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Geology of the Millen Thrust System, Northern Victoria Land, Antarctica

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Abstract: Rocks of the Millen Schists were analysed during GANOVEX X (2009/10) to evaluate the nature of the contact between the Ross-age Bowers and Robertson Bay Terranes in northern Victoria Land. The majority of this work was carried out in proximity to the Millen Thrust System, a major structure that separates the whole Millen Shear Belt into two overlying tectonic units. The Millen Shear Belt has been widely acknowledged to represent the tectonic contact between the two terranes. Lithological similarities between the rocks in the hanging wall and footwall of the Millen Thrust System and those located in the Bowers and Robertson Bay Terranes support this suggestion. The structural history of the Millen Schists can be divided into three stages: (i) formation of isoclinal folds and pervasive S1 foliation that largely parallels bedding S0; (ii) upright D2 folding along northwest-southeast axes and (iii) localised D3 high-strain that was dominantly related to reverse transport along the Millen Thrust System. Interpretations based on field observations and the available geochronological data supports a model where: (i) sub-horizontal northeast-southwest directed pure shear shortened the juxtaposed (by the late Cambrian) Bowers and Robertson Bay terranes; (ii) strain localisation along the Millen Thrust System resulted in the development of a complex finite strain pattern in the Millen Schists, which records evidence of dominant northeast directed reverse transport with minor lateral displacement.

Zusammenfassung: Während der BGR-Expedition GANOVEX X (2009/10) wurden Gesteine der Millen Schists untersucht, um die Kontaktzone zwischen den ross-orogenetischen Bowers und Robertson Bay Terranes Nord-Victoria-Lands besser charakterisieren zu können. Die Untersuchungen wurden hauptsächlich in unmittelbarer Nähe des Millen-Überschiebungssystems durchgeführt, ein bedeutendes Strukturelement, das den gesamten Millen Shear Belt in zwei übereinanderliegende tektonische Einheiten teilt. Der Millen Shear Belt wird als der tektonische Kontakt zwischen beiden Terranes angesehen. Ähnliche Lithologien im hangenden und im liegenden Block des Millen-Überschiebungssystems, nämlich im Bowers- und Robertson Bay Terran, stützen diese These. Die strukturelle Entwicklung der Millen Schists kann in drei Stadien unterteilt werden: (1) Bildung isoklinaler Falten D1 und eine überwiegend schichtungsparallele penetrative S1-Foliation. (2) aufrechte Faltung D2 parallel NW-SE streichender B2-Faltenachsen. (3) lokale intensive Verformung D3 hauptsächlich im Zusammenhang mit aufschiebenden Bewegungen entlang des Millen-Überschiebungssystems. Die Interpretation der Geländebeobachtungen und existierender geochronologischer Daten stützen ein Modell, in dem (1) eine subhorizontale NE-SW gerichtete reine Scherung eine tektonische Verkürzung der (ab dem späten Kambrium) direkt aneinander grenzenden Bowers und Robertson Bay Terranes bewirkte und (2) die Konzentration intensiver Verformung entlang des Millen-Überschiebungssystems zur Bildung eines komplexen finiten Verformungsmusters in den Millen Schists führte, das einen nach NE überschiebenden tektonischen Transport mit untergeordneten Lateralbewegungen belegt.

INTRODUCTION

One of the main aims of GANOVEX X (German Antarctic North Victoria Land Expedition 2009/10) was to examine the kinematic history of the major tectonic contacts that define the architecture of northern Victoria Land. Representing part of the 18000 km long Terra-Australis Orogen (CAWOOD 2005), northern Victoria Land was largely assembled during the Ross Orogeny, which developed out of response to subduction along the margin of Gondwana. The geological record of northern Victoria Land therefore holds vital clues into the evolution of the Ross Orogeny and the nature of subduction and accretion along the Antarctic segment of the Terra-Australis Orogen.

Two conflicting geodynamic models are presented in the literature to explain the geological architecture of northern Victoria Land. The first model interprets the three main tectonic units, namely the Wilson, Bowers and Robertson Bay Terranes (Fig. 1; 'Terrane' is used to be consistent with the literature; see ROLAND et al. 2004 for discussion) as 'far travelled', with collision resulting in their accretion from the down-going plate onto the overriding Gondwana margin (BRADSHAW et al. 1985). The second model requires a supra-subduction setting for the Gondwana margin, where the development and assembly of the terranes took place on the overriding plate and in close proximity to the continental plate (ROLAND et al. 2004,

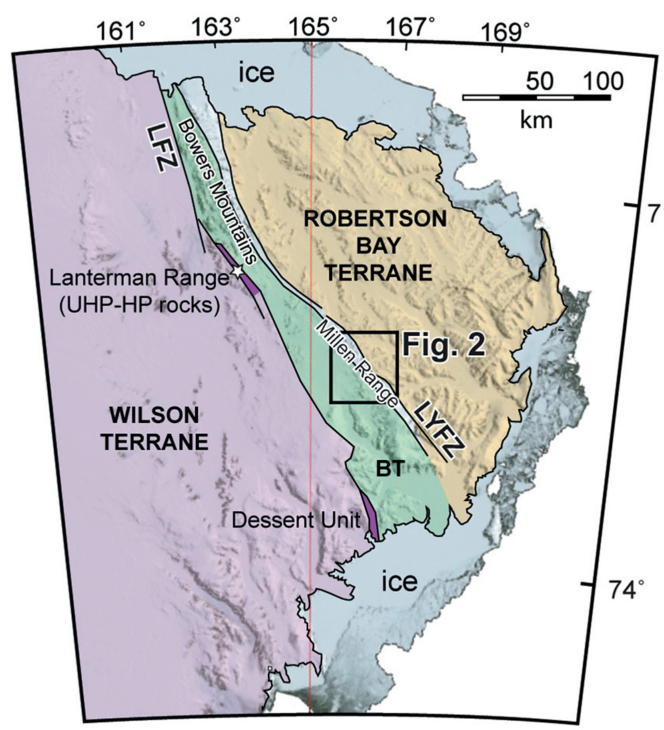

Fig. 1: Geological map of northern Victoria Land showing the distribution of the main terranes and tectonic boundaries. Abbreviations: BT = Bowers Terrane; LFZ = Lanterman Fault Zone; LYFZ = Leap Year Fault Zone.

Abb. 1: Geologische Karte von Nord-Victoria-Land mit der Lage der drei Terranes und ihrer tektonischen Grenzen.

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ROCCHI et al. 2011). These models demand contrasting settings for major tectonic contacts that separate the Wilson, Bowers and Robertson Bay terranes. For the 'far travelled' model, the terrane boundaries would be sutures, marking the site(s) of collision and accretion. For the supra-subduction model, the terrane boundaries represent internal fault zones that facilitated the translation of terranes along the continental foreland. To test these two models, the tectonic contact between the Robertson Bay and Bowers Terranes (defined by the Millen Schists) was analysed during GANOVEX X. Here we present the preliminary results of fieldwork, kinematic analysis and subsequent interpretations of these new data. These results are incorporated with existing studies of the Millen Schists and its western boundary, the Leap Year Fault Zone, to present a comprehensive kinematic history of the tectonic contact between the Bowers and Robertson Bay Terranes.

GEOLOGICAL SETTING

The general architecture of the Ross Orogen in northern Victoria Land comprises the inboard Wilson Terrane, the Bowers Terrane and the outboard Robertson Bay Terrane (Fig. 1). As detailed descriptions of these terranes have been published (GANOVEX TEAM 1987, ROLAND et al. 2004, TESSENSOHN & HENJES-KUNST 2005, ROCCHI et al. 2011), only brief descriptions of each terrane will be presented here. Separating these terranes are (i) the Lanterman Fault Zone between the Wilson and Bowers Terranes and (ii) the Millen Shear Belt, a high-strain structural unit between the Bowers and Robertson Bay Terranes). The Leap Year Fault Zone and the Handler (previously Lillie) Fault are generally regarded to represent the two boundary faults of the Millen Shear Belt in the west and in the east, respectively (e.g., CRISPINI et al. 2014). The Millen Thrust System represents the main structural element of the Millen Shear Belt, separating the Millen Schists into an upper and lower tectonic unit (e.g., CAPPONI et al. 2003). As the Millen Thrust System provides the central theme of this paper, a detailed description of this structure, along with the associated rocks of the Millen Schist is presented.

The Wilson Terrane is made up of variably metamorphosed (greenschist to granulite facies) rocks that are intruded by plutonic and volcanic rocks of the Granite Harbour suite (GREW et al. 1984). Isotopic data points to a Cambrian to Early Ordovician age (520-480 Ma) for the timing of magmatism, high-grade metamorphism and deformation (BORG et al. 1987, HENJES-KUNST et al. 2004, SCHÜSSLER et al. 2004). The Lanterman Fault Zone defines the eastern margin of the Wilson Terrane and its contact with the Bowers Terrane (Fig. 1). Significantly, it contains blocks of ultrahigh to high-pressure metamorphic rocks (located in the Lanterman Range and Dessent Unit; Fig. 1) and evidence of a complex, high strain structural evolution (ROLAND et al. 1984, GIBSON 1984). In contrast to the largely siliciclastic nature of the Wilson Terrane, the Bowers Terrane ranges from basal units of mafic volcanics, carbonates, greywakes and mudstones, followed by shallow marine limestone, mudstones and sandstone, which are capped by coarse grained conglomerate, quartzite and mudstones of continental character (LAIRD et al. 1982). In comparison to the relatively higher levels of strain identified along the western boundary of the Bowers Terrane (Black Spider Greenschist), a single generation of upright variably plunging, northwest-southeast trending folds characterises the interior of the terrane (Fig. 2b; GIBSON et al. 1984). To the east of the Bowers Terrane, the Robertson Bay Terrane comprises a monotonous package of turbidites and subordinate fossiliferous limestones (Fig. 2a-b; WRIGHT et al. 1984). Similar to the Bowers Terrane, the deformation style of the Robertson Bay Terrane is relatively homogeneous and comprises a single generation of upright folds (KLEINSCHMIDT & SKINNER 1981).

Originally acknowledged to represent the main tectonic contact between the Bowers and Robertson Bay Terranes, the northwest-southeast trending Leap Year Fault Zone records a complex tectonic history (BRADSHAW et al. 1985). Evidence of contractional, extensional and strike-slip transport along the fault zone supports this complex dynamic evolution (WRIGHT 1982, JORDAN et al. 1984). The Millen Schists are exposed east of this fault zone and provide evidence of a more complex kinematic deformation history compared to the interiors of the Bowers and Robertson Bay Terranes (TESSENSOHN 1984, CAPPONI et al. 2003). FINDLAY (1986) regarded the Millen Schists as the basal mylonitic reverse shear zone marking the contact between the overlying Robertson Bay

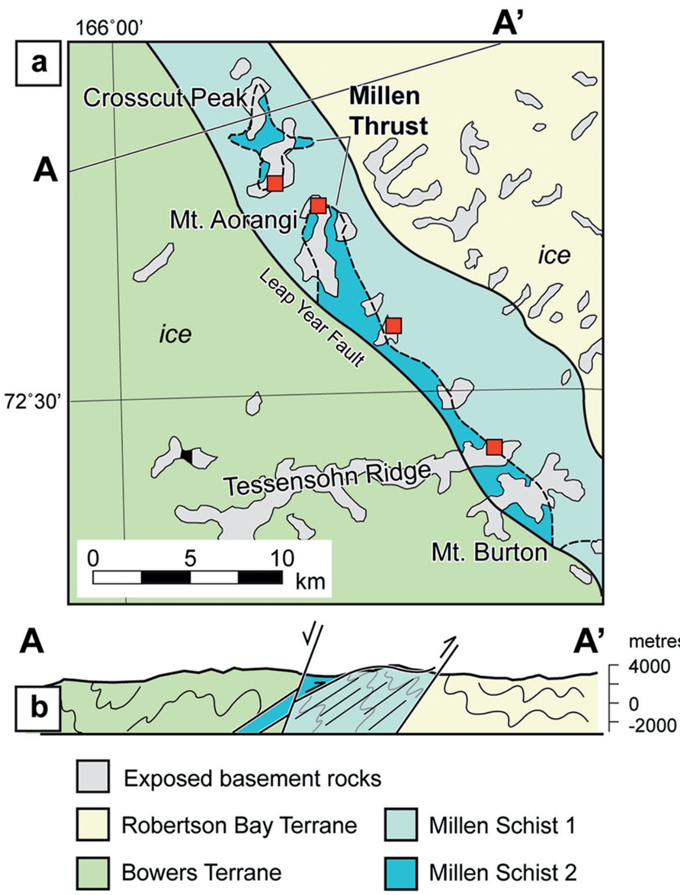


Fig. 2: (a) = Geological map of the Millen Range. Visited localities (red filled squares) and locations of the Millen Thrust (dashed line) are shown. (b) = Schematic cross section through the Bowers and Robertson Bay Terranes (Revised from MECCHERI et al. 2004). Note the location of cross section A-A' is shown on the geological map.

Abb. 2: (a) = Geologische Karte der Millen Range mit den besuchten Lokationen (rote Quadrate) und der Lage der Millen-Überschiebung (gestrichelte Linie). (b) = Schematisches Profil durch das Bowers- und Robertson-Bay-Terrane (verändert nach MECCHERI et al. 2004). Die Lage des Profils A-A' ist in der geologischen Karte (a) markiert.

Terrane metasedimentary sequences and the underlying metasedimentary and metavolcanic rocks of the Bowers Terrane. This led BRADSHAW (1987) to use the term Millen Shear Zone to describe the Bowers-Robertson Bay terrane boundary because rocks of both terranes are tectonically mixed within a broad zone rather than a single linear fault and that the actual terrane boundary is therefore located within the whole shear belt (cf. ROLAND et al. 2004).

Based on previous work carried out in the Millen Range, two main rock units have been suggested to make up the Millen Schists (CAPPONI et al. 2003). Of these two units, there is a lower package that comprises metaphyllites, metagreywakes and metalimestones (shown as Millen Schist 1 in Figure 2a-b) and an upper package of volcanoclastic sandstones (shown as Millen Schist 2 in Figure 2a-b). Whereas the contact between these two units, termed the Millen Thrust (CAPPONI et al. 2003; Fig. 2a) or Crosscut-Aorangi Thrust (CRISPINI et al. 2014), consistently records a reverse sense of transport, the direction of transport remains disputed (either NE over SW (FINDLAY 1986) or NW over SE (BRADSHAW 1985, WRIGHT, 1985).

The Millen Schists record two well-developed foliations (S1 and S2; CAPPONI et al. 2003). S1 is parallel to bedding and forms in an axial planar orientation to rare isoclinal folds (CAPPONI et al. 2003). S2 is a steeply dipping, northwest-southeast striking crenulation cleavage that is oriented parallel to the axial plane of asymmetric northwest-southeast trending F2 open folds (CAPPONI et al., 2003). The timing relations proposed by these authors are that transport along the Millen Thrust was coeval with the formation of the S1 fabric. Sparse K-Ar and Ar/Ar data from these rocks constrain the timing of deformation along the Millen Thrust to the late Cambrian (c. 505–500 Ma; WRIGHT & DALLMEYER 1991).

FIELD OBSERVATIONS FROM THE MILLEN RANGE

Four locations in the Millen Range were visited during GANOVEX X. These locations were selected to assess the nature of deformation along the Millen Thrust System and to identify rock types in the direct hanging wall and footwall of the contact. From SE to NW, the visited localities were (Fig. 2): (i) the eastern most point of Tessensohn Ridge (73°32'16.6'' S / 166°39'42.3'' E); (ii) an unnamed ridge (72°23'22.5''S / 166° 22'16.9'' E); (iii) the northern ridge of Mount Aorangi (72°23' 24.1'' S / 166°22'29.1'' E) and (iv) the southern ridge of Crosscut Peak (72°21'51.7''S / 166°18'54.1'' S). Owing to clear similarities in the structural histories identified at locations (i), (ii) and (iv), these kinematic data are compiled in Figure 4. The exposure of the Millen Thrust System at location (iii) results in a more complex structural history and, as a result, data are presented separately (Fig. 5).

At the easternmost point of Tessensohn Ridge, a fine transposed fabric comprising bedding (S0) and an S1 foliation is crenulated around a northwest-southeast striking, sub-vertically dipping crenulation cleavage (S2; Fig. 3a, 4b). The transposed nature of the S0 and S1 fabrics is supported by petrography, where an alignment of fine-grain white mica is observed parallel to bedding. Quartz fibres on S0/S1 surfaces have an average plunge of 40-60° towards ~240° and record evidence of flexural slip along bedding surfaces. The dominant S2 cleavage is also warped around rare F3 axes that strike northwest-southeast and dip sub-vertically, which could be interpreted to be related to strike-slip displacements in the Millen Schists.

At the unnamed ridge, deformed siltstones record evidence of open to closed metre- to cm-scale folds (Fig. 3b). Bedding is again paralleled by a fine-grained slatey S1 cleavage, which together are folded into a number of upright, asymmetric F2 folds that plunge 5-20° toward the southeast and verge to the northeast (Figs. 3b, 4a, 4c). The S0/S1 fabric dominantly strikes northwest-southeast and dips variably (10-70°) to the northeast and southwest (Fig. 4a). At this locality, we also observed minor evidence that the Millen Schists were affected by two phases of late- and/or post-Ross lateral shearing indicated by two sets of quartz veins: (i) an older phase with NW-SE trending dextral off-sets of thin NNE-SSW striking veins, and (ii) a younger NW-SE trending sinistral reactivation with thick veins oriented in an en-echelon-type geometry that suggests left-lateral shear along a NNW-SSE striking principle deformation zone.

At the northern ridge of Mount Aorangi, the Millen Thrust is clearly exposed (Fig. 5a; WRIGHT & FINDLAY 1984). A detailed inspection of the rocks distal and proximal to the contact was undertaken to assess the nature of deformation along the fault zone. Distal to the contact, rocks are partly recrystallised

Fig. 3: Field photographs of the Millen Schists distal to the Millen Thrust. (a) = S2 crenulation cleavage identified at the eastern part of Tessensohn Ridge. (b) = Open folded S0/S1 and associated upright S2 identified at an unnamed ridge in the Millen Range.

Abb. 3: Geländefotos der Millen Schists in einiger Entfernung zur Millen-Überschiebung. (a) = S2 Krenulationsschieferung im Ostteil von Tessensohn Ridge. (b) = Offen verfaltetes S0/S1 und damit assoziierte aufrechte S2-Schieferung auf einem namenlosen Rücken in der Millen Range.

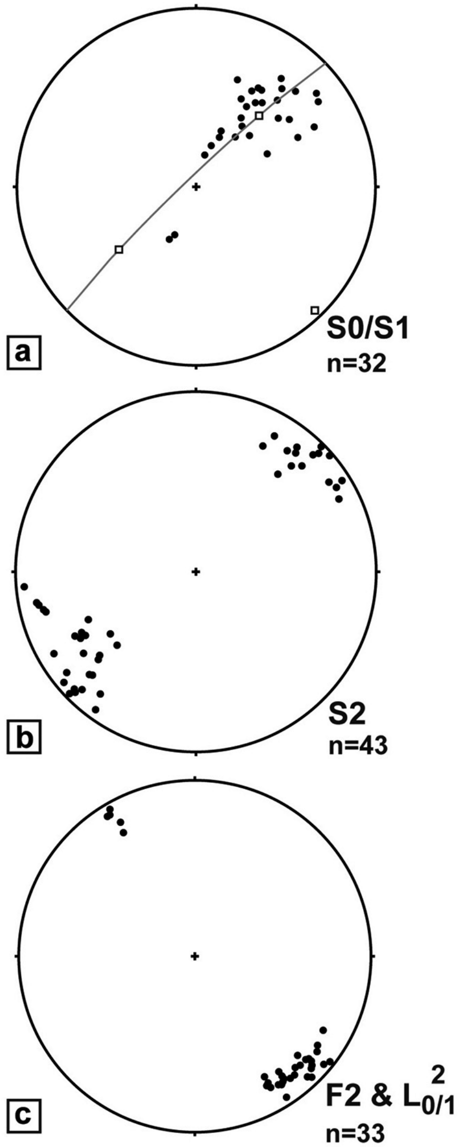


Fig. 4: Kinematic data collected from field locations away from the Millen Thrust zone (i.e., eastern Tessensohn Ridge, unnamed ridge and Crosscut Peak. (a) = S0/S1 data (as poles) and calculated best-fit girdle showing the profile plane of F2 folds. (b) = Orientations of S2 (as poles). (c) = Orientations of F2 folds and L0/12 intersection lineations.

Abb. 4: Kinematische Geländedaten von Lokationen in einiger Entfernung von der Millen-Überschiebung (östlicher Tessensohn Ridge, einem namenlosen Rücken und Crosscut Peak). (a) = S0/S1 Daten (als Polpunkte) und daraus gerechneter Großkreis der F2-Faltenprofilebene. (b) = Orientierungen der S2-Flächen (als Polpunkte). (c) = Orientierungen von F2-Falten und L0/12-Schnittlinearen.

poorly sorted matrix supported sandstones that are dominated by angular clasts of quartz and minor plagioclase. Regions of higher D2 strain contain dynamically recrystallised metasiltstones comprising a strong S2 foliation. This foliation is axial planar to cm-scale F2 folds that are defined by a composite S0/S1 fabric (Fig. 6a). F2 folds plunge 5-20° to the northwest (Fig. 5c; 6a). Evenly spaced (~30 cm) bedding parallel shear zones are also ubiquitous and show a reverse sense of transport on southeast-northwest striking, steeply dipping (60-75 °C to southwest and northeast) planes (Figs. 5b-c, 6b). These zones could represent syn-D2 flexural slip along bedding surfaces, or, a later D3 structural event. Closer to the Millen Thrust contact, the S2 fabric is shortened into cm- to m-scale open F3 folds that wrap around axial planes striking 140-160 °C and dipping 60-80° to the east (Fig. 5d). Due to the identification of these F3 folds, we suggest that the bedding parallel shearing described above was the response of a D3 event (as shown in Fig. 5b).

The Millen Thrust is folded and dominantly parallels the S0/S1 fabric (Fig. 6c). In the hanging wall of the contact, green schists are exposed atop of poorly sorted siliciclastic rocks in the footwall. Local offsets of the Millen Thrust along the sub-vertical S2 fabric are also common. In the direct fault zone, S-C fabrics show a reverse sense of movement (Fig. 6d). Below the fault zone, F3 folds are tight to isoclinal, plunge moderately (~30°) to the southeast (~160°) are folded around axial planes that parallel the thrust. Even though the Millen Thrust is folded by F2 structures, S-C fabrics consistently record a reverse sense of transport (Fig. 5e). As a result, reverse transport along the contact must have taken place after F2 folding; otherwise opposite shear sense indicators would be recorded on the opposing limbs of the folded thrust. Rocks in the hanging wall show a simple kinematic history with upright F2 folds defined by S0/1 and the development of an upright S2 foliation (Fig. 6e). S2 in these rocks strikes to the southeast-northwest and dips steeply (~80°) to the northeast, whereas the F2 folds shallowly plunge (~20°) toward the southeast (140-150°).

At Crosscut Peak, a dominant slatey cleavage strikes northwest-southeast and dips steeply (> 65°) to sub-vertically. Rare examples of folded bedding, sub-parallel quartz veins and a parallel micaceous cleavage (S1; identified microscopically) indicates that this main foliation is S2. Bedding and S1 strike to the northwest-southeast and have a moderate to shallow dip (25-55°) toward the southwest (Fig. 4a). F2 folds and intersection lineations plunge between 3 to 20° to the southeast (Fig. 4c). A second orientation of slatey cleavage showing a varying intensity across the outcrop forms at an acute angle to the S2 fabric (~330/55 W). Microscopic analysis does not reveal clear overprinting relationships between the two fabrics, which instead, show an anastomosing relationship. As a result, the two fabrics probably formed during the same event, and reflect subtle change in stress field orientation. At higher structural levels, the Millen Thrust is again exposed along the northern face of Crosscut Peak (Fig. 7). Viewed during helicopter reconnaissance, a contact between a lower package of open folded rocks and an upper package of apparently massive rocks was identified (Fig. 7). Interestingly, the fault at this location cuts across bedding on the western limb, yet is parallel to bedding on the eastern limb of the fold.

DISCUSSION

The provenance and kinematic evolution of the Millen Schists has direct implications for geodynamic models of the Ross Orogeny. With respect to the competing geodynamic models of the Ross Orogeny, the Millen Schists should represent one of either: (i) an exotic terrane that was accreted to the Bowers Terrane (Tessensohn & Henjes-Kunst 2005) or (ii) an internal transport surface between the Bowers and Robertson Bay Terranes (Capponi et al. 2003). The provenance of the Millen Schists provides a test for these models, as the exotic model requires a contrasting provenance to the neighbouring

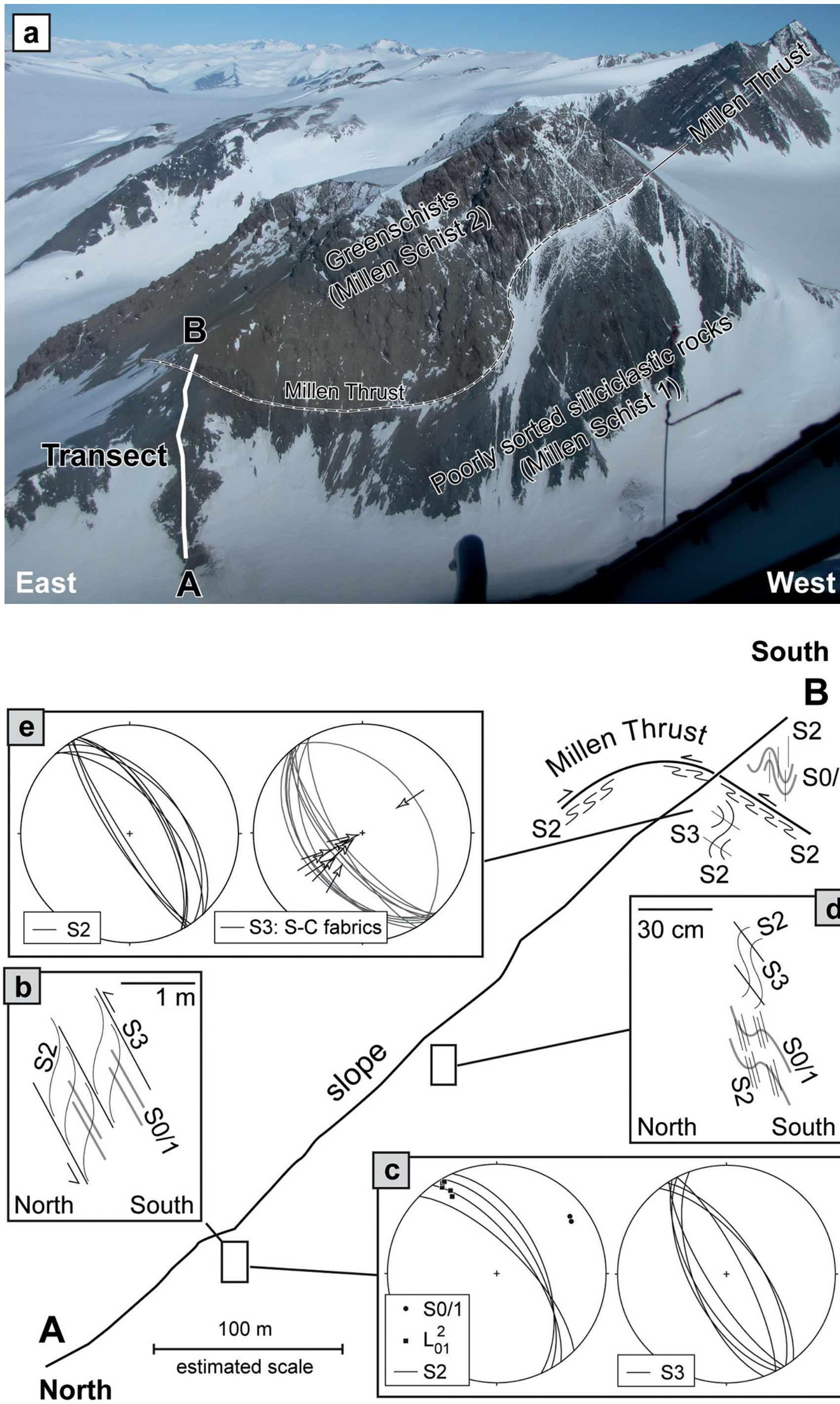
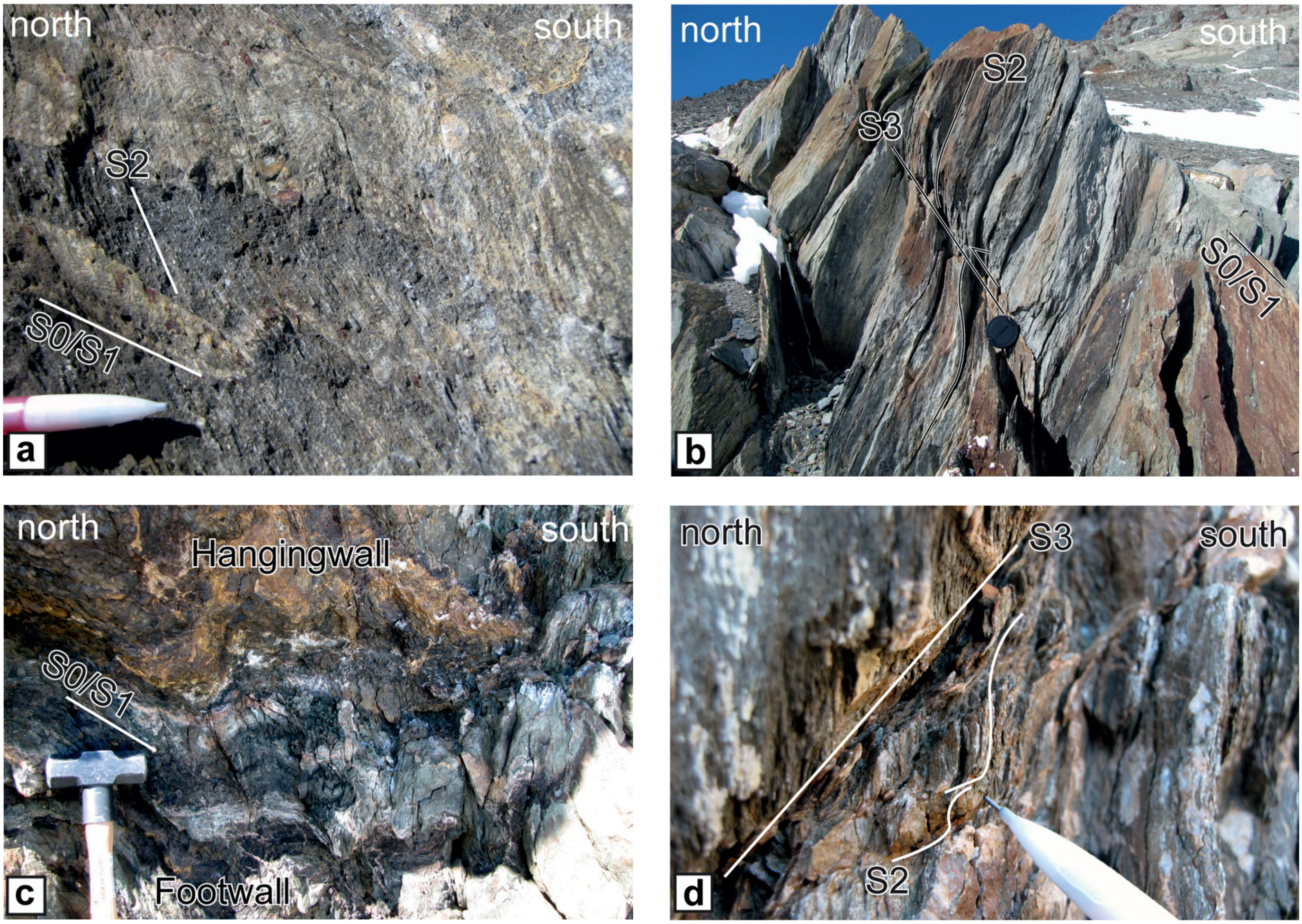


Fig. 5: Summary of key observations and data collected in close proximity to the Millen Thrust at Mt Aorangi. (a) = Photograph is taken looking south from a helicopter and shows the architecture of the geological units, the location of the Millen Thrust and the location of the field traverse A-B. A cross-sectional view of this transect (looking east) is below (A-B) with key overprinting observations and structural data shown. (b) = Schematic diagram of S0 to S3 overprinting relationships. (c) = Kinematic data from S0/S1, S2, L0/12 and S3 shear planes. (d) = Complex overprinting relationships in closer proximity to the fault surface. (e) = Orientations of S2 and S3 S-C fabrics in the direct hanging wall of the fault zone.

Abb. 5: Zusammenfassung der Schlüsselbeobachtungen und Daten in unmittelbarer Nähe zur Millen-Überschiebung am Mt. Aorangi. (a) = Foto aus dem Hubschrauber mit dem Aufbau der geologischen Einheiten, der Lage der Millen-Überschiebung und der Lage der Geländetraverse A-B. (b) = Schematisches Diagramm mit Überschneidungskriterien von S0 bis S3. (c) = Kinematische Daten von S0/S1, S2, L0/12 und S3-Scherflächen. (d) = Komplexe Überschneidungskriterien in größerer Nähe zur Störungsfläche. (e) Orientierungen von S2 (links) und S3-formende SC-Gefüge (rechts) im Hangendblock unmittelbar über der Störungsfläche.

terranes, whereas the internal model requires lithological similarities. Based on field observation and microscopy, the rock units located in the hanging wall and footwall of the Millen Thrust comprise volcanoclastic sandstones and poorly sorted siliciclastic sandstones, respectively. Similarities with rock units of the largely volcanoclastic Sledgers Group of the Bowers Terrane and the siliciclasitc rocks of the Robertson Bay Group supports a local provenance for the rocks of the Millen Schists (Jordan et al. 1984, Capponi et al. 2003). The Millen Thrust therefore represents a transport surface between the rocks of the Bowers and Robertson Bay Terranes. As a result, clues into the juxtaposition of these terranes can be inferred from the kinematic record of the Millen Schists.

The kinematic evolution of the Millen Schists involved three main stages of deformation. The first was largely identified petrographically, and involved the formation of a bedding parallel foliation that developed in an axial planar orientation to small isoclinal folds of bedding. Away from the Millen Thrust, the S0/S1 foliation is folded into upright asymmetric folds (F2) that plunge at low angles (5-20°) to the southeast and northwest (Fig. 5a-c). A sub-vertical S2 cleavage, which is the dominant foliation identified at most outcrops, is aligned along the axial plane of these folds. Whereas fold structures of similar orientation are also reported from the Bowers and Robertson Bay Terranes, these structures are associated with a single deformation event (D1; Meccheri et al. 2004). Asym-



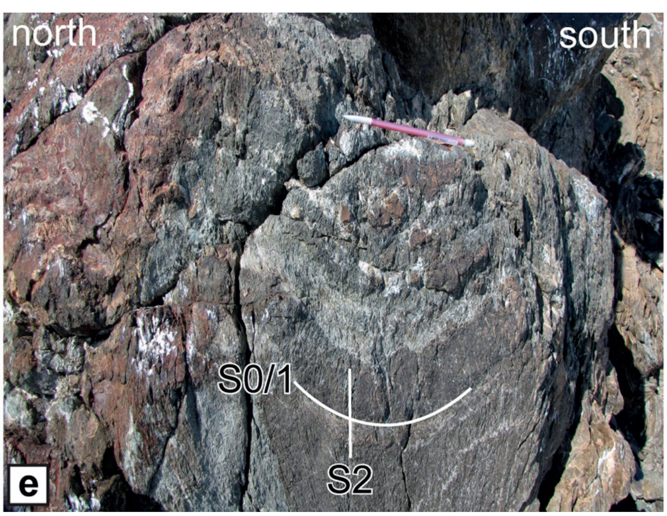


Fig. 6: Field photographs of the Millen Schists in close proximity to the Millen Thrust. (a) = Folded S0/S1 and the dominant S2 foliation. (b) = Reverse offset of S2 along high-angle, bedding parallel S3 shear planes. (c) = The folded thrust zone parallel to bedding. (d) = S-C fabrics (D3) showing a reverse sense of transport on the fault zone. (e) = Upright folds in the hanging wall of the thrust zone.

Abb. 6: Geländefotos der Millen Schists in unmittelbarer Nähe zur Millen-Überschiebung. (a) = Verfaltetes S0/S1 und dominierende S2 Foliation. (b) = Aufschiebende Versätze von S2 entlang steiler, schichtungsparalleler S3-Scherflächen. (c) = Verfaltete Störungszone, parallel zur Schichtung. (d) = SC-Gefüge (D3) mit aufschiebender Bewegung der Überschiebungszone. (e) = Aufrechte Falten im Hangendblock der Überschiebungszone.

Fig. 7: Photograph of the Millen Thrust exposed at Crosscut Peak. Photograph was taken from helicopter.

Abb. 7: Blick nach Süden aus dem Hubschrauber auf die Millen-Überschiebung am Crosscut Peak.

metric F2 folds in the lower units of the Millen Schists (i.e., Millen Schist 1) consistently verge to the northwest and indicate that the primary direction of tectonic transport along the Millen Thrust was probably also in this direction (CAPPONI et al. 2003). This is in contrast to the neighbouring Bowers and Robertson Bay Terranes, which record neutral vergence. It can therefore be reasonably suggested that the Millen Schists record the transportation of the Bowers Terrane over the Robertson Bay Terrane. However, owing to the dominant upright orientation of the S2 cleavage, the majority of this transport was probably facilitated by a low angle detachment located below the Millen Schists (i.e., as in KLEINSCHMIDT 1992 for the Robertson Bay Terrane).

Toward the Millen Thrust, the intensity of D3 strain increases. Distal to the contact, D3 strain is recorded by the localised formation of open F3 warps and evenly spaced reverse shear planes. At the contact, a <1 m wide zone contains cm-scale S-C fabrics that consistently record a reverse shear sense indicators. The contact consistently strikes northwest-southeast, yet owing to the presence of metre-scale F2 folds, dips to the northeast and southwest. The change in dip, yet consistent reverse sense of transport along the contact may be responsible for previous conjecture surrounding the direction of transport along the fault zone (BRADSHAW 1985, WRIGHT 1985, FINDLAY 1986). As S-C fabrics on both northeast and southwest dipping limbs of the contact record a reverse sense of transport, folding of the contact must have taken place prior to the D3 thrusting; otherwise, reverse and normal transport direction would be recorded by fold limbs dipping in opposing directions. Based on this relationship, F2 folding of the contact between the Bowers and Robertson Bay Terrane must have taken place prior to the localisation of higher strain (D3) along the Millen Thrust. Whereas absolute constraints are not available to confirm the timing of D2 and D3 deformations, a clear similarity in the stress field responsible for their development (cf. Figs 4a-b, 5e) supports their synchronicity. We therefore view the deformation process in the high strain components of the Millen Schists as a localisation of high strain (responsible for D3 structures) along pre-existing weaknesses in a progressively folded tectonic pile.

JORDAN et al. (1984) published an account of the structural geology of the Millen Schists exposed in the Bowers Mountains (see Fig. 1). These authors recognised the following structures: (i) a dominant S1 cleavage that strikes northwest to north and dips steeply to the east; (ii) associated F1 isoclinal folds that plunge steeply to near horizontally in the plane of S1; (iii) an S2 crenulation cleavage that strikes northwest to north and dips steeply to the east and west; (iv) F2 crenulations plunge shallowly to the southeast, and to a lesser extent, northwest and (v) an east- and west-dipping spaced S3 cleavage that forms axial planar to dextral kink folds. Similarities and disparities exist between the kinematic frameworks of the Bowers Mountains and Millen Range. Firstly, S1 forms axial planar to F1 isoclinal folds and forms the dominant foliation in the Bowers Mountains; S1 in the Millen Range is in contrast sub-parallel to bedding and crenulated/folded around the dominant S2 fabric. Secondly, the orientations of the S1 and S2 (Bowers Mountains) and S2 (Millen Range) foliations consistently strike northwest-southeast and dip steeply to the east or west. Thirdly, the localised formation of F3 warps and kinks that may indicate normal movement along the main fault zones is reported from both of the locations. Therefore, apart from variable levels of D1 and D2 strain, which can explain the different intensities of the D1 and D2 structures at either location, the kinematic framework of both regions is remarkably consistent. Of further significance, potential evidence of normal movement along the Leap Year Fault (CAPPONI et al. 2003, CRISPINI et al. 2014) and likely also according to the interpretation of our own data set of the Millen Thrust System signifies a more complex structural history than a simple thrust surface. We therefore prefer the term Millen Shear Belt for the whole zone taking into account a polydeformational history not only linked to reverse movements along the Millen Thrust System alone.

Available stratigraphic and isotopic data from northern Victoria Land (summarised in TESSENSOHN & HENJES-KUNST 2005) provides constraints on the timing of deformation of the Millen Schists. If the units of the Millen Schists represent components of the Bowers and Robertson Bay Terranes, a constraint on the timing of deformation is the age of sediment deposition in these terranes. Isotopic data collected from detrital zircon (only Robertson Bay Terrane; FIORETTI et al. 2003) and mica (both Bowers (Molar Formation) and Robertson Bay Terranes; HENJES-KUNST 2003) limits the timing of sediment deposition in these terranes to after c. 490 Ma (excluding single analysis populations). Based on these constraints, the timing of deformation must be after 490 Ma. Interestingly, this time period marks the cessation of convergent deformation in the neighbouring Delamerian Orogeny of southeastern Australia (FODEN et al. 2006), and is younger than the main phase of deformation in the Pensacola Mountains (ROWELL et al. 2001). Whereas the reasons for these along strike variations (with respect to the greater Terra Australis Orogen) in deformation age remain beyond the scope of the present paper, our work supports an Early Ordovician (or even younger) deformation age for the rocks of the Millen Schists. The c. 505-500 Ma age obtained from Ar-Ar analyses by WRIGHT & DALLMEYER (1991) are too old in this regard. On the other hand, CRISPINI et al. (2014) and DI VICENZO et al. (2014) report a much younger age of c. 460 Ma for the oldest deformation along the Millen Thrust System based on recent Ar-Ar analyses of metamorphic white mica.

A second implication of our work is that the Bowers and Robertson Bay Terranes may have formed as a single tectonic entity throughout the Middle to Late Cambrian, rather than far removed arc and continental terranes (KLEINSCHMIDT et al. 1987). Whereas this interpretation is favoured by several workers (ROLAND et al. 2004, CRISPINI et al. 2014), the provenance of the two terranes does raise significant questions. The Bowers Terrane comprises a volcanic basement associated with volcanoclastic rocks that are overlaid by terrestrial quartzites. The volcanic components of this pile are suggested to represent a rifted intra-oceanic arc (WEAVER et al. 1984). The rocks of the Robertson Bay Terrane are derived from a proximal mature continental source (HENJES-KUNST et al. 2004) with limited evidence of volcanic detritus. The character of the Robertson Bay Terrane is therefore surprising given its outboard position and its inferred isolation from the only known continental source (i.e., the Wilson Terrane) by the Bowers Terrane. Whereas the far-travelled migration of sediments parallel to the trench could explain the enigmatic character of the Robertson Bay Group, the highly angular nature and poorly sorted character of the rocks does not support a distal sedimentary source. Alternatively strike-slip displacement provides a mechanism to explain the current positioning of the two terranes (Weaver et al. 1984); as a matter of fact, evidence for strike-slip to oblique-slip transport was reported for both boundary faults of the Millen Shear Belt (Wright 1982, Jordan et al. 1984, Crispini et al. 2014) and minor evidence of lateral displacements in the Millen Schists was also found in our target area. This led Crispini et al (2014) to interpret the structural setting of the Millen Range as the result of left-lateral pop-up tectonics.

The current work supports the significance of the Millen Schists as a key unit recording evidence of assembly processes in a convergent margin orogen. In addition to the Leap Year Fault, the Lanterman Fault Zone that is located in a more inboard position (Fig. 1), accommodates northeast-directed thrusting along a southwest-dipping fault zone. Given the comparatively low levels of finite strain recorded by the internal parts of the Bowers and Robertson Bay Terranes, it is reasonable to suggest that the Leap Year and Lanterman Fault Zones accommodated the majority of strain in the outboard part of the Ross Orogen in the northern Victoria Land sector (Gibson & Wright 1985). A contrasting geometry is observed in the inboard parts of the orogen, where opposite directed thrust systems are located in the Wilson Terrane (i.e., the Exiles and Wilson Thrusts; Flöttmann & Kleinschmidt 1991). Interestingly, classical fold and thrust belt models do predict this contrasting detachment architecture in outboard and inboard parts of orogenic belts. Analogue modelling (Davis et al. 1983) shows this, where basal shear results in the development of opposite directed thrust systems in the rear of the deforming wedge and consistently dipping detachment zones in the front of the wedge. The geometry of the major detachments in northern Victoria Land is therefore consistent with this architecture, which, in this case, would require southwest-directed dextral shear below northern Victoria Land. This deformation regime is consistent with southwest-directed subduction below northern Victoria Land throughout the late Cambrian to at least early Ordovician.

CONCLUSION

The Millen Schists record evidence of a polyphase deformation history that is more complex than the internal deformation patterns of the Bowers and Robertson Bay Terranes. The development of F1 isoclinal folds and S1 foliation resulted in the transposition of bedding and cleavage to form a composition S0/S1 fabric. Shortening of this fabric into upright, asymmetric folds was responsible for the development of the dominant northwest-southeast striking sub-vertical slatey S2 cleavage. F2 folds verge to the northeast, supporting the widely acknowledged conclusion that tectonic transport during the Ross Orogeny in northern Victoria Land was toward the northeast. The contact between the two main units of the Millen Schists record evidence of a more complex kinematic history, where folds attributed to normal movement along the contact are proximally located to S-C fabrics recording a reverse sense of movement. Owing to the consistent reverse sense recorded by S-C fabrics on both northeast and southwest dipping segment of the Millen Thrust, reverse transport must have taken place after folding of the contact. Based on the observations made at the contact, the Millen Thrust is suggested to represent a significant flexural slip surface, rather than a major tectonic boundary that facilitated the juxtaposition of two exotic terranes. This interpretation is further supported by lithological similarities between the rocks exposed in the hanging wall and footwall of the Millen Thrust System and the neighbouring Bowers and Robertson Bay Terranes. Available timing constraints limit the maximum timing of deformation in the Millen Schists to the early to middle Ordovician.

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