2.1 Strain by displacement

This method was based on the equation:

γ mean= displacement / width(Fusseis et al., 2006)

where displacement refers to that of a marker layer across a shear zone, and the width being the width of the shear zone, definied by the points to either side of the shear zone where the marker layer begins to deviate from its original orientation (Fig. 4.1). This method was accomplished in ArcGIS by tracing gneissic layering, recognizable on the photomap, across shear zones and marking it as a polyline shapefile. Likewise, width polylines were constructed for each shear zone. The polylines for displacement and width could then be easily measured in ArcMap using the ruler tool. The displacement was judged by observing the distance from where a layer enters a shear zone, to where the same layer comes out of the other side of the shear zone i.e. from where the marker layer crossed the shear zone edge polyline, to where the marker layer crosses the shear zone edge polyline on the other side of the shear zone. The width polyline was drawn by joining points where successive layers deviate from their average strike in the wall rock. The width and displacement were all measured to be perpendicular to each other in order for the equation to work properly and to maintain consistency. For straight shear zones maintaining this perpendicular relationship was not a problem. For shear zones with a significant curvature maintaining the perpendicular relationship was more complicated.

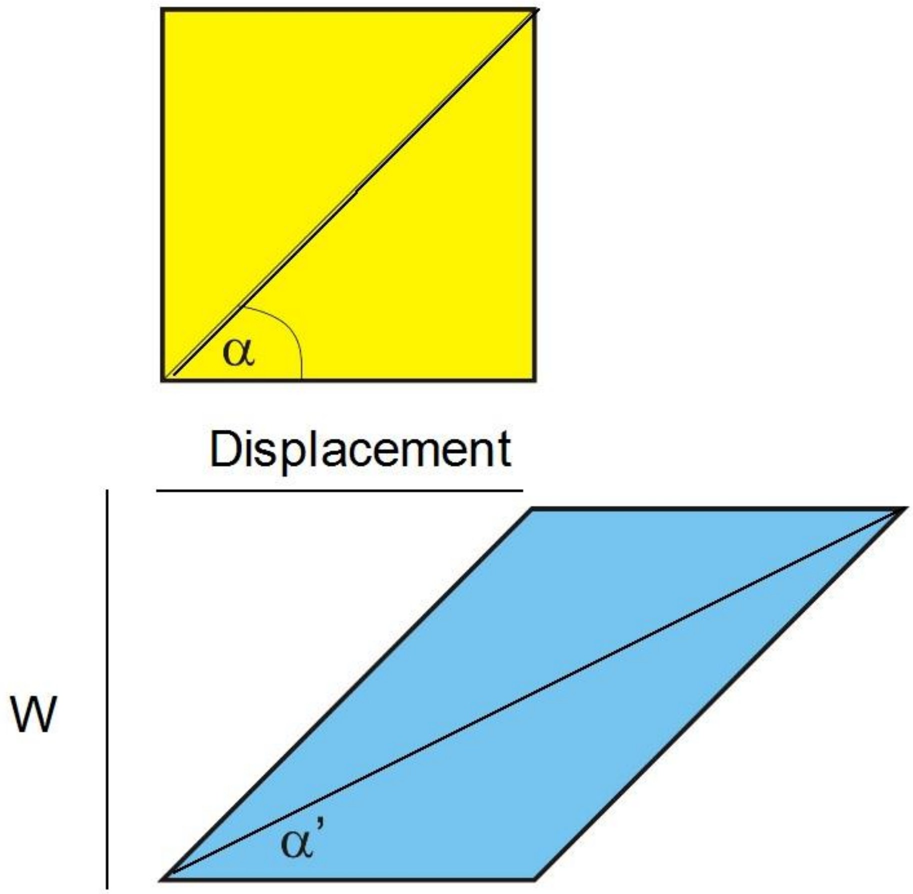


Figure 4.1: the yellow cube is sheared by a γ of 1, and yields the blue rhomb. In this hypothetical shear zone, the width and displacements are labelled, which would be needed to calculate γ mean. α and α' are also labelled which can also be used to calculate γ.

In the γ mean method, it was necessary to be able to trace a layer into a shear zone, trace a layer so that it could be seen going into, and exiting a shear zone in a continuous trace in order to judge the displacement. This method is hindered by poor exposures, photo-faulting, and a map inaccuracy where neighbouring panoramas on the map do not line up, where it became impossible to trace a layer completely through a shear zone. In the case of poor exposures, layers were traced as far as possible within the shear zone. The latter is effectively a minimum estimate of strain, since the strain would be larger if the layer was further traceable. The minimum strain is useful because it gives us a fraction of the actual shear strain. In fact if it is possible to trace a layer half way across a shear zone then the total strain can be calculated.

4.2.2 Strain by α- α'

Strain by angles is based on the equation

$\gamma = \cot(\alpha) - \cot(\alpha')$ (Fusseis et al., 2006)

where α is the angle of undeformed wall rock layering to the shear zone boundary, and α' is the angle of a strained layering at a particular point in the shear zone, (Fig. 4.1). Unlike the displacement shear strain method, it is not necessary to trace one layer across the shear zone. With the α-α' method several different layers can be used so long as they are in the same restricted and are continuous with layering in wall rock that is parallel.

In order to measure angles of the change in the strike orientation of gneissic layering as they enter shear zones, the photomerge map was displayed in ArcMap with the shear zone trace and boundary shapefiles layers turned on. The emphasis was to have a close up view of a shear zone of interest along with shear zone trace and boundary shapefiles in order to measure the angles α and α’ in the shear zone. By switching to the layout view in ArcMap, a centimetre scale bar could be added to the close up of the shear zone, and then the entire display was exported into CorelDraw X4 for the actual measurement. Once in CorelDraw X4, the image was rotated so that the shear zone was oriented approximately north south. The angles of gneiss layering were measured by using the dimension function, which can be accessed by holding down the freehand tool and selecting the dimension function. To ensure consistency with the angles that were measured the angles were measured to the left side of the vertical orientation of the shear zone.

This method calculates strain at a point (α’) thus to get an idea how strain changes from point to point, across a shear zone several measurements are taken. These snapshots of strain are then plotted on a graph in Excel showing the strain against the distance from the center of the shear zone to each point of measurement (α’). A typical graph has a bell curve shape with shear strain peaking at the 0 cm mark, or center of the shear zone, with strain tapering off towards the edges of the shear zone (Fig. 4.2).

In order to calculate strain over the entire width of the shear zone the curve of shear strain versus distance from shear zone center must be integrated. Since many of the curves are irregular, integration was performed apporximately by calculating the area beneath the curve by fitting it with 3.5 cm wide rectangles. The area beneath the curve is the width of a shear zone segment times strain, gives the displacement for that small section of shear zone. Now that the total displacement had been calculated, the width of the shear zone was measured in ArcMap and by using the equation γ mean = d/w, an average γ was calculated (Fusseis et al., 2006).

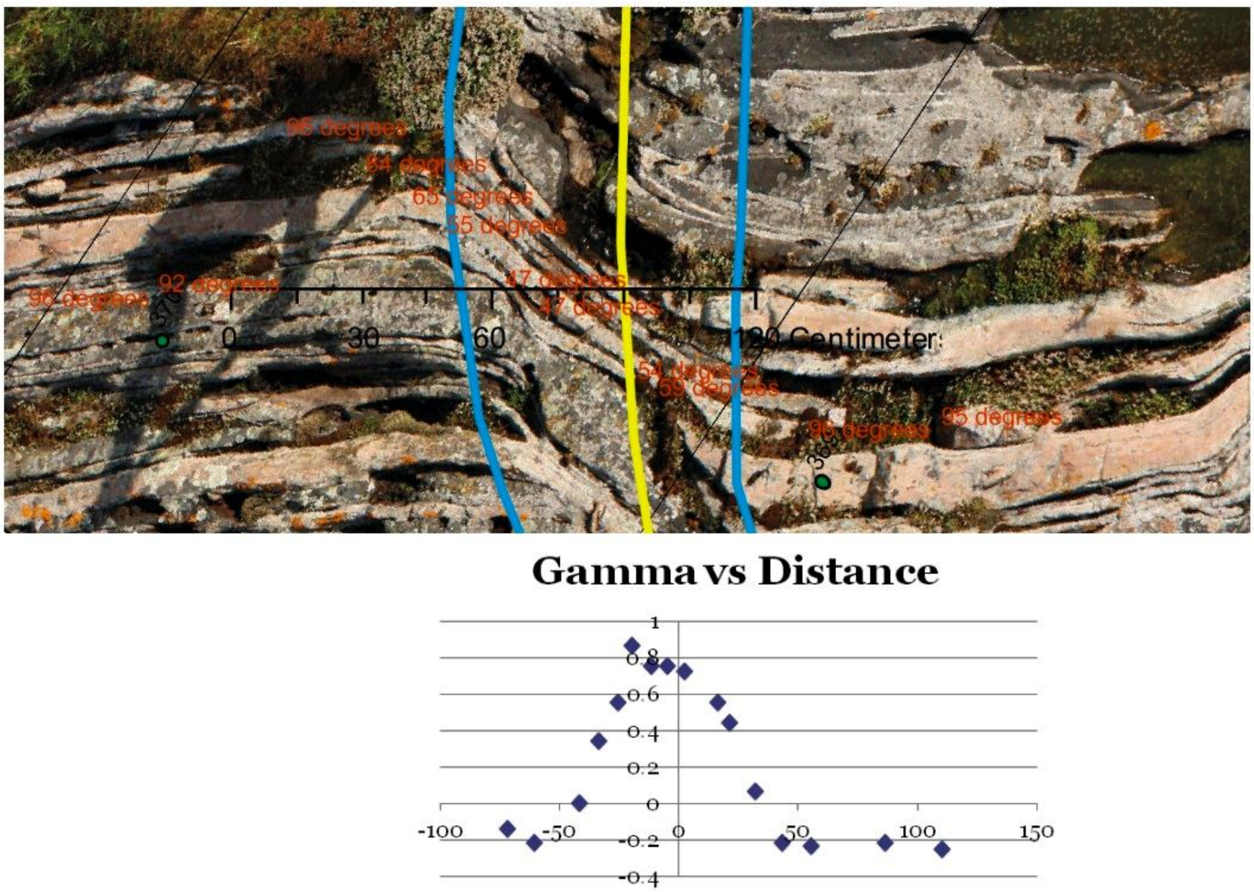


Figure 4.2: The photograph shows a shear zone, with the center being the yellow line and boundaries being the blue lines. The red writing across the shear zone is the angles measured for the α-α' calculation. Below there is a graph showing how γ changes with distance from the center of the shear zone, with g on the y axis and distance (cm) on the x.

Chapter 5: Map Results

5.1 Photomerge Map

Matches Island was mapped for the purpose of quantifying shear strain and characterizing deformation processes in a transitional zone in which the granulite facies gneisses of the PSD were reworked to form the nappe-bounding straight gneisses of the TMBSZ (Fig. 5.1).

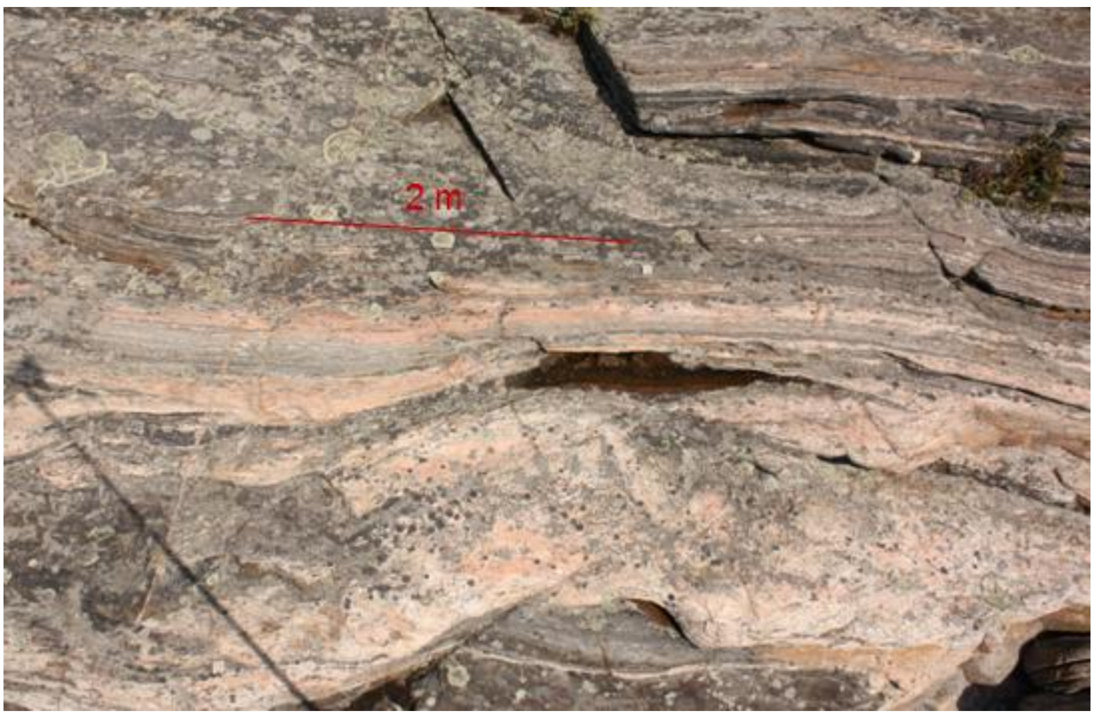


Figure 5.1: A photo of transposed gneiss on PBE Island, in the TMBSZ

The first major output of the work was the completion of the photomerge map of Matches Island shown in Figure 5.2. The map gives a detailed vertical view of the island with a common scale for all areas. The map also includes layers

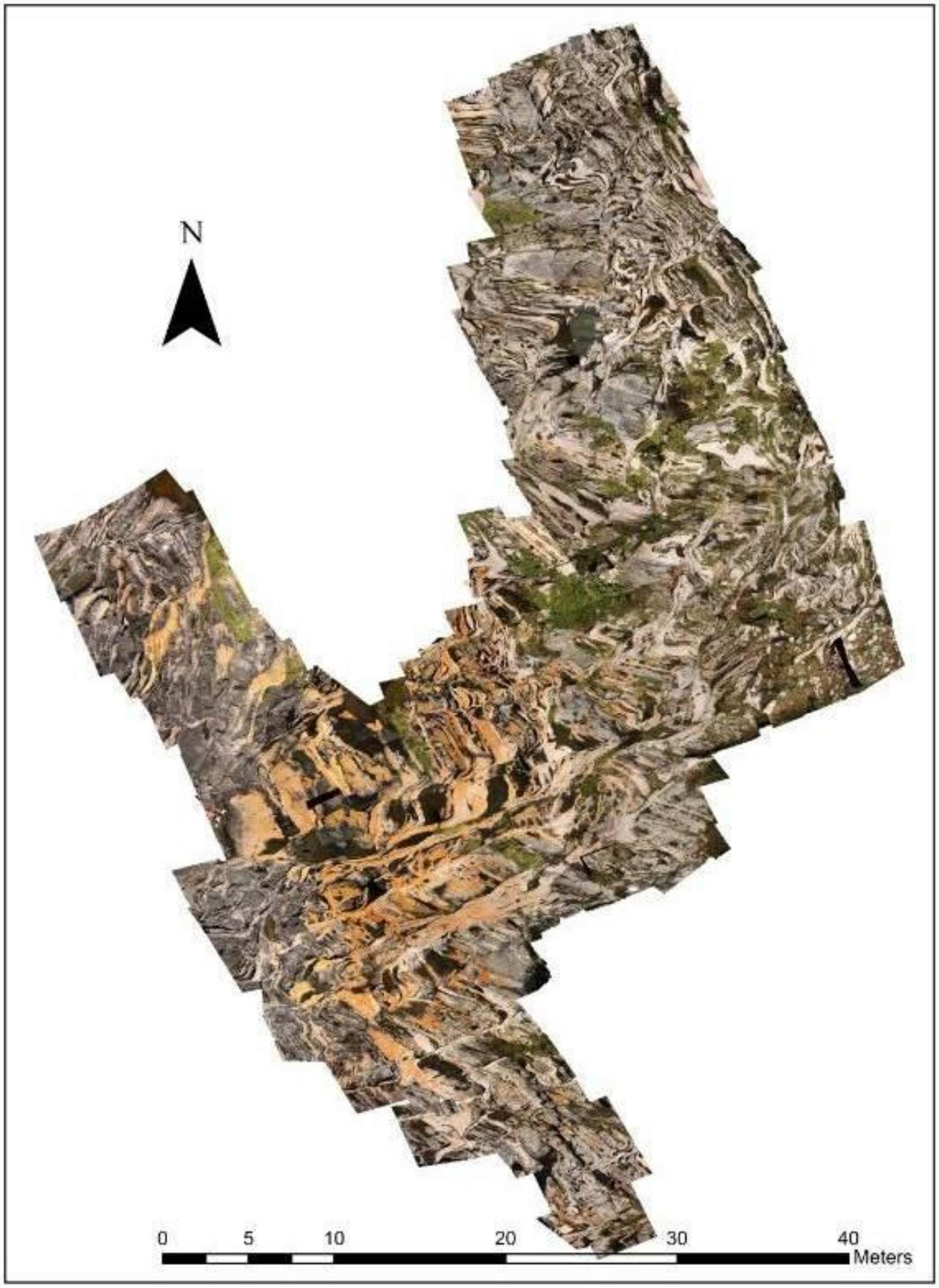


Figure 5.2: The photomerge map of Matches Island showing the shear zone network and structure. See larger print out for detail.

of shapefiles that can be turned on or off at will within ArcMap. Because the map was created with a GIS program, is can be used for quantitative structural geology. Figure 2.7 shows shear zone traces, which approximate the center and highest strain areas of the shear zones, and shear zone boundaries which separate the wall rock from shear zones. Figure 5.3 shows shapefiles of layers that have been traced to use for displacement/width calculations, and the polyline displacement/width lengths that label the shear zones and display the strain by the displacement/width method.

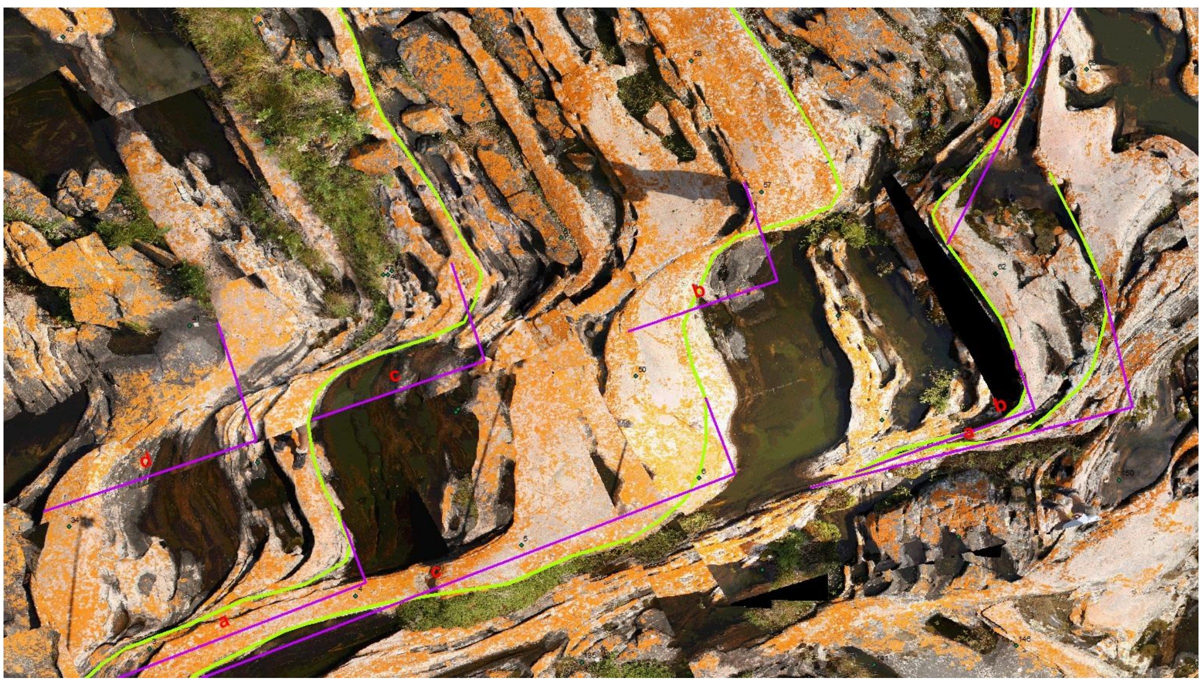


Figure 5.3: A close-up of a screengrab of Arcmap. Green lines are polylines that were used to trace layering across shear zones, and the purple lines are the displacement and width polylines

5.2 Map Analysis

Using the map, 36 distinct shear zones were indentified and highlighted. By using the ruler tool in ArcMap average dimensions of shear zones were found. The average length of a shear zone exposed on the map section of Matches Island was 11.73 m, with the longest being 45.83 m, and an aggregate length of 310.32 m. The average width of the shear zones was 0.74 m, with a maximum width of 1.34 m. By multiplying these two average dimensions, gives an approximate average area of the shear zones of 8.62 m^2. The map covers an area of approximately 1300 m^2, 25% of the area is made up of shear zones. The average spacing between shear zones is 2.09 m.

Chapter 6: Structural Analysis Results

6.1 Strain Calculations

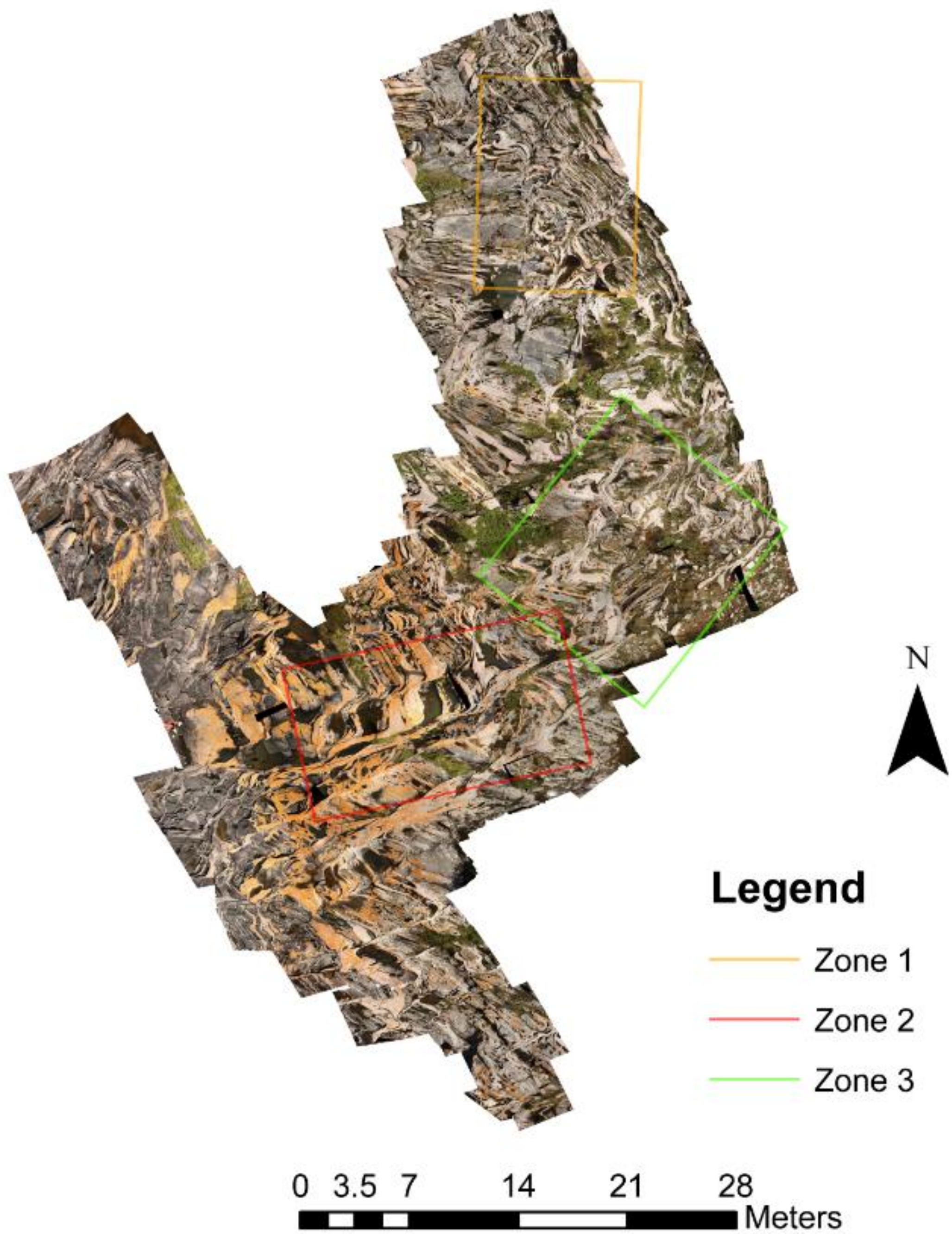
To properly understand the spatial distribution of the data below consider Figure 6.1. It has the locations of the where the shear zones were measured on the map. The shear zones used for the strain were clustered in three separate areas, the north being Zone 1 (Fig. 6.1a), the southwest being Zone 2 (Fig. 6.1b), and east being Zone 3 (Fig. 6.1c). The different shear zones within a Zone were each numbered. Each shear zone was subdivided and each location where a measurement was made was then assigned a letter to organize data for more than one shear zone.

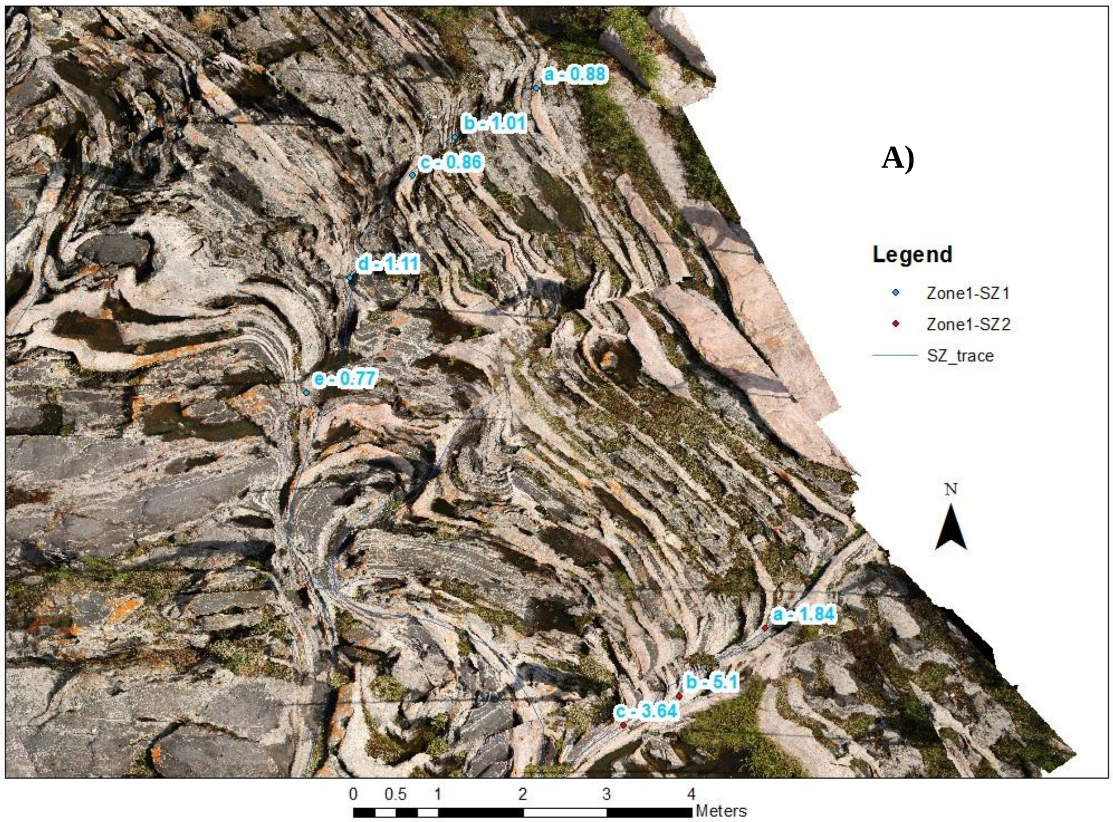
6.1.1 Strain by Displacement

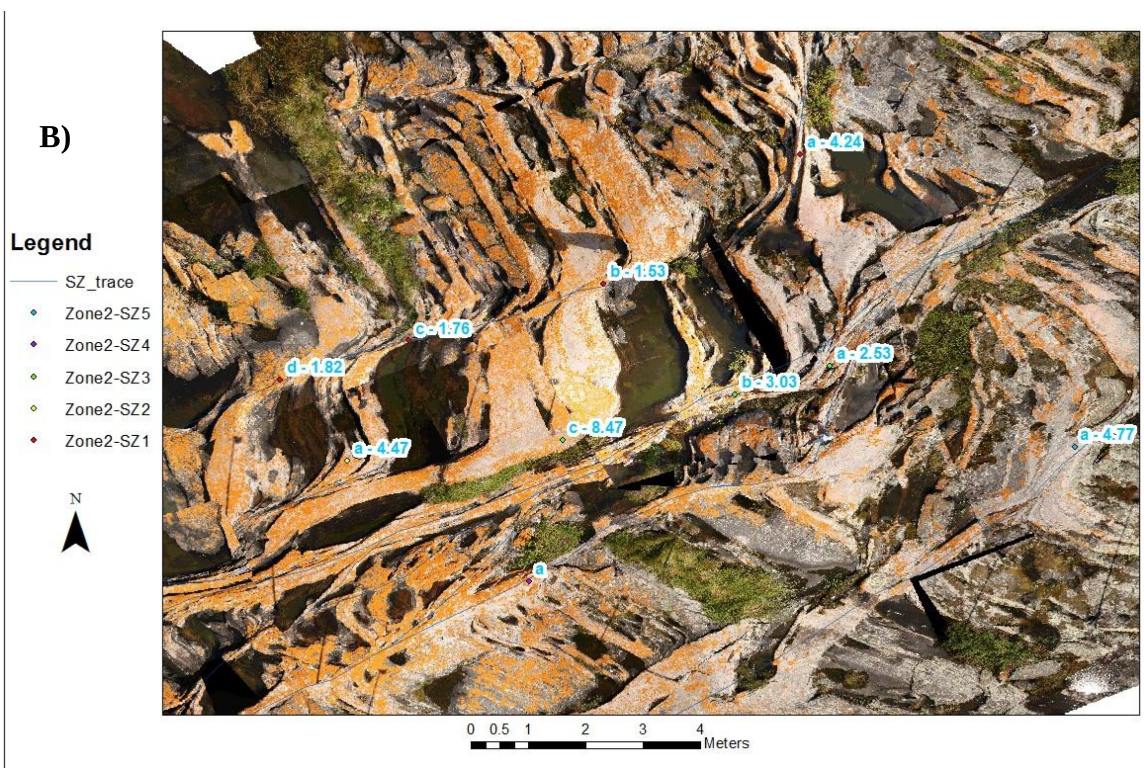
γ mean calculated from the displacement/width method is displayed in Table 6.1. These values are also shown in the Figure 6.1 a-c, which displays the quantified shear strain next to the corresponding shear zone in the photomerge map.

Table 6.1: Shear strain (γ) calculations by displacement/width methods. The asterisk represents minimum shear strain as discussed in Chapter 2. Bulk shear strain represents the amount of shear strain over several shear zones.

Zone	SZ	Displacement (m)	Width (m)	γ
1				
	SZ 1a	0.56	0.64	0.88
	SZ 1b	0.68	0.67	1.01
	SZ 1c	0.57	0.66	0.86
	SZ 1d*	0.99	0.89	1.11
	SZ 1e*	0.69	0.9	0.77
	SZ 2a*	1.14	0.62	1.84
	SZ 2a*	1.53	0.3	5.10
	SZ 2c*	1.2	0.33	3.64
2				
	SZ 1a	2.88	0.68	4.24
	SZ 1b	1.62	1.06	1.53
	SZ 1c	1.87	1.06	1.76
	SZ 1d	2.31	1.27	1.82
	SZ 1-2 bulk*	5.54	1.98	2.80
	SZ 1-2-3? bulk*	11.84	2.72	4.35
	SZ 2a*	3.04	0.68	4.47
	SZ 3a	3.41	1.35	2.53
	SZ 3b	1.94	0.64	3.03
	SZ 3c*	7.03	0.83	8.47
	SZ 5a*	4.2	0.88	4.77


N
Legend
Zone 1
Zone 2
Zone 3
0 3.5 7 14 21 28
Meters


a - 0.88
b - 1.01
c - 0.86
d - 1.11
e - 0.77
a - 1.84
b - 5.1
c - 3.64
A)
Legend
Zone1-SZ1
Zone1-SZ2
SZ_trace
N
0 0.5 1 2 3 4
Meters


B)
Legend
SZ_trace
Zone2-SZ5
Zone2-SZ4
Zone2-SZ3
Zone2-SZ2
Zone2-SZ1
N
a - 4.24
b - 1.53
c - 1.76
d - 1.82
a - 2.53
b - 3.03
c - 8.47
a - 4.47
a - 4.77
a
0 0.5 1 2 3 4
Meters

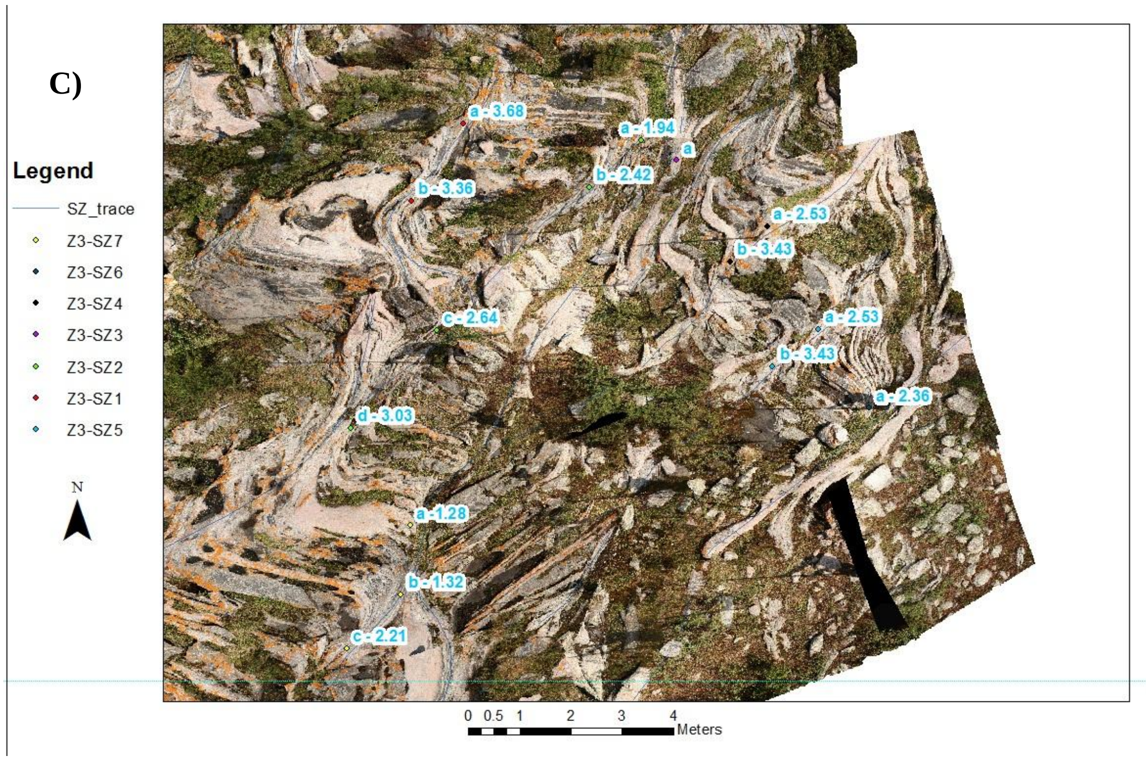
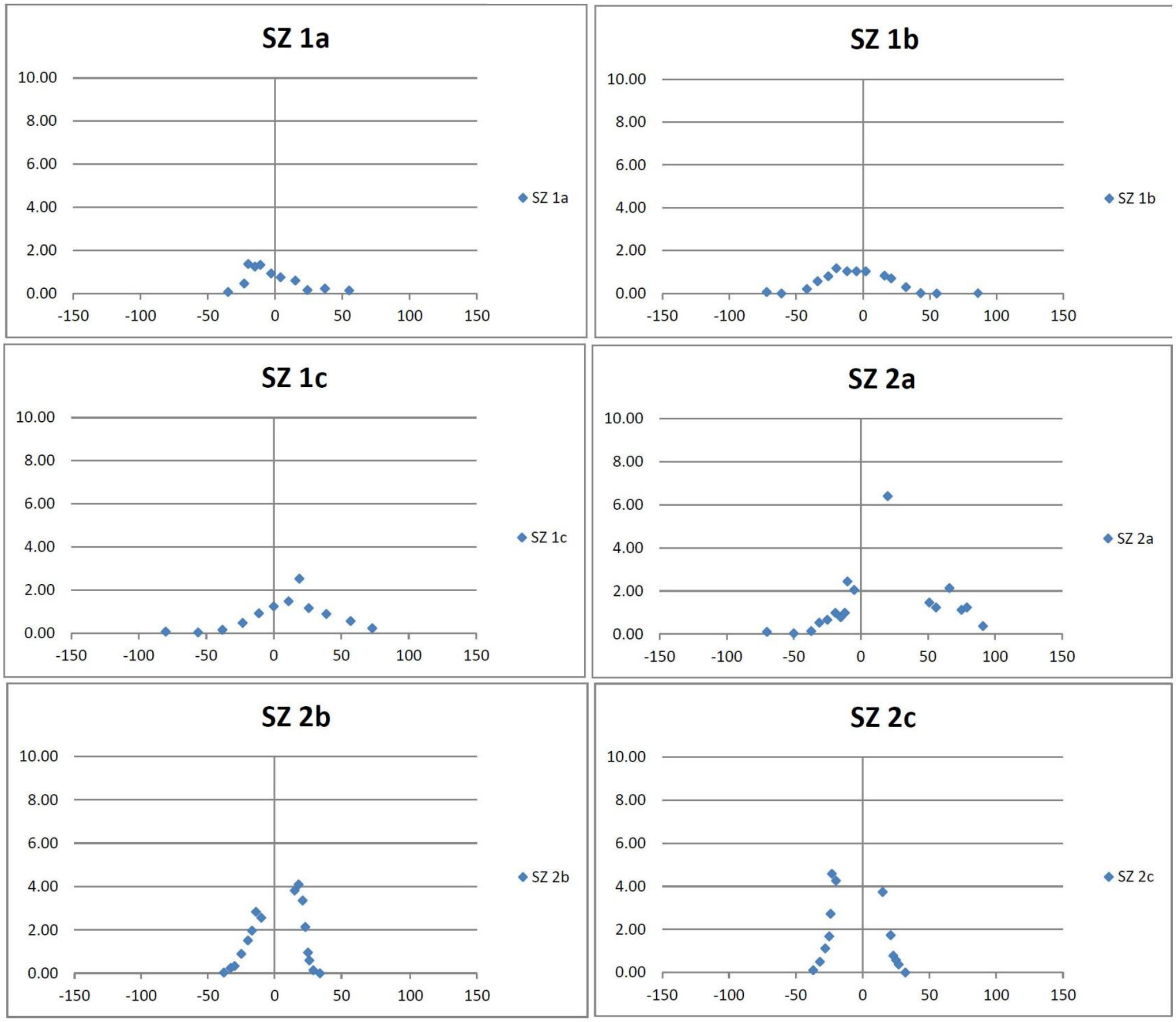


Figure 6.1: Photomerge map showing Zone 1 shear zones in the orange box, Zone 2 shear zones in the red box, and Zone 3 shear zones in the green box. The close ups (a-c) show shear strains labeled where they were measured. (a) is Zone 1, (b) is Zone 2, and (c) is Zone 3.

6.1.2 Strain by α-α′

The shear strain calculated by the α-α' was plotted against distance from the center of the shear zone, which can be seen in Figure 6.2. These graphs result in a snapshot of strain over the shear zone and do not represent the entire width. To get a more representative result from this method the strain-distance graphs were integrated to produce an average strain across the entire shear zone (Fig. 6.3).

Zone 1)


SZ 1a
SZ 1b
SZ 1c
SZ 2a
SZ 2b
SZ 2c
10.00
8.00
6.00
4.00
2.00
0.00
-150
-100
-50
0
50
100
150

Zone 2)

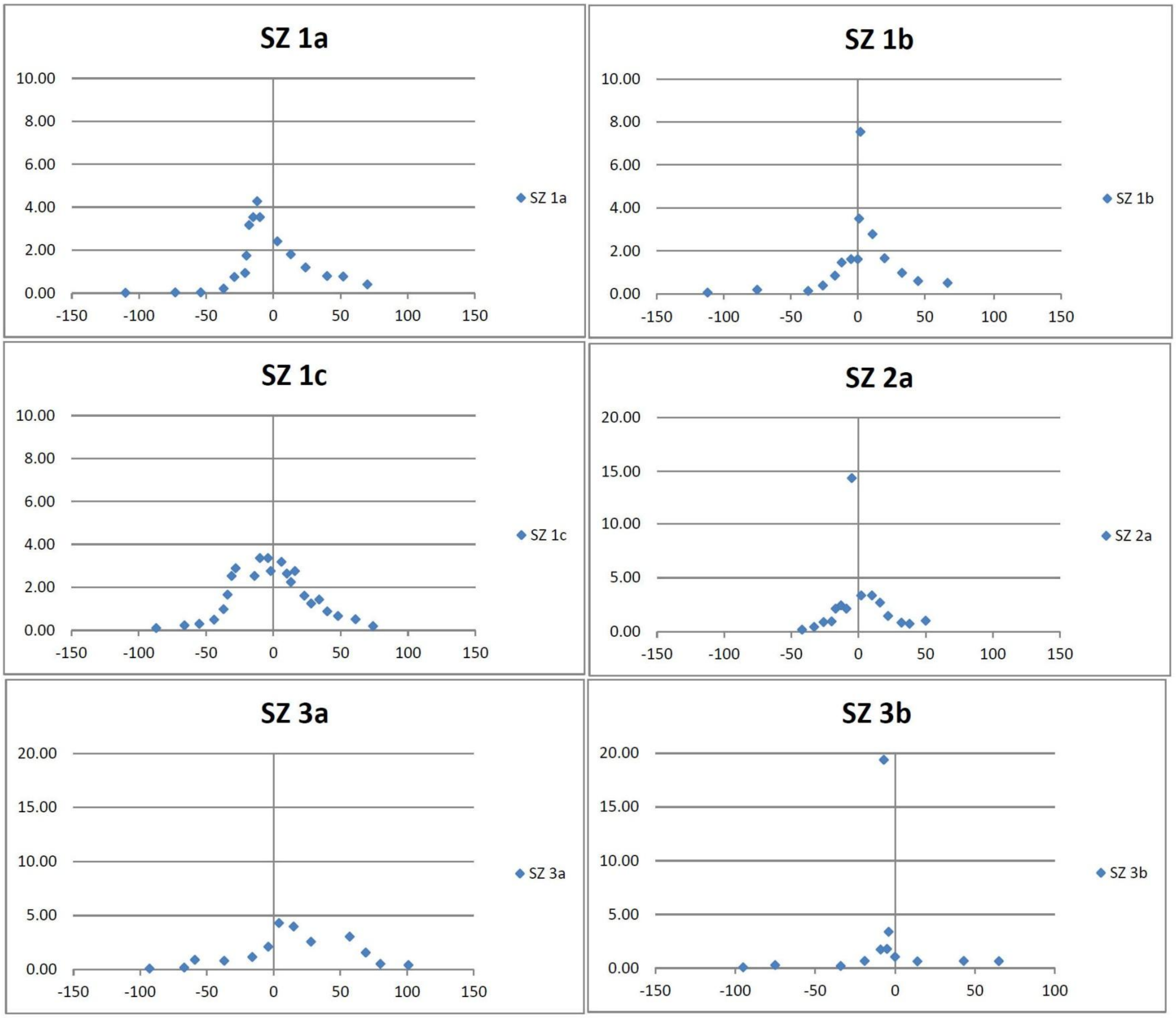


Figure 6.2: γ (y) plotted against distance (x) away from shear zone center. The centre of the shear zone is approximately on 0 cm. Note the scale change in Zone 2, shear zone 2a.

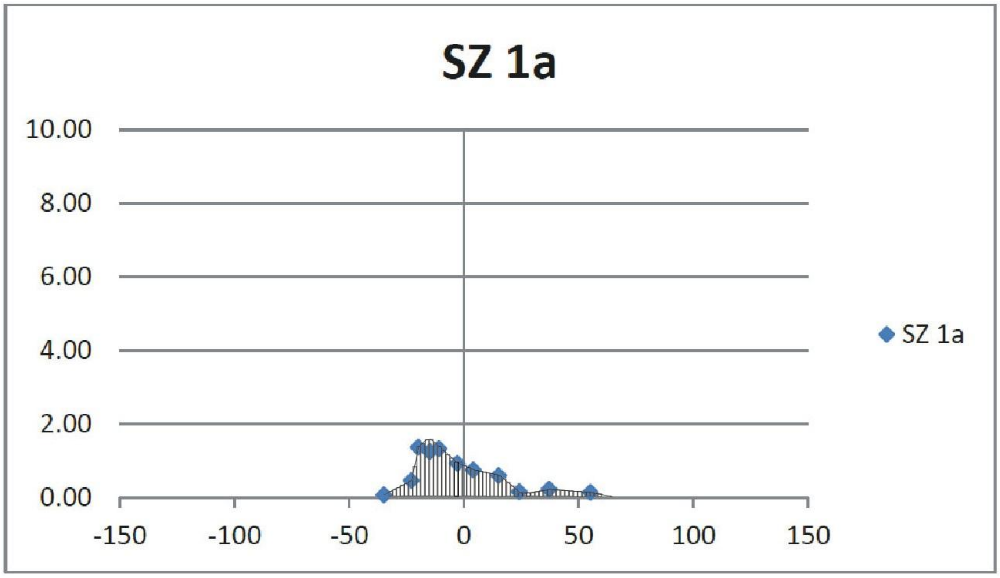


Figure 6.3: A plot of γ against distance from shear zone center, integrated for area under the curve to find the total displacement. This was used to calculate average γ.

6.2 Structures

As well as calculate shear strain, this study looked at structures that were associated with the shear zones, and formed under high shear strain conditions.

6.2.1 Shear Zone 'Fish'

Shear zone fish are lenses or pods of wall rock, which are sandwiched between shear zones (Fig. 6.4). There were 8 shear zone fish identified, where their distribution on Matches Island can be seen in Figure 6.5. Compositionally, the fish were commonly mafic blocks, or an aggregate of layering with a significant mafic component. With the case of these 'fish', the gneissic layering often does not match the regional strike for other wall rocks. The fish range in size and can be very large (3 m in long axis), or smaller (~ 0.5m). The bounding shear zones often flow into the same shear zone on either side of the fish.

Figure 6.4: A shear zone fish, being bounded by shear zones. The fish is a large mafic panel has been deformed and rotated.

6.2.2 Development of Isoclinal Folds

Another structure of note on Matches Island is the development of isoclinal folds along shear zones (Fig 6.6). Further along transposition towards PBE and TMBSZ we see isoclinal folds in the transposed unit (Fig. 6.7), which can be interpreted as originating earlier in transposition, potentially at a Matches Island-type stage.

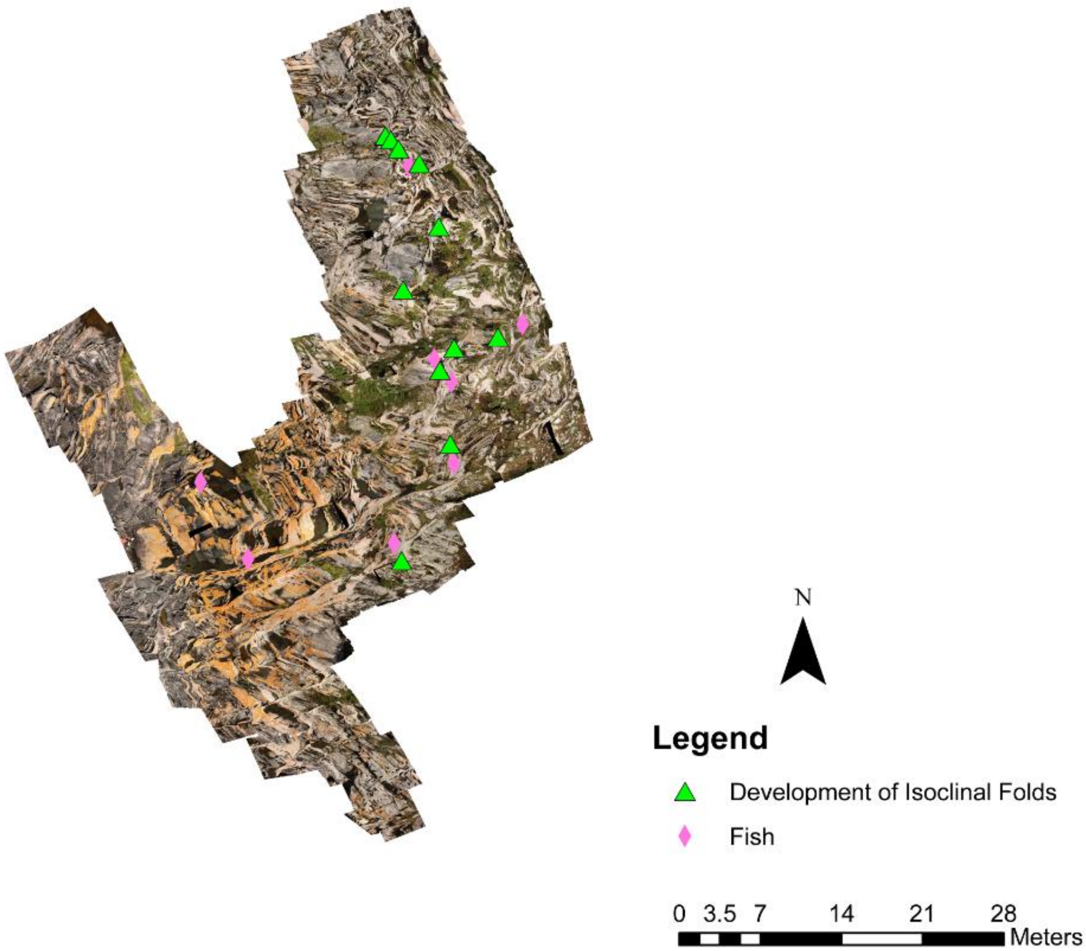


Figure 6.5: The distribution of fish and proto-isoclinal folds on Matches Island.

The distribution of proto-isoclinal folds can also be seen in Figure 6.5, where it is clear to see they are commonly found around the margins of shear zone fish, which means that they are related structures. Of the 11 proto-isoclinal folds identified, 9 of which were found to occur in the vicinity of a shear zone fish. This correlation could mean that they are formed by related processes.

Figure 6.6: The development of isoclinal folds on Matches Island. The proto-isoclinal fold can be seen in the mafic layer, which pushes into the softer felsic material.

Figure 6.7: Isoclinal folds in transposed straight gneiss of TMBSZ, photo taken on PBE Island.

6.2.3 Linkage

Linkage is the degree of connectivity exhibited by a shear zone network. By using the quantitative map in ArcMap, linkage could be viewed by tracing the shear zone network with polylines. Linkage was quantified by how many triple junctions were concentrated in an area, where triple junctions were defined as the point at which three segments of a polyline converged. 19 shear zone triple junctions were identified on Matches Island, with 13 (68%) triple junctions were focused on one corridor in particular, which can be seen in Figure 6.8. This corridor has significantly more triple junctions per unit area than anywhere else on Matches Island.

When looking at the distribution of triple junctions in Figure 6.8 compared to shear zone fish in Figure 6.5, there is a correlation between the two. Several shear zones tend to link on either side of the shear zone fish and envelope it (Fig. 6.9). The formation of a shear zone network by linkage could lead to the formation of shear zone fishes.

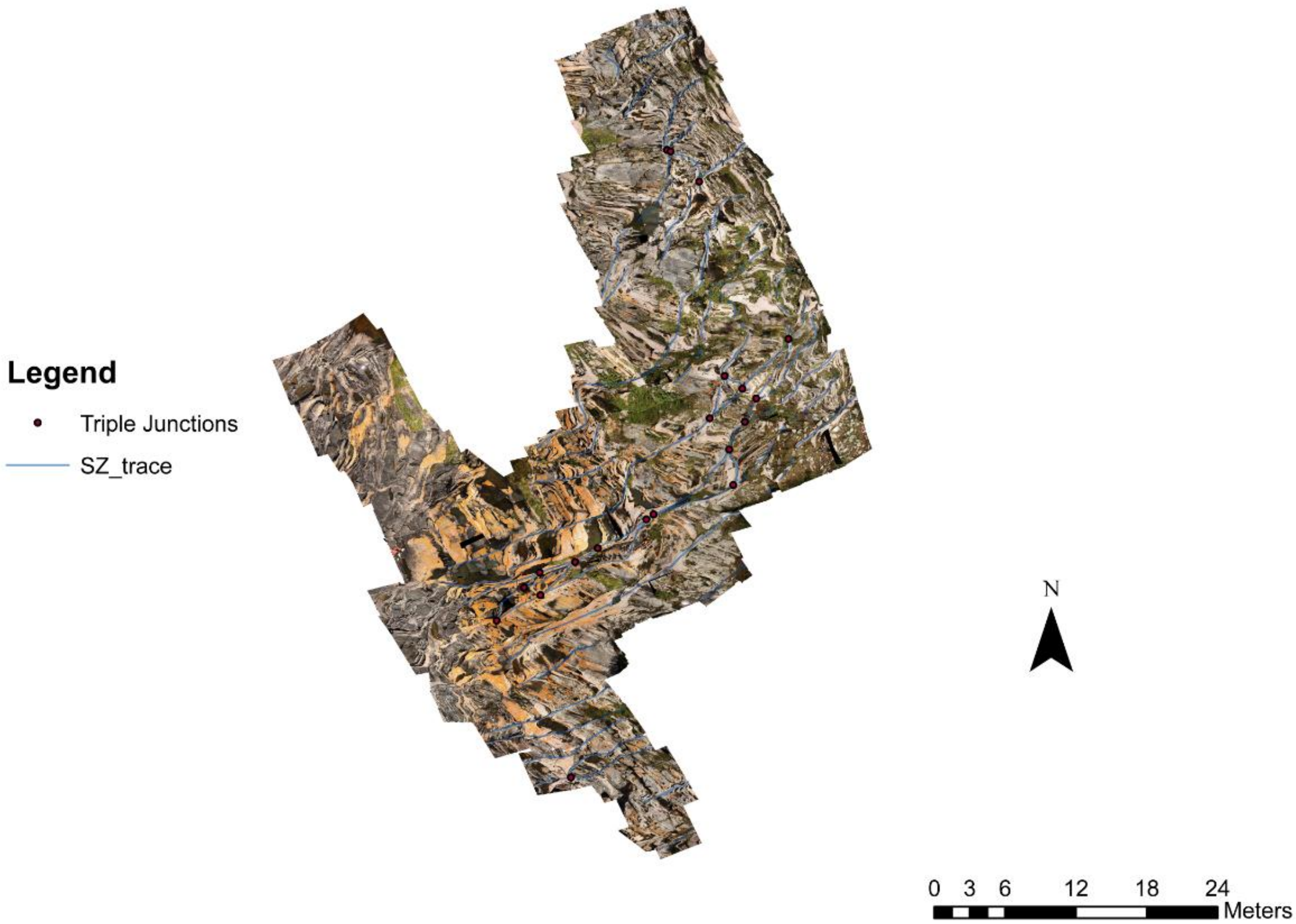


Figure 6.8: Shear zone traces in blue, and triple junction points of red show the shear zone network of Matches Island.

Figure 6.9: A large shear zone fish, surrounded by bounding shear zones, with proto-isoclinal folds forming along side it.

Chapter 7: Discussion

7.1 Methods

7.1.1 Effect of Topography on Map

Matches Island was assumed in the beginning to have no significant changes in elevation that would produce errors within the map, so a single grid was established.

The assumption that the Matches Island topography would not significantly affect the outcome of the map was not valid. Areas that had a variance of topography on the island proved to be the areas where photo-faults were most common on the map (Fig. 7.1). While there are photofaulting issues that seem unrelated to topography, the worst areas of the map are situated in a region of uneven terrain.

Figure 7.1: A close up of ArcMap showing a photofault in a region of change in elevation. It is clear to see, the panoramas do not overlap perfectly.

7.1.2 Solutions for Topographic Distortion

To get around this issue of topography related photofaulting in the future, there are two possible solutions. One solution would be to create a digital elevation model (DEM) using the z coordinates collected from the DGPS rover. Once a DEM is created, it could lain overtop the grid so that topography will be considered when georeferencing. The second solution is to use an orthorectification program that is used to stitch and correct aerial photographs. The problem with this solution is that in order to use the orthorectification program, the angle between the camera lens and the horizontal surface must be known, which in the case of this study was never recorded. If this angle was measured however, it would make for a relatively simple conversion into an orthorectified format (C. Walls, pers. comm., 2012).

7.2 Shear Zone Comparisons

7.2.1 Results compared to previous work

In a previous field study of Matches Island, Culshaw et al. (2011) conducted a similar study, calculating shear strain in the field. The results of this study will be compared to the Culshaw et al.'s results. Culshaw et al. employed the same methods for calculating shear strain, $\gamma = D/W$, and $\gamma = \alpha - \alpha'$. For the $\gamma = D/W$, the method of measuring layers were different. Culshaw traced layers with DGPS, and/or measured displacements and widths on site (tape measure), while the measurements in this study were taken from a scaled photomerge map. The $\gamma = \alpha - \alpha'$ methodology is similar in both study. Culshaw et al. taking scaled pole-camera photos of shear zones, and then importing the photos into CorelDraw for angular measurements.

Figure 7.2 shows the map of shear strain on Matches Island made by Culshaw et al. (2011). Some of the results are quite similar for a few areas, for the section that corresponds to Zone 2, Culshaw et al. had calculated an average shear strain of 8.1 with a maximum shear strain of 19.2, with the maximum shear strain being the greatest shear strain found at a point using the $\gamma = \alpha - \alpha'$ method. Shear zone 3c showed similar results, with a $\gamma = D/W$ value of 8.47, and a $\gamma = \alpha - \alpha'$ value of 7.33, with the maximum shear strain being 18.25.

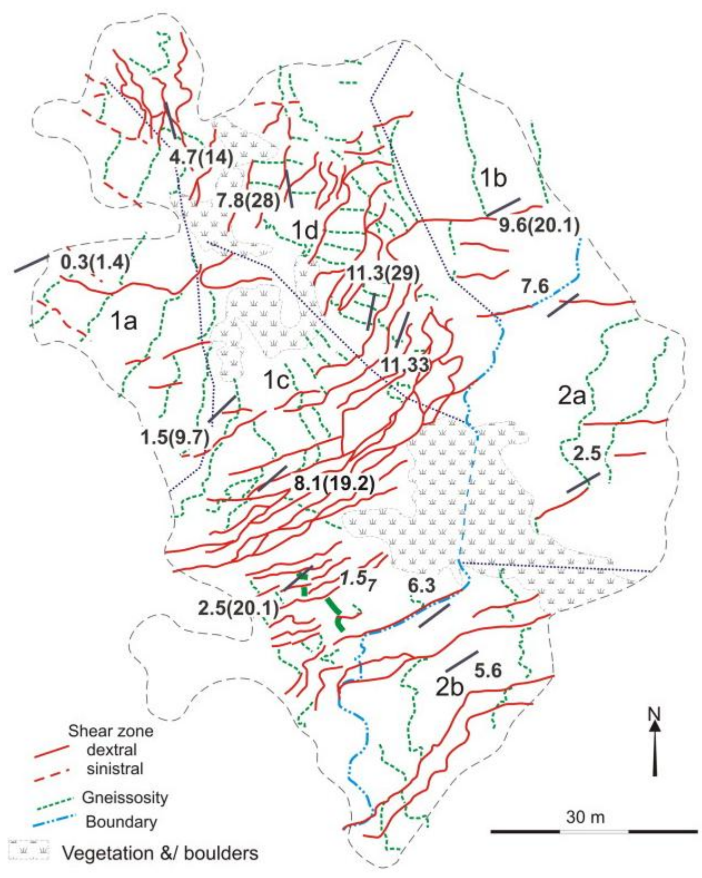


Figure 7.2: Culshaw et al. 2011 map of Matches Island. Average shear strain is displayed, with maximum shear strain in brackets.

The sections Culshaw et al. 2011 calculated shear strain that corresponded to zone 1 and 2 showed fewer similarities. Generally the shear strains in this study were much lower than Culshaw's calculations.

7.2.2 Straight versus Curved Shear Zones

The straight shear zones on Matches Island show a general pattern of increasing shear strain along the same shear zone from northeast to southwest. The shear strain increases the highest in areas where shear zone are wider. The trend of shear strain increasing along a shear zone to the southeast is also is true for curved shear zones.

7.2.3 Displacement/Width versus α-α'

Table 7.1 shows the shear strains calculated for the same shear zones by the two different methods; γ = D/W, and $\gamma = \alpha - \alpha'$. The absolute difference between the two shear strains generated was shown as well. It was interesting to note that some of the same areas yielded similar shear strains. Zone 1 shear zone 1 showed nearly identical values for average shear strain. Zone 2 shear zone 3 showed the largest difference in the two values calculated.

It is worth noting that the shear strain values are most similar when a $\gamma = \alpha - \alpha'$ generated value is compared with a γ = D/W generated value that has been traced across an entire shear zone. In contrast, the γ = D/W values that were calculated using the 'minimum strain' method which are indicated with an asterisks in Table 7.1, were as would be expected, are less then that of the corresponding $\gamma = \alpha - \alpha'$ generated values, because the minimum strain represents only a fraction of the real shear strain.

The largest difference of shear strain values occurred in shear zone 1a of zone 2, where there is a difference of γ of 2.42 between the two methods. This particular measurement was made in the curvature of the shear zone, where the γ = D/W value is much higher (4.24) than other values on the same shear zone (1.53, 1.76, and 1.82). The γ = α - α' generated value for zone 1 shear zone 1a (1.82) is much more consistent with the other γ = D/W values on the same shear zone, than the γ = D/W for zone 1 shear zone 1a (4.24). This leads to the hypothesis that the γ = α - α' method is better for calculating shear strain of curved shear zones.

Table 7.1

Zone	**SZ**	γ by D/W	g by α – α'	Difference
Zone 1				
	SZ 1a	0.88	0.83	0.05
	SZ 1b	1.01	0.96	0.05
	SZ 1c	0.86	1.19	0.33
	SZ 1d*	1.11	-	
	SZ 1e*	0.77	-	
	SZ 2a*	1.84	3.52	1.68
	SZ 2b*	5.1	3.78	1.32
	SZ 2c*	3.64	4.59	0.95
Zone 2				
	SZ 1a	4.24	1.82	2.42
	SZ 1b	1.53	0.92	0.61
	SZ 1c	1.76	1.33	0.43
	SZ 1d	1.82	-	
	SZ 1-2 bulk*	2.8	-	
	SZ 1-2-3? bulk*	4.35	-	
	SZ 2a*	4.47	3.61	0.86
	SZ 3a	2.53	1.28	1.25
	SZ 3b	3.03	1.47	1.56
	SZ 3c*	8.47	7.33	1.14
	SZ 5a*	4.77	-	

Zone 3				
	SZ 1a*	3.68	-	
	SZ 1b	3.36	-	
	SZ 2a*	1.94	-	
	SZ 2b*	2.42	-	
	SZ 2c	2.64	-	
	SZ 2d*	3.03	-	
	SZ 2e*	1.81	-	
	SZ 3a		-	
	SZ 4a*	2.71	-	
	SZ 4b*	1.57	-	
	SZ 5a	2.53	-	
	SZ 5b*	3.43	-	
	SZ 6a*	2.36	-	
	SZ 6b*	0.74	-	
	SZ 7a*	1.28	-	
	SZ 7b*	1.32	-	
	SZ 7c*	2.21	-	

7.3 Shear System Development

7.3.1 Shear Zone Networking

The shear zone networking on Matches Island can be compared to the Northern Cap de Creus shear belt of Spain (Carreras, 2001), where there have been in depth studies of networking. Like the Matches Island shear zone system, the Northern Cap de Creus shear belt developed under retrograde metamorphic conditions from greenschist facies, compared to the much higher grade metamorphism of upper amphibolite to granulite facies that is present on Matches Island. The network of ductile shear zones of the Cap de Creus system developed post-peak metamorphism with a significant drop in temperature. (Carreras, 2001),

The main differences between the two systems are that the Cap de Creus system has straight shear zones linked by minor oblique ones, and at Matches Island we see both straight and curved shear zones. Despite this difference the overall structure of the shear zone network of Cap de Creus the looks strikingly similar to the shear zone network on Matches Island (Fig. 7.3).

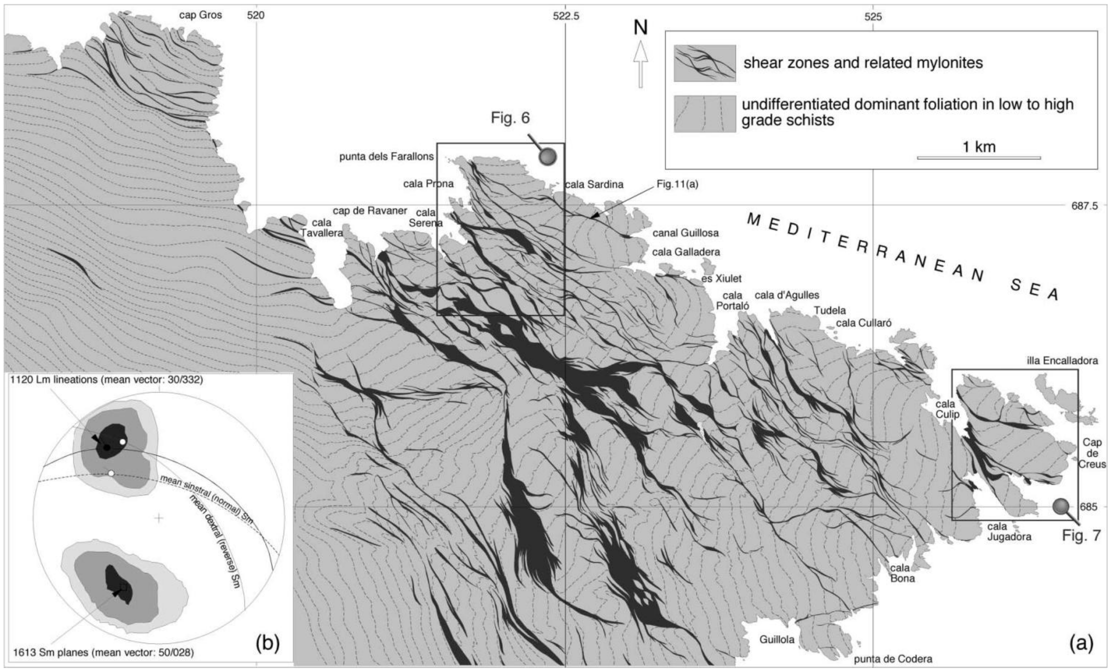


Figure 7.3: Carreras 2001 map of the shear zone network of Cap de Creus. When compared with Fig. 5.2 or 2.5, they look quite similar.

The development of the shear zone network leads to the widening shear zones. This widening is process is a result of the relationship of shear strain with rock strength, as the shear strain increases; the rock becomes weaker (Fig. 7.4) (Fusseis et al., 2006). By creating a more connected network, the wall rock becomes more and more enveloped and isolated resulting from propagation of shear strain into the wall rock. This can be seen on Matches Island where one corridor of shear zones show the greatest concentration of triple junctions, the greatest shear zone widths, and the formation of shear zone fish and proto-isoclinal folds (see below for definition).

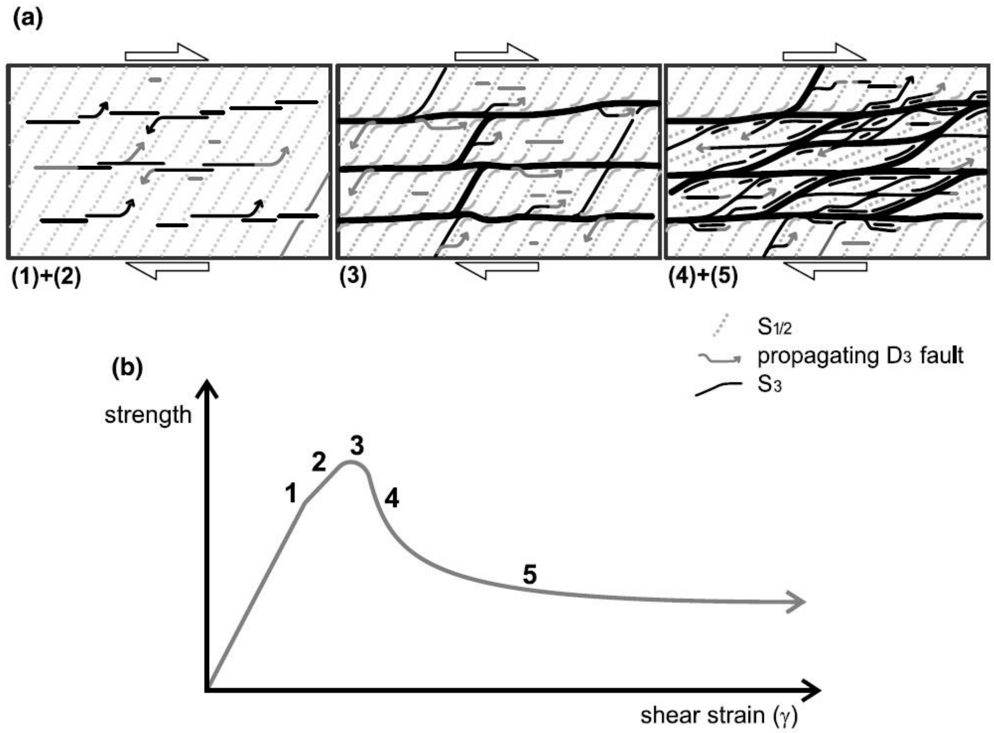


Figure 7.4: The relationship between shear strain, rock strength, and shear zone connectivity (Fusseis et al., 2006).

7.3.2 Shear Zone Fish

'Shear zone fish' refers to structures that form in between two closely spaced shear zones, where the wall rock has been deformed to form a sigmoidal shape. The shear zone fish have been hypothesised in this study as being a by product of the widening of a shear zone. Figure 7.5 shows a model of how the shear zone fish could form with increasing strain. At time 1, the wall rock is undeformed, with bounding shear zones that are well developed. At time 2 the bounding shear zones are developed further, and because of the increase of shear strain in the shear zones, the margins of the wall rock begin to deform. This effectively shrinks the width of the undeformed wall rock, and therefore widens the shear zone. By time 3, the shear strains are now much higher in the bounding shear zones and have had a profound affect on the wall rock. The wall rock is now hardly wall rock at all, as it is almost thoroughly deformed as the shear strain has propagated into the wall rock, with only a small core of wall rock remains undeformed. It is at about time 3 where we see the deformed wall rock begining to resemble what we see on Matches Island (Fig. 6.4). By this model it seems that shear zone fish form in high shear strain environments, with shear strain persisting for long periods of time.

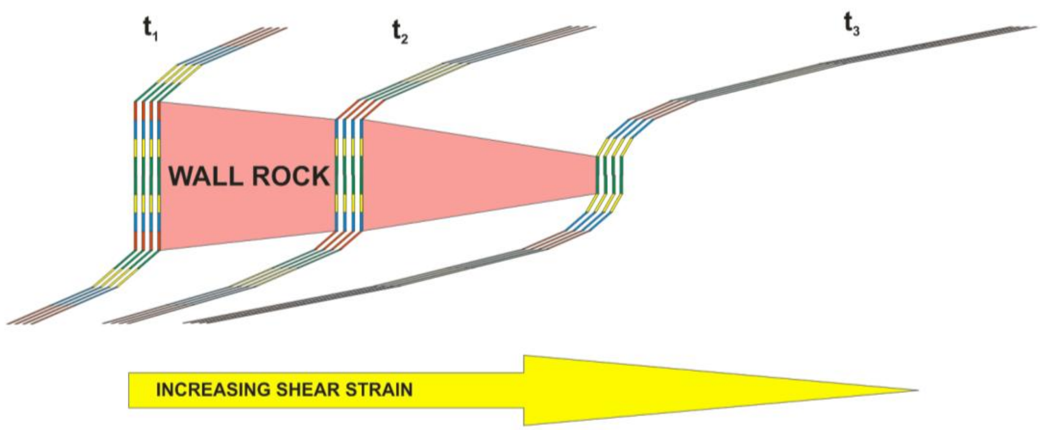


Figure 7.5: A model for the development of shear zone fish, with progressive wall rock collapse by the increase in shear strain.

This seems logical as each of the shear zone fish are bounded by shear zones to either side, where the fish represents wall rock that has begun to deform significantly in response to the shear strains of the neighboring shear zones. With the collapse of the sheared wall rock (fish) separating the shear zones, the older bounding shear zones are able to consume the shear zone fish separating them, which leads to a larger shear zone by the merging of two.

It is clear to see that with increasing strain, the shear zone fish will eventually be assimilated into the bounding shear zones, merging the two shear zones, which is a mechanism for shear zones growing wider. This degradation of the wall rock integrity leads to two things to occur; first by the propagation of shear strain into the wall rock causes it to deform, and second, the shear zone is widening by the consumption of the wall rock.

7.3.3 Development of Isoclinal Folds

The development of isoclinal folds within shear zones is closely related to the formation of shear zone fish and widening of the shear zones. The proto-isoclinal folds are small folds, which are eventually sheared into isoclinal folds seen in TMBSZ layering that occur on the margins of shear zone fish. They occur when a hard mafic layer resists deformation, while adjacent layering flows around the knob of hard mafic material. As the shear strain increases, the mafic knob will rotate to align with the shear zone, pushing into the softer adjacent layers. The knob with force the softer layers into a fold which becomes amplified with shear strain.

This is yet another method by which the wall rock becomes deformed, and therefore is a clue that simple strain may not govern this process. The isoclinal development was noticed to be related to the formation of shear zone fish, which can be explained by two ways; first, the proto-isoclinal folds and shear zone fishes form under the same conditions, which may not be simple shear, and are proximal because they form in areas of high strain, second, the shear zone fish are predominately composed of mafic material that is more resistant to shear strain than other layers, which can provide the resistant mafic knobs that the proto-isoclinal folds nucleate from.

Chapter 8: Conclusion

8.1 Further Work

The first additional work that should be done is a similar analysis for PBE Island, which is further along the transposition gradient, to compare with results found on Matches Island. With a working knowledge of this transpositional gradient regional shear strains can begin to be calculated.

A proper study on the linkage of the shear zone network would be informative for future works. By quantifying the degree of connectivity in regions of Matches Island would lead to a better understanding of the widening process.

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