

The Mulgandinnah Shear Zone; an Archean crustal scale strike-slip zone, eastern Pilbara, Western Australia

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Abstract

A large part of the deformation in the Archean Pilbara granitoid–greenstone terrain is localized in relatively narrow shear zones. The Mulgandinnah shear zone (MSZ) is a major one of these, with a width up to 8 km, that can be followed for over 70 km along strike in the Shaw Batholith in the eastern Pilbara. It forms part of the Mulgandinnah Lineament, that can be traced to the Lalla Rookh Basin and the Carlindi Batholith in the north, giving it a total length of over 150 km. The MSZ contains both mylonites and ultramylonites, both of which have foliations that are subvertical to steeply dipping, with the ultramylonitic foliation overprinting the mylonitic foliation to form more localized zones of high strain. Stretching lineations are mostly subhorizontal to shallow south plunging for both the mylonites and ultramylonites, but can vary between 50°N and 50°S. Both foliations formed under upper-greenschist to amphibolite grade conditions. The MSZ displays a consistent sinistral sense of shear, as indicated by σ and δ -type porphyroclasts, S–C fabrics and rotated pegmatite veins. The mylonites and ultramylonites are interpreted to have developed as part of a progressive deformation event leading to strain localization in the ultramylonites.

Timing constraints indicate that the MSZ has been active at ca. 2930 Ma, but it is likely to have been a long lived structure that was reactivated at that stage, when it acted as a conjugate shear during a NW–SE crustal shortening in the eastern Pilbara. The final juxtaposition of the various domains in the Pilbara granitoid–greenstone terrain occurred during this deformation phase. © 1998 Elsevier Science B.V.

Keywords: Archean; Strike-slip; Granite

1. Introduction

Major shear zones are important structural features in crustal blocks of all ages. In orogenic belts a large part of the deformation is localized in such shear zones and they often form the boundary between different tectonostratigraphic terranes.²

In recent years, terrane analysis, including geochronological and structural studies, have been applied successfully to Archean cratons (Myers, 1995; de Ronde and de Wit, 1994; Jackson and Cruden, 1995). The recognition, and the structural/

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²The term terrane is used in the sense of tectonostratigraphic terrane (Jones et al., 1983), whereas the term terrain is used for a geographic area, i.e. Pilbara terrain. Domain is a general term for a geologic terrain that is thought, but not proven, to be a tectonostratigraphic terrane.

kinematic study, of major shear zones is an important step towards unraveling the often complex tectonic evolution of such areas. From a more fundamental point of view, the kinematics of major shear zones can have important implications for the rheological properties of the lithosphere. Sleep (1992) showed that major (>100 km) strike slip zones are a kinematic consequence of rigid lithospheric plates. In addition, major shear zones in Archean terrains also have an important economic significance because large lode gold deposits, late in the history of the belts, tend to be spatially associated with them (Bursnall, 1989; Eisenlohr et al., 1989; Groves et al., 1992).

The Pilbara granitoid–greenstone terrain has been subdivided into a number of tectonostratigraphic domains on the basis of lithostratigraphic studies (Krapez and Barley, 1987; Krapez, 1993). Krapez and Barley (1987) studied the sedimentary basins associated with some of the domain boundaries and concluded that these basins (the Lalla Rookh and Whim Creek Basins) formed as pull-apart basins in a strike-slip system. However, the shear zones that form the north- to northeast-trending domain boundaries have not been studied in detail. Here, we report a detailed structural/kinematic study of part of one of these boundary structures, the MSZ. It consists of a set of anastomosing ductile shear zones that occur along the western part of the Shaw Batholith and which truncate the Split Rock Shear Zone (SRSZ, Figs. 1 and 2). The SRSZ was a major extensional shear zone during deposition of the Warrawoona Group at ca. 3460 Ma (Zegers et al., 1996). The MSZ is part of the north-trending Mulgandinnah Lineament, which was previously called the Shaw Batholith Fault by Krapez (Krapez, 1989) and which consists of two major strands that extend from the Shaw and Yule Batholiths to the Lalla Rookh Basin in the north (Fig. 1). The MSZ forms the eastern strand of the Mulgandinnah Lineament.

This contribution covers the geometry, the kinematics, the conditions of deformation and the time constraints of the MSZ and will conclude with a discussion on the tectonic significance of the craton scale shear zones in the eastern Pilbara.

2. Regional setting

The Pilbara Craton consists of a granitoid–greenstone terrain with ovoid outcrops of granitoids surrounded by greenstone belts, unconformably overlain by the relatively undeformed late Archean Fortescue Group. Four major stratigraphic units are recognized in the greenstones (Fig. 1); the Coonterunah Succession, the Warrawoona Group, the Gorge Creek Group and the Whim Creek Group (Hickman, 1983; Horwitz, 1990; Buick et al., 1995). The Coonterunah Succession contains a bimodal suite of volcanic rocks of which a rhyolite was dated at 3515 ± 3 Ma (U–Pb, single zircon, Buick et al., 1995). The unconformably overlying, 3475–3435 Ma Warrawoona Group is mainly comprised of basalt with subordinate peridotitic komatiite, dacite and rhyolitic tuff and agglomerates and minor sedimentary rocks (Hickman, 1983; Thorpe et al., 1992; Barley, 1993). The Warrawoona Group is unconformably overlain by the 3325–3200 Ma Gorge Creek Group, consisting of sandstone, conglomerate, BIF and basalt (Thorpe et al., 1992; McNaughton et al., 1993; Krapez, 1993). In the western Pilbara, the Gorge Creek Group is unconformably overlain by the Whim Creek Group, dated between 3100 and 2900 Ma (Horwitz and Pidgeon, 1993). The sediments of the Lalla Rookh Basin (Fig. 1) are thought to be part of this group (Krapez and Barley, 1987).

The granitoids show the same age range as the greenstones. They typically consist of several plutons or granitoid sheets, intruded during different episodes. Age data on granitoids are largely restricted to the eastern Pilbara. The earliest recorded age is 3578 ± 4 Ma (U–Pb, single zircon, McNaughton et al. (1988)) from an anorthositic gabbro suite in the Shaw Batholith. A widespread first intrusive event of granodiorite/tonalite is dated between 3500 and 3400 Ma (Bickle et al., 1993; McNaughton et al., 1988, 1993; Thorpe et al., 1992; Williams and Collins, 1990; Buick et al., 1995). Sm–Nd isotopic systematics imply their derivation from a heterogeneous source, including crust and depleted mantle (Bickle et al., 1993). A second group of ages for tonalite/granodiorite intrusives cluster around 3300 Ma

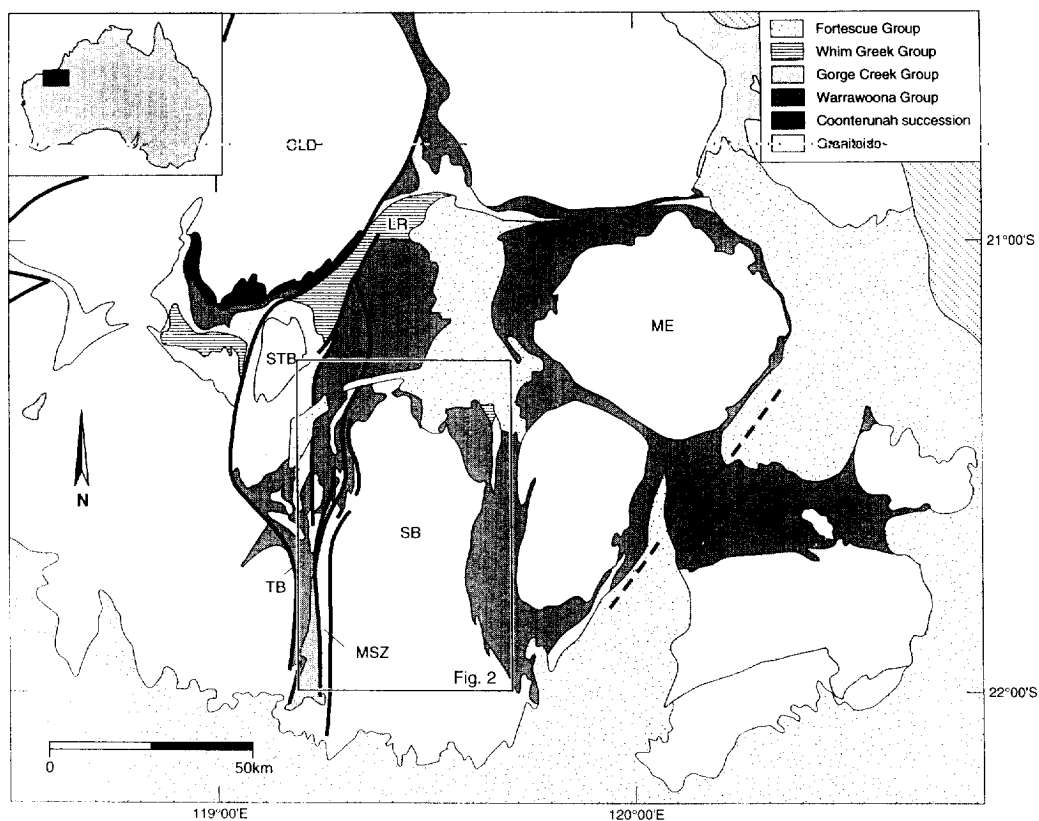


Fig. 1. Schematic representation of the eastern Pilbara granitoid–greenstone terrain, based on previously published geological maps (Krapez, 1993) and TM satellite images. MSZ = Mulgandinnah Shear Zone, SB = Shaw Batholith, ME = Mount Edgar Batholith, STB = Strelley Batholith, CLB = Carlindi Batholith, TB = Tambourah Greenstone Belt, LR = Lalla Rookh Basin.

(Pidgeon, 1978; Williams and Collins, 1990; Bickle et al., 1993) and can be modeled as remelt of a pre-existing tonalitic/dacitic crust (Collins, 1993). Intrusives of this group appear to be more restricted than the 3450 Ma group. Late- to post-tectonic adamellites, which are thought to represent remelts of the 3.5–3.3 Ma crust, have been dated between 3050 and 2840 Ma (Bickle et al., 1989).

Much of the metamorphic pattern in the Pilbara appears to be related to the granitoid intrusions, with the metamorphic grade increasing towards the granitoids. The metamorphism is characterized by low pressure/high temperature metamorphic mineral assemblages. One exception is the relatively high pressure (6.5 kb) assemblage in a pelitic enclave in the South Dalton Pluton (Bickle et al.,

1985). Generally, $^{40}\text{Ar}/^{39}\text{Ar}$ ages of metamorphic hornblendes reflect the intrusion age of the adjacent granitoid. An exception is a group of ages between 3.3 and 3.1 Ga, which may reflect a more regional metamorphic event (Wijbrans and McDougall, 1987; Davids et al., 1997; Zegers, 1996).

The structural evolution of the Pilbara granitoid–greenstone terrain was originally explained by the diapiric rise of a granitic basement into the overlying greenstones (Hickman, 1983, 1984). A similar emphasis on diapirism has been given to the evolution of the Mount Edgar Batholith by Collins (1989). In the Western Shaw area, Bickle et al. (1985) and Boulter et al. (1987) recognized a fold and thrust event that they constrained to between 3325 and 3200 Ma. The resultant struc-

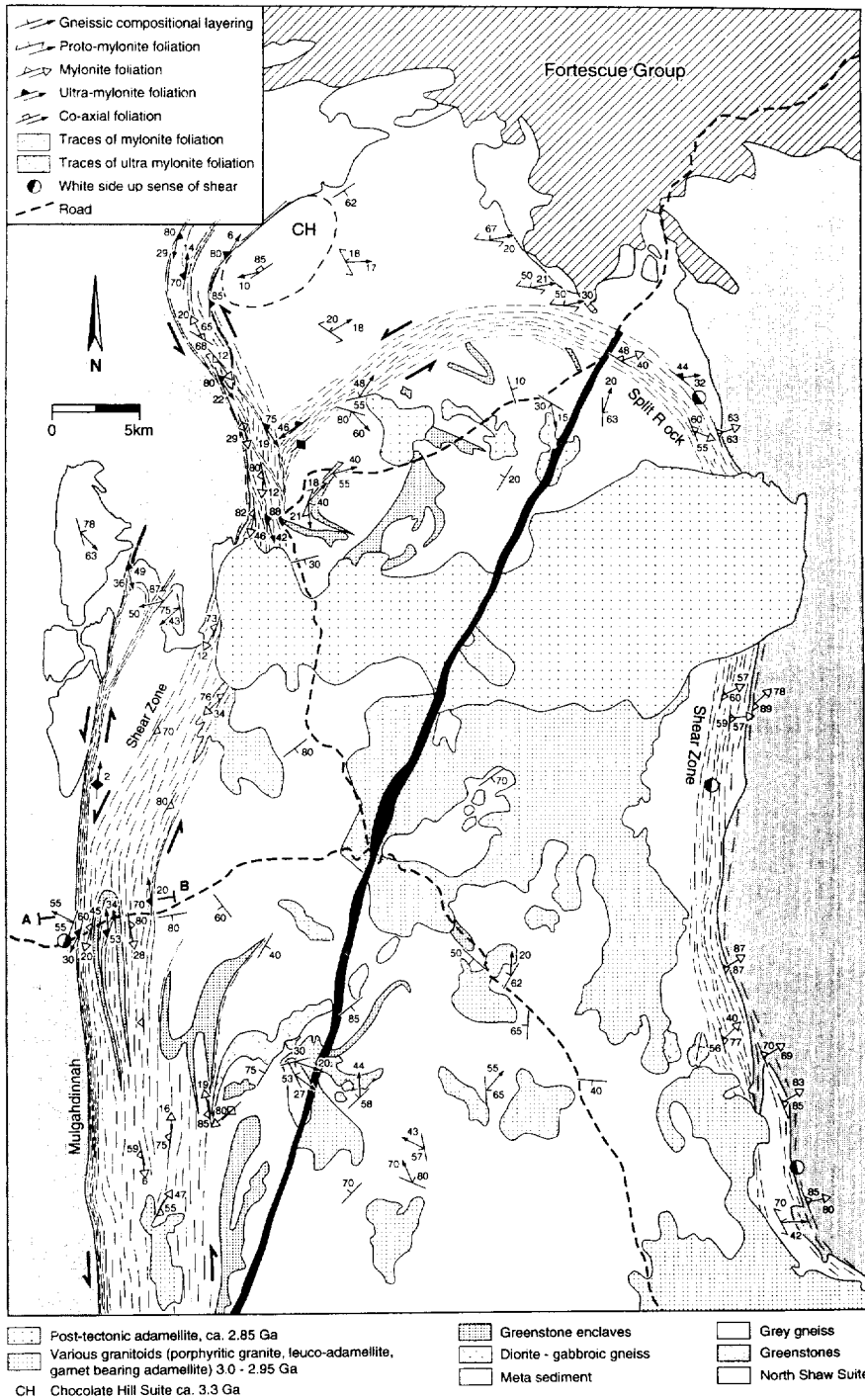


Fig. 2. Structural map of the Shaw Batholith, showing the Split Rock Shear Zone, the Mulgandinnah Shear Zone and the various granitic lithologies in the Batholith. A-B is the Tambourah traverse on which Fig. 4 is based.

tures were found to be overprinted by 'steep structures' that were thought to be related to diapirism (Bickle et al., 1985). Krapez and Barley (1987) describe N–NE trending strike-slip faults as being active during deposition of the ca. 2950 Ma Whim Creek Group in the Lalla Rookh Basin. Similarly, Boulter et al. (1987) mention metre-wide north-trending mylonite zones with subhorizontal lineations in the area west of the Shaw Batholith. Zegers et al. (1996) describe core complex type extensional structures in the Shaw area, that developed during deposition of the Warrawoona Group and the emplacement of the North Shaw Granitoid Suite. The most significant extensional structure is the SRSZ, which crops out within and adjacent to the eastern margin of the Shaw Batholith (Figs. 2 and 3) and was dated at ca. 3460 Ma. The SRSZ is cut in the west by the major north trending MSZ (Figs. 2 and 3), which is the subject of this paper.

3. Field observations

The MSZ forms the western margin of the Shaw batholith. It has reworked the granitoid rocks of the Shaw Batholith and part of the greenstones of the Tambourah Belt (TB in Fig. 1, part of the Western Shaw Belt, Griffin, 1990). Lithologies within the Shaw Batholith have extensively been described by Bettenay et al. (1981), and we will only briefly summarize them, concentrating on the precursor rocks of the MSZ (Fig. 2).

3.1. *Migmatic gneiss and enclaves*

The central part of the Shaw Batholith contains extensive areas of migmatic gneiss with enclaves of variable rock types. The paleosome of the migmatic gneiss is mainly a biotite-granodiorite and is light grey in colour. The foliation in the fine grained light grey gneisses is formed by variations in biotite content and layer parallel pegmatite–aplite veins. The biotite–granodiorite is interlayered with complex, medium grained clinopyroxene-bearing dioritic gneisses, with a strong compositional banding. Both the grey and the dioritic gneisses show a completely statically

recrystallized microstructure. The gneisses are complexly deformed and the gneissic layering frequently displays dm-scale folds with an associated axial planar cleavage (see Fig. 5 (a)). Neither the folds nor the cleavage have consistent orientations (see Fig. 2). Leucosomes are typically formed as axial planar structures, but occasionally melting has been so extensive that a nebulitic schlieren textured gneiss has developed.

Enclaves that occur in the migmatic gneisses include amphibolitic metabasalts, metasediments, mostly pelites and calcsilicates (Bickle et al., 1985), and coarse to very coarse-grained dioritic to gabbroic anorthosites, which are the oldest rocks in the Pilbara, having been dated at 3577 ± 4 Ma (U–Pb single zircon, McNaughton et al. (1988)).

3.2. *North shaw suite*

The North Shaw Suite granodiorite–tonalites have been extensively studied by Bickle et al. (1993) and they are separated from the migmatic gneisses of the central part of the Shaw Batholith by the SRSZ. That is, the North Shaw Suite is structurally above the gneisses. The North Shaw Suite has been dated at ~ 3460 Ma (Pidgeon, 1978; McNaughton et al., 1988; Bickle et al., 1989, 1993) and is inferred to be a syn-kinematic intrusion into the SRSZ (Zegers et al., 1996).

Structures in the SRSZ and at the contact with the adjacent Coongan Belt have been described in detail by Zegers et al. (1996). The SRSZ is a domal shaped zone (see Fig. 2) characterized by a mylonitic foliation with a stretching lineation consistently trending ENE. The sense of shear is E-up with subsidiary sinistral movement on the E–W trending part and a subsidiary dextral movement on the N–S trending part.

3.3. *Younger granitoids*

The gneisses and North Shaw Suite rocks are intruded by a number of younger, late-to post-tectonic granitoids. The oldest of these is the Garden Creek Adamellite which is dated at 3007 ± 48 Ma (Pb–Pb, Bickle et al. (1989)). It is a garnet-bearing muscovite–biotite adamellite that occurs in the southern part of the Shaw Batholith.

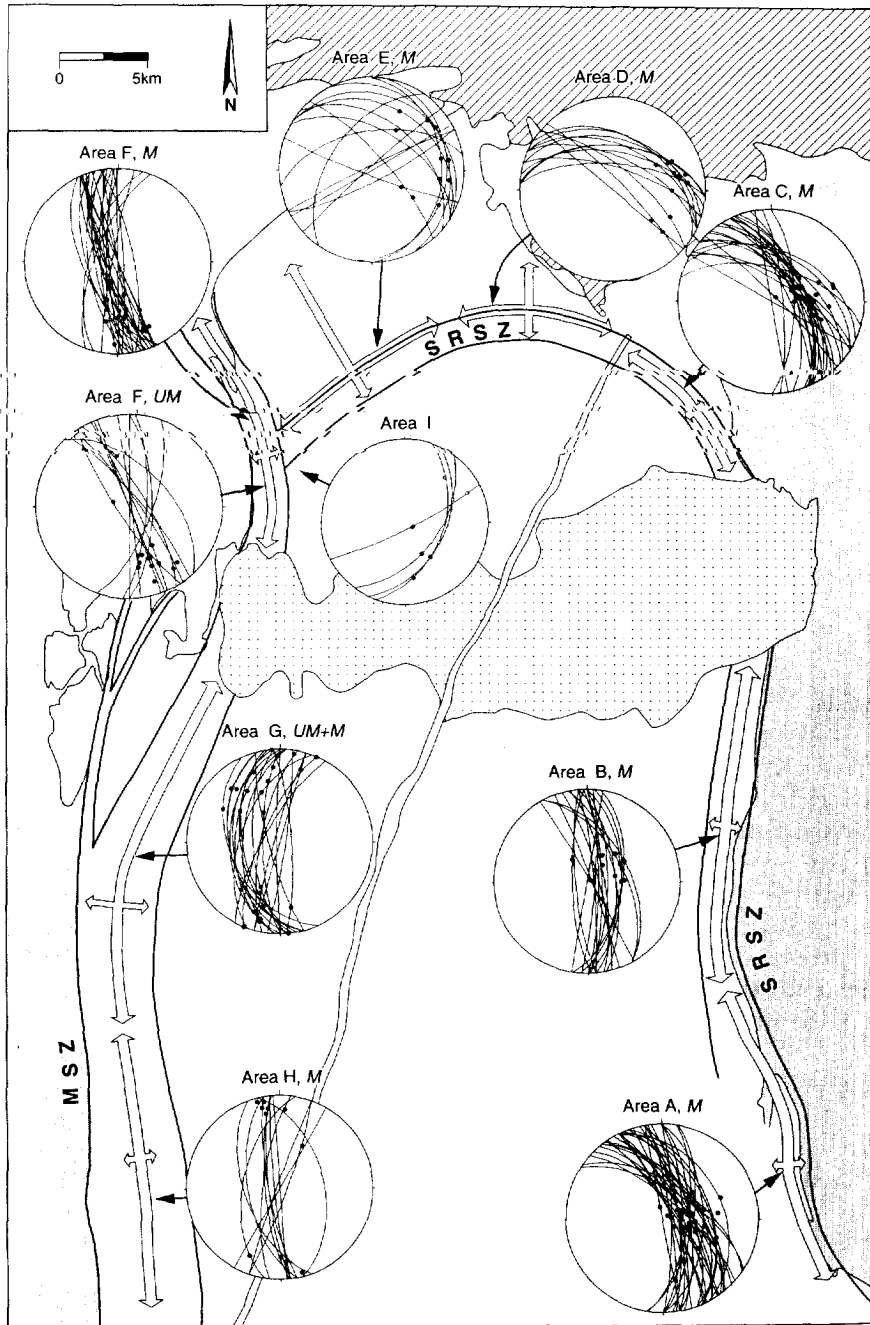


Fig. 3. Structural data from the SRSZ (areas A–E) and MSZ (areas F–H) in lower hemisphere equal area projections. Great circles represent mylonitic (M) or ultramylonitic (UM) foliation planes, dots represent mineral and stretching lineations. In the plot for area I, foliations with two stretching lineations are shown. The filled dots represent lineations belonging to the MSZ, the unfilled dots represent lineations belonging to the SRSZ.

A second group of granitoids, dated at ca. 2950 Ma (Pb–Pb, Bickle et al. (1989)), intruded large areas of the gneiss in the central Shaw Batholith. They consist of K-feldspar porphyritic adamellites and fine-grained leuco-adamellites. These two groups of granitoids are undeformed in the eastern Shaw Batholith but appear to be locally deformed in the western Shaw Batholith.

A late, post-tectonic muscovite–adamellite intrudes the Shaw Batholith at ca. 2850 Ma (Pb–Pb, Bickle et al. (1989)).

4. Mulgandinnah Shear Zone

The MSZ is a complex high strain zone along the western margin of the Shaw Batholith. It can be traced over a strike distance of at least 70 km and is up to 8 km wide in the southwest of the Shaw Batholith, but narrows to a width of ca. 2.5 km wide in the northern part of the Shaw Batholith.

Typical structures within and adjoining the MSZ are shown diagrammatically in Fig. 4. The overprinting relations are highlighted and are discussed further in the following section

4.1. Lithologies in the mulgandinnah shear zone

Rocks in the MSZ are so strongly deformed that it is usually not possible to convincingly identify the protolith granitoid or gneiss. In the less deformed parts towards the east, the transition to gneisses can be seen. Here, the variably folded gneisses become progressively more deformed as the MSZ is approached, with the development of a N–S to NE–SW trending foliation. In the MSZ, the gneissic layering is transposed to the mylonitic foliation of the MSZ ($S_{M,MSZ}$). This produces a heterogeneous mylonitic rock with varying proportions of mafic minerals, thought to reflect the initial variations in the precursor gneisses. Other parts of the MSZ consist of a more homogeneous augen gneiss, the protolith of which could well have been part of the North Shaw granodiorite suite. In the western part of the MSZ there are abundant enclaves of amphibolite and minor metasediments. These enclaves occur not only as

metre-scale lenses but also as layers that can be traced in a km-scale rootless fold (see Fig. 2). Several generations of pegmatites are present in the MSZ and they show a complex spatial distribution. These pegmatites make up to 30% of the total outcrop.

4.2. Mylonites

The mylonitic foliation in the MSZ (see Figs. 2–4) is subvertical to steeply west dipping over its total length. A mineral lineation on the mylonitic foliation ($L_{M,MSZ}$) is defined by quartz–feldspar rods and biotite streaks in the granitic rocks and by oriented dark hornblende crystals and plagioclase rods in the mafic layers. The orientations of the mineral stretching lineations are variable. In the northern area (F in Fig. 3), $L_{M,MSZ}$ are shallowly to moderately south plunging, whereas in the central area (G in Fig. 3) the plunge varies from 50° north to 50° south, and in the southern area (H in Fig. 3) they are subhorizontal.

Numerous σ and δ -type porphyroclasts of K-feldspar occur on surfaces normal to the foliation and parallel to the lineation, whereas other mineral phases, such as quartz and plagioclase, have recrystallized to a finer grain size. There are some especially good examples of δ -type porphyroclasts. The recrystallized tails of these clasts show a non stairstepping geometry [Fig. 5 (b)] in which the tails of the δ -clast and the centre of the clast lie in one plane (Passchier et al., 1993). The porphyroclasts consistently indicate a sinistral sense of shear.

Boudins of amphibolite layers are extended and pulled apart along planes at a high angle (60–70°) to the amphibolite layering (Fig. 5 (c)). The separate blocks in the boudins are subsequently rotated with a sinistral sense.

The mylonitic foliation, $S_{M,MSZ}$, is truncated by at least three sets of pegmatites, with one set (P1, Fig. 4) typically parallel to $S_{M,MSZ}$. A second set (P2, Fig. 4) is often boudinaged and displays a small angle to $S_{M,MSZ}$. A third set (P3, Fig. 4) is generally folded and occurs at a high angle to $S_{M,MSZ}$. Locally, the $S_{M,MSZ}$ shows a very consistent folding pattern next to the P2 pegmatites (Fig. 5 (d)). A single isoclinal fold hinge forms on the

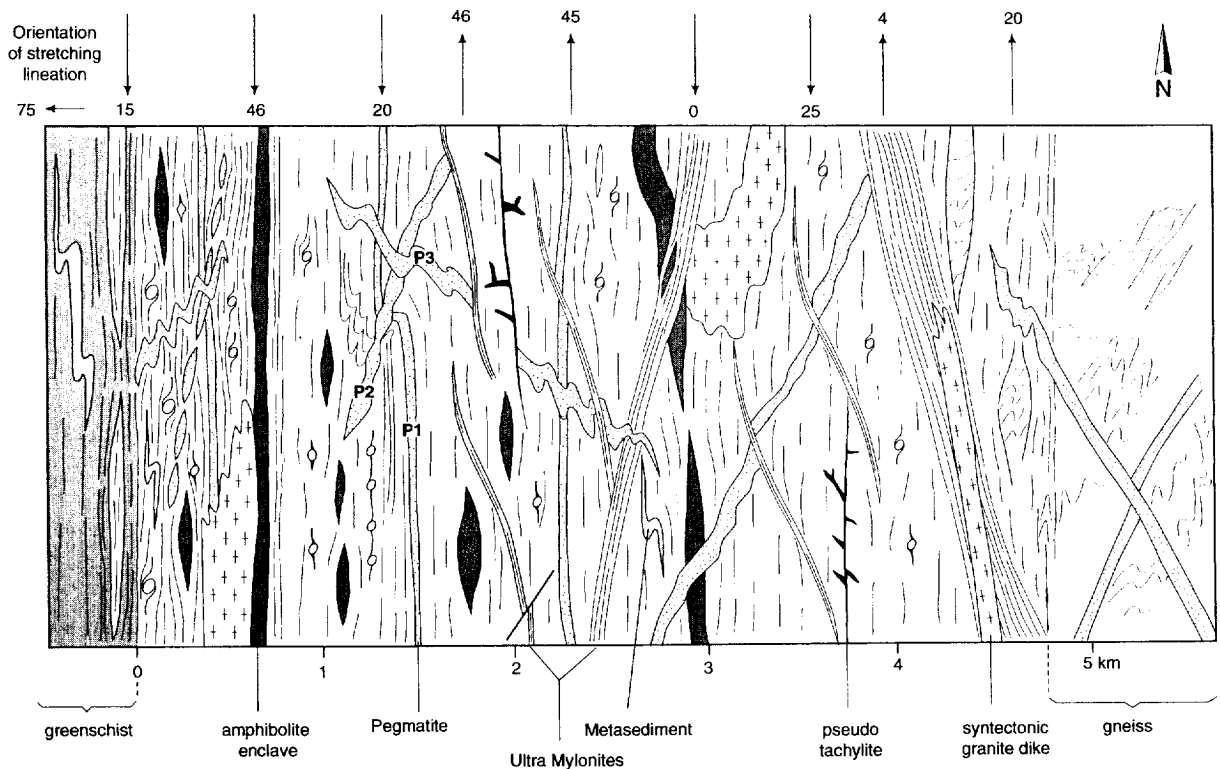


Fig. 4. Diagram showing the structures and their relationships as found in the MSZ on the horizontal plane, based on the Tambourah traverse (see Fig. 2). For the description of these structures see the text.

southeastern side of the pegmatite whereas multiple folds are seen on the northwestern side. The overall fold pattern has a sinistral vergence and is consistent with sinistral rotation and deformation of the pegmatites after their intrusion into the mylonite.

Pseudotachylites are present in a number of mylonite outcrops. They contain a dark glassy matrix with minor rock fragments floating in the matrix. The planar generating surface is parallel to $S_{M,MSZ}$ with injection veins extending into the host rock, often infilling tension fractures with an orientation consistent with sinistral movement in the MSZ.

4.3. Ultramylonites

Towards the western side of the MSZ, the deformation intensifies into an ultramylonite zone which is ca. 500 m wide. The foliation within this zone,

$S_{UM,MSZ}$, is defined by fine-grained biotite flakes and by extremely attenuated quartz and feldspar grains in a very fine grained matrix in which grains cannot be identified in hand specimens. The attenuated quartz and feldspar grains define a stretching lineation $L_{UM,MSZ}$. Microscopically, the matrix consists of equigranular, rounded quartz grains (20–30 μ m), with aligned biotite grains of similar dimensions. Mineral assemblages (quartz, plagioclase, biotite and hornblende) indicate amphibolite grade conditions during deformation. The stretching lineation has a variable plunge ranging from 50° north to 50° south. In the ultramylonites, the σ and δ porphyroclasts of K-feldspar are well rounded and are relatively small (2–4 mm) compared to the cm-dm size objects in the mylonitic zones. The asymmetry of the above porphyroclasts and of S–C fabrics consistently indicate a sinistral sense of shear (Fig. 5 (e)). Pegmatite veins in the ultramylonite zones are more intensely deformed

than in the mylonite zones. Folded veins have strongly boudinaged limbs and commonly the angles between the ultramylonite foliation and pegmatite veins are small.

In the main part of the mylonitic MSZ, ultramylonite zones, which are 20 cm to 5 m wide, form an anastomosing pattern that cuts across the mylonitic foliation. In the few cases where the termination of the thin ultramylonitic bands could be seen, it was found that they bend into the mylonitic foliation (Fig. 4).

Fine-grained biotite–granite dikes intruded into the ultramylonite zones parallel to $S_{UM,MSZ}$ and locally cut across the ultramylonite foliation at a small angle (Fig. 5 (f)). The granitic dikes themselves show a foliation and lineation similar to the ultramylonitic host. The granitic dikes are therefore inferred to have intruded when the ultramylonite zones were tectonically active.

4.4. Contact zone with greenstones

There is a sharp contact between the Shaw Batholith granitoids and the Tambourah Greenstone Belt. The greenstones contain chlorite schists and metasediments which have a steeply west dipping, partly mylonitic foliation and a downdip stretching lineation. Shear bands, which are weakly developed, indicate a west up sense of shear. There is a sharp increase in the metamorphic grade, from greenschist to amphibolite facies, over a distance of tens of metres towards the Shaw Batholith. The metabasalts and metasediments are isoclinally folded with steeply plunging fold axes. In a 40 m-wide zone, supracrustal rocks alternate with granitic dikes, both of which show an ultramylonitic foliation and shallowly south plunging stretching lineation. Sense of shear indicators (σ and δ clasts and S–C fabrics) in this zone of mixed supracrustals and granites all consistently indicate a sinistral sense of shear. The above mixed zone grades into the granitic ultramylonite zone of the MSZ.

4.5. Relationship between the Mulgandinnah and the Split Rock Shear Zone

Shear activity on the MSZ postdates the SRSZ. This can be seen from the foliation pattern in Fig. 2. The MSZ mylonitic and ultramylonitic foli-

ations can be traced north, past the intersection area between the SRSZ and the MSZ, implying that the MSZ truncates the SRSZ. Additional evidence was found in a greenstone enclave to the southeast of the MSZ/SRSZ intersection area. In a number of outcrops in this area, two stretching lineations were found on the foliation plane (see plot in Fig. 3). The northeast plunging mineral lineation formed by pale green amphiboles (grunerite) is overprinted by a south plunging stretching lineation of millimetres to centimetres scale elongate spots with randomly oriented fine-grained chlorite and mica. The first lineation is thought to be related to the SRSZ and the second to the MSZ.

4.6. Northward continuation of the MSZ

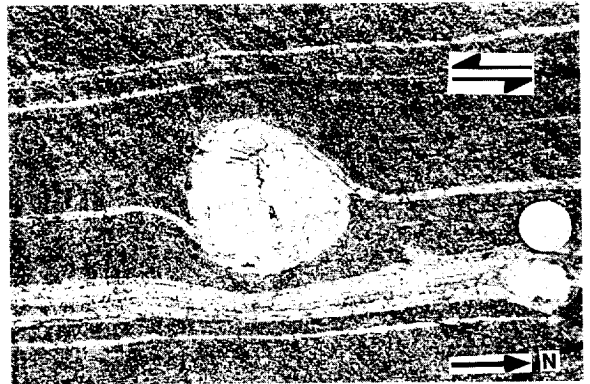
It is difficult to trace the continuation of the MSZ to the north. The foliation associated with the zone bends into a more north-westerly trend, thereby crossing the contact between the granite and greenstones. In the greenstones, the deformation is localized into shear zones which are tens of metres wide and which have shallowly plunging lineations, leaving relatively undeformed areas in between. However, the intensity of deformation and the total width of the shear zones do not appear to match the MSZ as found in the Shaw Batholith a few km to the south. No trace of a mylonitic foliation was found in the northwestern area of the Shaw Batholith, where Bickle et al. (1993) sampled a range of granitoids, called the Chocolate Hill Suite, giving a Pb–Pb age of 3338 ± 52 Ma. The hornblende rich granodiorite has a weak subvertical foliation (see Fig. 2), which follows the contact with the greenstone belt. A weakly developed gently plunging mineral lineation is locally developed. All structures found in this area are symmetric, indicating that deformation in this granitoid was non-rotational. This observation, plus the local presence of an almost E–W trending foliation in the granitoid, make it unlikely that this fabric is of the same age and tectonic significance as the MSZ.

5. Discussion

The MSZ forms a high strain shear zone that can be traced over a distance of at least 70 km



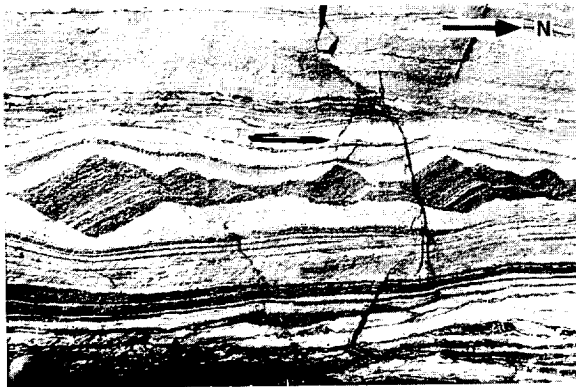
(a)



(b)



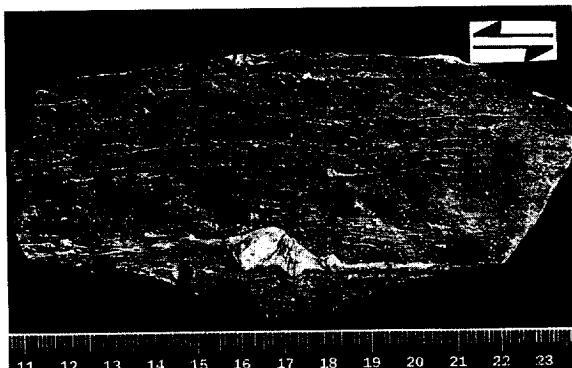
(d)



(c)



(f)



(e)

with a width of up to 8 km in the south, decreasing to 2 km in the north. It truncates the SRSZ and the complex structures in the migmatic gneisses towards the east.

The MSZ forms part of an anastomosing group of shear zones that form a major N–S trending lineament (Fig. 1) that runs along the Tambourah Belt, the Lalla Rookh Basin and the Strelley Granitoid. Krapez and Barley (1987) relate these faults to the deposition of the Lalla Rookh Basin which has an inferred age of 2950 Ma. This means that at least part of the movement on the MSZ occurred around that time and is coeval with a suite of granitoids in the Shaw Batholith, dated at ca. 2950 Ma (Pb–Pb, Bickle et al. (1989)). This has recently been confirmed by the U–Pb SHRIMP age of the granitic dike, which intrudes the MSZ during its final stages of activity, at 2934 ± 2 Ma (Zegers, 1996)

The decrease in width towards the north is partly explained by strands of the MSZ splitting off the main shear zone. Another marked decrease in width occurs north of the junction between the SRSZ and the MSZ, where the MSZ bends into the greenstone belt. A possible explanation of the decrease in width is that part of the MSZ continued north, but was intruded by the ca. 3340 Ma Chocolate Hill Suite and thereby obliterating the shear zone. This would imply that part of the MSZ was older than 3340 Ma. A more plausible explanation in view of the timing constraints discussed above is that the MSZ followed and reactivated older structures, such as the continuation of the SRSZ, on the western side of the Shaw Batholith. Where the MSZ follows the SRSZ, the shear zone is relatively wide, where it does not follow the older structure it splits into a number of narrow high strain zones.

The internal structure of the MSZ is complex. The temporal relationship between the mylonitic

and ultramylonitic foliation is uncertain: do they record two separate events or do they reflect one progressive deformation event with strain becoming more localized in time? The ultramylonites consistently overprint the mylonitic foliation. However, they form an anastomosing pattern, with strands of ultramylonite merging with the mylonitic foliation. This pattern can be interpreted as a 100 m scale shear band pattern (Fig. 4) with the ultramylonite zones forming in the R- and P-shear orientations within the MSZ during the sinistral movement [for a full discussion of internal shears and their geometry in shear zones see Rutter et al. (1986) and White et al. (1986)]. Mineral assemblages in the mylonitic and ultramylonitic foliation are similar, chiefly quartz, plagioclase, biotite and hornblende, indicating lower amphibolite facies conditions, in both, during deformation. The mylonitic and ultramylonitic foliations have similar orientations. Lineations associated with both have a dominant shallow southern azimuth but the plunge can vary between 50°N and 50°S , with rapid changes along and across strike. In the southern part of the MSZ lineations are subhorizontal, in the middle part both south and north dipping plunges occur and in the northern part they are mainly south plunging. This pattern can be partly explained by the variations in the strike of the shear foliation, with a releasing bend in the north causing south plunging lineations. However, in the Tambourah Creek traverse, which formed the basis for Fig. 4, the foliations are N–S trending but lineations still show variable plunges. Here, the ultramylonite lineation appears to have a shallower plunge than the mylonitic lineation. The sense of shear, as indicated by the kinematic indicators, is always sinistral, irrespective of mylonite type and plunge of the lineation. The above points are consistent with the mylonite and ultramylonite developing during one progressive defor-

Fig. 5. (a) Folded grey gneiss with leucosomes (L) following the crenulation foliation planes. (b) σ -type porphyroclast with a non-stairstepping geometry, showing a sinistral sense of shear in the mylonitic foliation of the MSZ. (c) Broken and boudinaged amphibolite layer in the mylonitic foliation of the MSZ. The amphibolitic layering in the boudins is rotated sinistrally with respect to the mylonitic foliation. (d) Pegmatite with adjacent folds. The folding pattern is thought to be the result of sinistral rotation of the pegmatite in the MSZ. (e) Ultramylonite foliation (plane parallel to lineation) with σ -type porphyroclasts in an ultramylonite zone, indicating a sinistral sense of shear. (f) Granitic dike (D) intruding an ultramylonite zone at a small angle. The same foliation and lineation occur in the ultramylonite and in the granite dike, indicating intrusion during deformation.

mation event. It is, however, likely that the MSZ is a reactivated older structure, evidence for which has been completely overprinted.

The pseudotachylite veins may be genetically related to the mylonitic and ultramylonitic foliation in the MSZ. They post-date the mylonitic foliation but have been observed to be deformed by the ultramylonites.

At the contact between the MSZ granitoids and Tambourah Greenstone Belt, the MSZ ultramylonite truncates an earlier east dipping greenschist facies mylonitic foliation with down dip lineations in the greenstone belt. Kinematic indicators in the greenschist facies foliation indicate earlier uplift of the greenstones relative to the granitoids. The uplift of the greenstones can be correlated to thrust and fold structures in the greenstones described by Bickle et al. (1985) and Boulter et al. (1987) further to the north, which formed between 3325 and 3200 Ma. This indicates that the MSZ ultramylonite at the contact formed later than ca. 3200 and locally exploited the earlier thrust structure. The consistent south plunging lineation and west dipping foliation of the MSZ ultramylonite, combined with the sinistral sense of shear, resulted in transtensional movements which produced the relative uplift of the eastern block and caused the final juxtaposition of the amphibolite facies rocks within the Shaw Batholith and the greenschist facies rocks of the Tambourah Greenstone Belt.

Van Kranendonk and Collins (1998) studied an area to the north that is enclosed by the two major strands of the Mulgandinnah Lineament. They concluded that the northeast trending folds and thrust faults in that area are both temporally and spatially related to a sinistral strike-slip movement on the shear zones forming the Mulgandinnah Lineament. Therefore, the data consistently indicate that the Mulgandinnah Lineament is a linked system of sinistral strike-slip shear zones over a strike distance of more than 150 km, and was active during the intrusion of a suite of K-rich granites in the Shaw Batholith which were dated at 2932 ± 2 Ma (U–Pb SHRIMP by Zegers (1996)). The size and strike-slip character of the shear zone system is direct evidence that the lithosphere mechanically behaved as rigid plates, allowing deformation to occur as a result of externally

applied tectonic forces (Sleep, 1992), at 2930 Ma in the Pilbara Craton.

Although the shear zones in the Mulgandinnah Lineament must have accommodated a considerable displacement, probably with tens of kilometres of horizontal offset, there is no compelling evidence for a tectonostratigraphic terrane-boundary significance of the Mulgandinnah Lineament, i.e. dividing rock masses which have a unique history before the event that brought them together (Jones et al., 1983). No dramatic changes in stratigraphy, metamorphism or deformation have been described, to date, on either side of the lineament. A similar conclusion was also reached by Van Kranendonk and Collins (1998). Although the general data indicate that the Pilbara granitoid–greenstone terrain stratigraphy gets younger toward the west (Horwitz and Pidgeon, 1993; Smith et al., 1998), the Mulgandinnah Lineament does not appear to be one of the fundamental breaks across which these changes occur. Rather, it seems to have been part of a strike-slip accommodation for NW–SE directed crustal shortening in the eastern Pilbara (van Haafren and White, 1998) during which accretion may have occurred in the western Pilbara (Smith et al., 1998).

In a geochronological study of the western most domain boundary in the Pilbara Craton, Smith et al. (1998) estimate that movement on the Sholl Shear Zone occurred at ca. 2.96 Ga. This indicates that activity of at least the Sholl and the Mulgandinnah Shear Zones occurred at approximately the same time and the shear zones may therefore have formed as a response to the same regional stress field.

The strike-slip related deformation in the eastern Pilbara is the final deformation event before cratonization and deposition of the Hamersley Basin. Prior to this, the east Pilbara has had a complex history involving extension during deposition of the Warrawoona Group (Zegers et al., 1996), E–W compression broadly during deposition of the Gorge Creek Group in the Shaw area (Bickle et al., 1980; Boulter et al., 1987; Zegers, 1996) and with a final phase of NE–SW expulsion (see van Haafren and White, 1998), followed by NW–SE shortening and major strike-slip activity described above. The last event, which was accompanied by

the intrusion of K-rich granites, reflects the final juxtaposition of the structural elements which make up the Pilbara granitoid–greenstone terrain. This sequence of deformation events, ending with the final cratonization after intrusion of K-granites and strike-slip deformation, is common throughout Archean granitoid–greenstone terrains and has been described in the Barberton Mountain Land (de Ronde and de Wit, 1994), the Abitibi Belt (Chown et al., 1992) and for parts of the Yilgarn Craton (Myers, 1995). However, the period over which this sequence of events takes place, varies from 500 Ma in the mid Archean terrains to ca. 200 Ma in the late Archean terrains. In the late Archean Superior Province and the Yilgarn Craton many of these strike-slip zones have been shown to be terrane boundaries, separating tectonostratigraphic terranes which were amalgamated during the final accretion event (Myers, 1995 and references therein). For the Pilbara Craton a similar accretion model has been proposed (Krapez, 1993). However, the geochronological and structural data from the independent domains remain insufficient to confirm or reject such a model.

6. Conclusions

- (1) The MSZ is a major ductile shear zone that is part of a group of N–S trending shears that form a lineament that can be traced further north where it runs along and influences the Lalla Rookh Basin.
- (2) The MSZ displays a consistent sinistral sense of shear, locally with a vertical component, causing uplift of the Shaw Batholith relative to the Tambourah Greenstone Belt.
- (3) The individual mylonitic and ultramylonitic foliations in the MSZ have probably formed during progressive deformation in one event. However, the possibility that part of the mylonitic foliation formed during an earlier event cannot be ruled out. The MSZ locally exploits an earlier thrust shear in the Tambourah Greenstone Belt.
- (4) Timing constraints imply that the MSZ has been active in the final stages of crustal development in the Pilbara granitoid–greenstone terrain, at ca. 2930 Ma., during intrusion of K-granites.
- (5) Although the MSZ must have had a considerable lateral displacement, the same stratigraphic successions have been recorded on either side of the Mulgandinnah Lineament, implying that it is not a true terrane boundary.
- (6) The MSZ is responsible for the final juxtaposition of the Shaw Batholith and the Tambourah Greenstone Belt.

Acknowledgment

We acknowledge the financial support of the Dr Schürmann Fonds (grants no. 1992/03, 1993/05, 1994/09) for the fieldwork that led to this publication. We thank Denis O'Meara for his hospitality in Marble Bar, Jan Kees Blom for general support during the fieldwork, Paul Dirks and Jan Wijbrans for valuable discussions on the MSZ and Julian R. Vearncombe and an anonymous reviewer for valuable comments on earlier versions of the paper.

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