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Mesoscopic structures produced by Plio-Pleistocene wrench faulting in South Sulawesi, Indonesia

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Abstract—The Bantimala Complex and overlying Cretaceous sediments of South Sulawesi, Indonesia, were intensely faulted in the Plio-Pleistocene as a result of the northward movement of the Banda Sea microplate with respect to Western Indonesia. The area is dominated by NNW-striking sinistral wrench faults. The structures in these faults formed at less than 250°C. Zones of intense rotation and faulting, 200 m wide, parallel the major faults. They consist of lenses of a wide range of sedimentary and metamorphic rocks separated by narrow zones of foliated cataclasite. Within the lenses, folding is non-cylindrical and there is a weak stretching lineation parallel to the shear direction. Extension fractures and veins occur at 70° to the stretching lineation. Sinistral and dextral faults within the lenses are symmetrical to the major faults. The fabric within these lenses suggests moderate horizontal extension rather than strong simple shear. Within the cataclasite, the foliation is composed of anastomosing microfaults. The sense of shear is demonstrated by offset on these microfaults and on smaller fractures within the microlithons. Elongate clasts are horizontally aligned within the cleavage and have symmetrical drag patterns. Many of the equidimensional clasts have asymmetrical drag patterns consistent with sinistral shear.

INTRODUCTION

THE NORTHWARD movement of the Australian Plate has produced a collision margin in Timor. Since this Late Miocene collision (Berry & Grady 1981, Berry & MacDougall 1987), the continued movement of the Australian plate has driven the Banda Sea northward with respect to continental South East Asia (Fig. 1) (Hamilton 1979, Berry & Grady 1981, McCaffrey *et al.* 1985). Much of this relative movement has occurred on a system of sinistral wrench faults exposed in Sulawesi (Katili 1970, Sukamto 1978, Tjia 1981). In North and East Sulawesi the tectonics are complicated by the E-striking wrench faults associated with sinistral shearing between the Australian and Pacific plates (Hamilton 1979, Silver 1981, Silver *et al.* 1985). There is no direct evidence of these E-striking wrench faults in South Sulawesi.

The pattern of Late Tertiary and Quaternary faulting in South Sulawesi is relatively simple. The dominant structure is the Walanae Fault Zone, a major N–S depression bounded on the east and west by major sinistral wrench faults (Fig. 2) (Van Leeuwen 1981). The East Walanae Fault apparently continues southwards into a deep oceanic trough interpreted as a Neogene trench by Hamilton (1979). In the north the Walanae Fault Zone is truncated by a major group of NW-striking sinistral faults which form the boundary of the Central Highlands of Sulawesi.

To the west of the Walanae Fault Zone is an uplifted area, dominated by a mountainous belt of Late Tertiary volcanic rocks. Calderas are still visible in this sequence and a Pleistocene stratovolcano in the south, Mt Lompobatang, lies on an active fault zone (Fig. 2). Older rocks are exposed in a low-lying strip 25–75 km north of Ujung Pandang. Within these older rocks, two fault-bounded blocks of Cretaceous basement are exposed. The crystalline basement rocks and overlying sediments contain excellent examples of mesoscopic structures produced by the Plio-Pleistocene wrench faulting in South Sulawesi. This study is restricted to faults observed within this 50 km strip of Mesozoic rocks. A brief summary of the structure within an area of Tertiary sediments has been presented by Van Leeuwen (1981).

GEOLOGY

The crystalline basement rocks, Bantimala Complex, consist of thrust-bounded slices of *L*/*S* schists and phyllites. The most common lithologies are glaucophane schist, eclogite, chlorite feldspar phyllite, serpentinite, graphitic phyllite and piemontite-bearing quartzites. Pelitic rocks are rare. Overlying the metamorphic rocks is a clastic sequence of Cretaceous age (Sukamto 1978, Van Leeuwen 1981). This includes a basal breccia, siliceous red mudstone, and a sequence of feldspathic greywacke and siltstone (Marada Sandstone). The

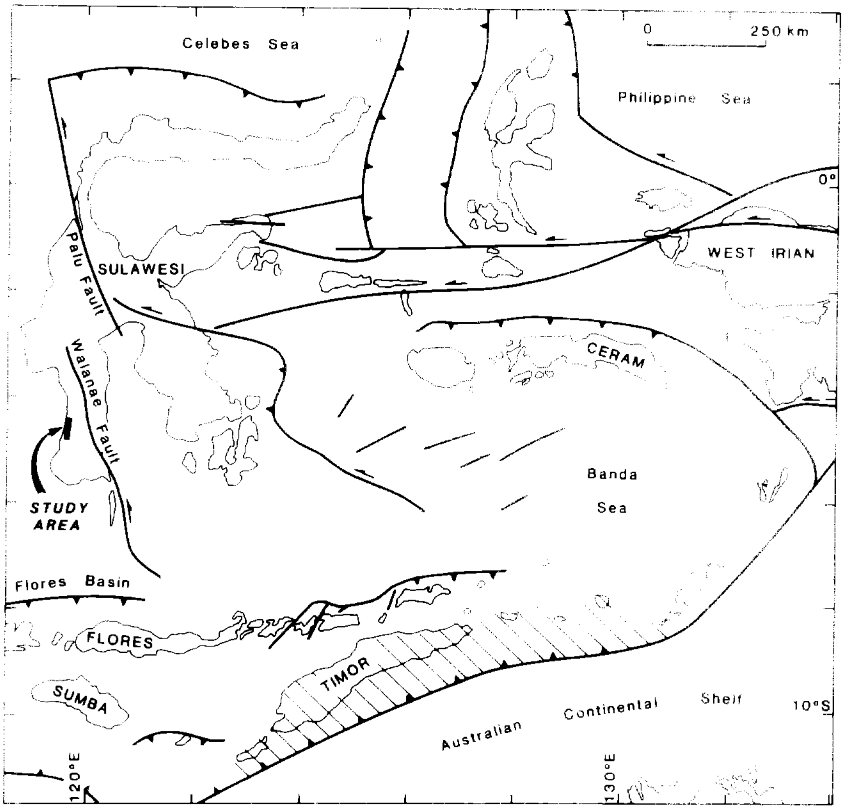
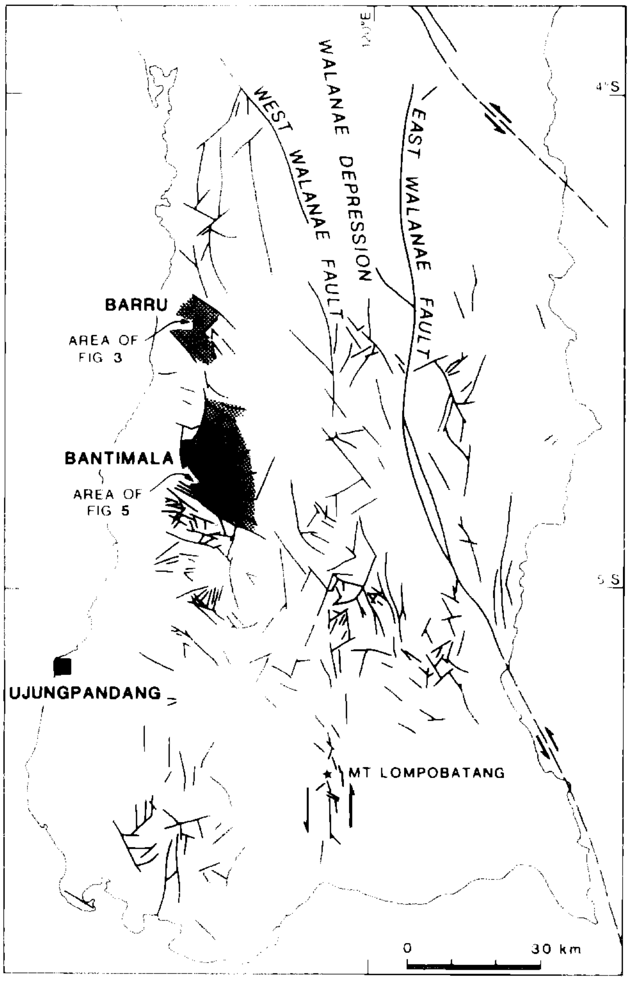


Fig. 1. Location map showing major faults at the intersection of the South East Asian, Pacific and Australian Plates. The faults, shown in thick lines, were compiled from Hamilton (1978), Sukamto (1978) and Silver *et al.* (1985). Thrusts are shown with teeth towards the overriding block. The collision zone on the NW margin of Australia is shown as diagonal lines.



Cretaceous sequence is more than 750 m thick and is overlain unconformably by a 2 km thick Tertiary sequence of limestone and volcanic rocks (Van Leeuwen 1981). Mio-Pliocene granodiorites and lamprophyres intrude the sequence. A detailed summary of the stratigraphy is given by Van Leeuwen (1981). The cataclasites in these zones contain quartz, illite and Fe-rich chlorite. The illite crystallinity suggests a metamorphic temperature of 200–250°C while the Fe_2O_3/MgO ratio and crystallinity of chlorite suggest a maximum temperature of 150–200°C using the calibrations of Weaver (1984, p. 198). The stratigraphic evidence suggests this temperature was reached at about 3 km depth.

STRUCTURE

Extensive areas of crystalline basement rocks are exposed at Bantimala and Barru on the west coast of South Sulawesi. Both are bounded to the west by a complex association of E-dipping thrusts and NNW-striking wrench faults. Everywhere the wrench faults offset the thrusts. In a few localities, NNW-striking faults offset poorly consolidated river gravels.

The north and south boundaries of the basement complexes are sinistral wrench fault zones striking NW. These zones were probably active during both phases of

Fig. 2. Fault pattern in South Sulawesi. The pre-Tertiary rocks are shown in stipple. Faults compiled from Djuri & Sudjatmiko (1974), Sukamto (1982) and Sukamto & Supriatna (1982).

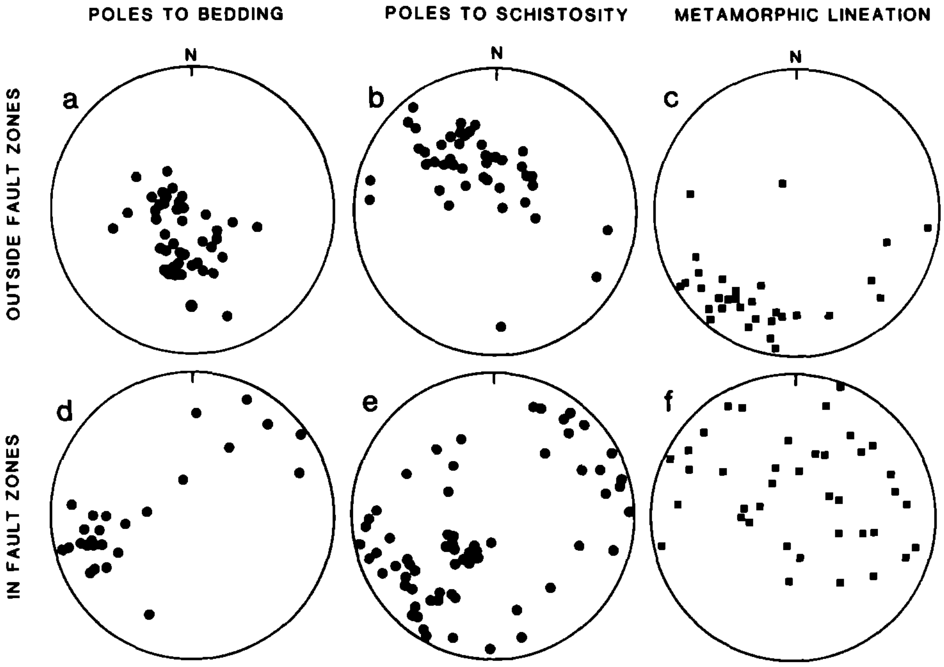


Fig. 3. Lower-hemisphere equal-area stereographic projections of structures from the Barru and Bantimala blocks: (a)–(c) are from areas distant from major fault zones; (d)–(f) are from the southern margin of the Bantimala Block, in and near major fault zones.

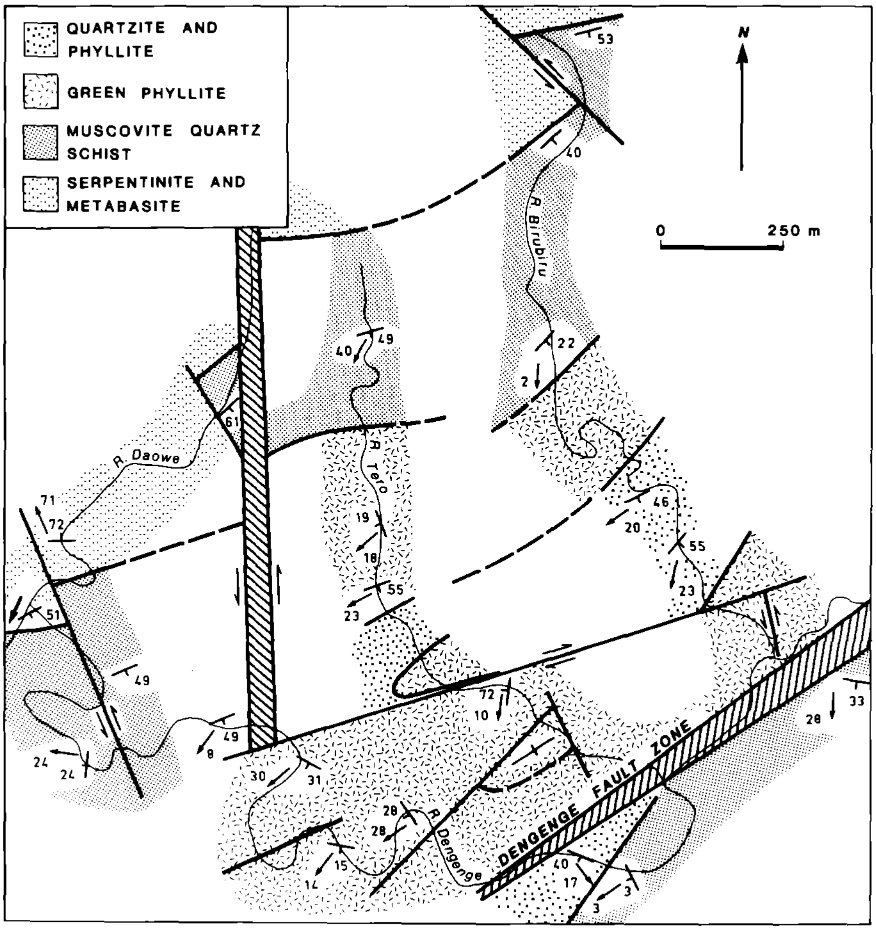


Fig. 4. Geological map of a section of the Bantimala Complex near the centre of the Barru Block.

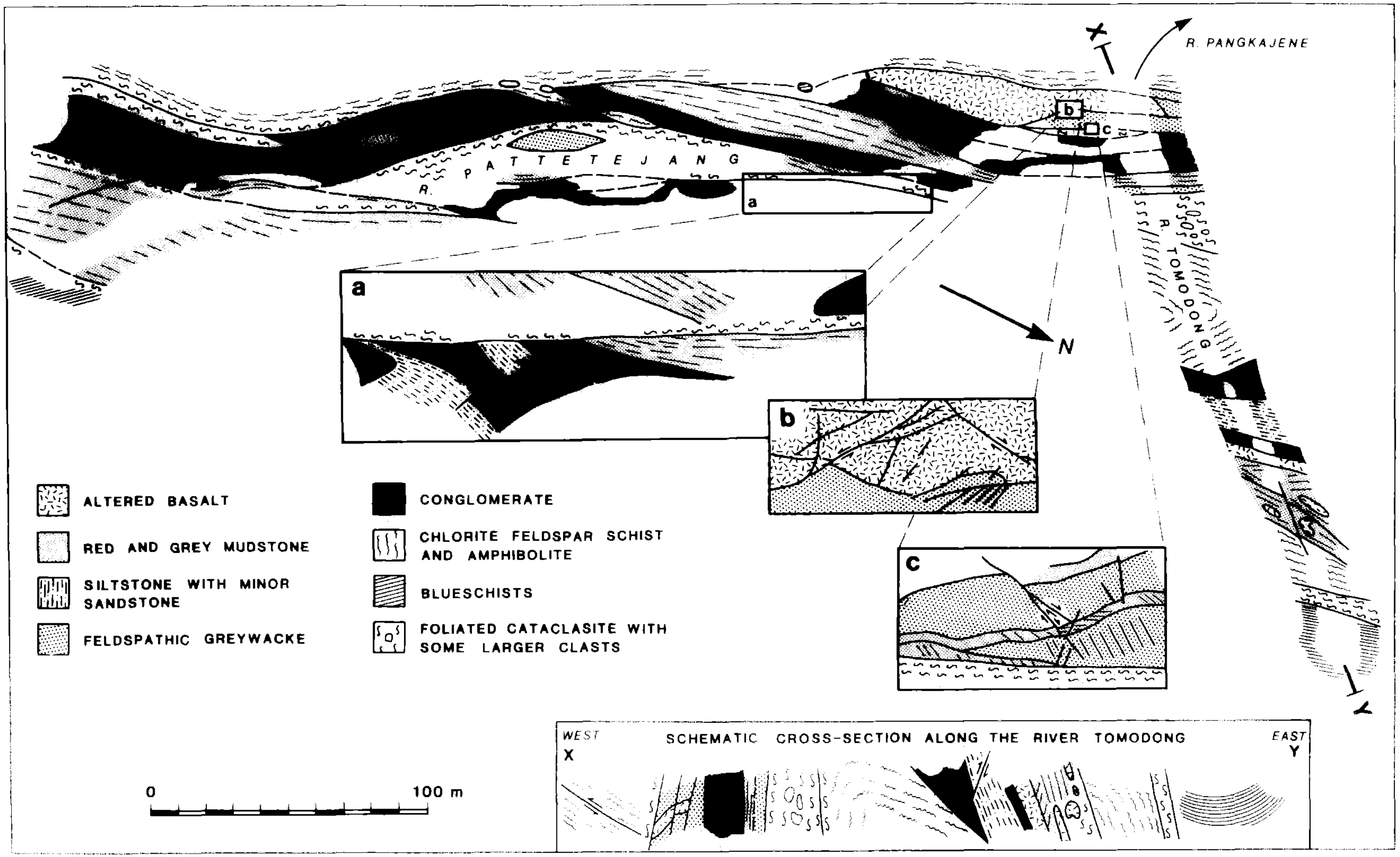


Fig. 5. Detailed sketch map of the NNW-striking fault zone at the junction of the Pattetejang and Pangkajene Rivers. Insets show details of the structure and a schematic cross-section. In inset (c) cleavages within the sandstone and mudstone are shown as lines oblique to the layering.

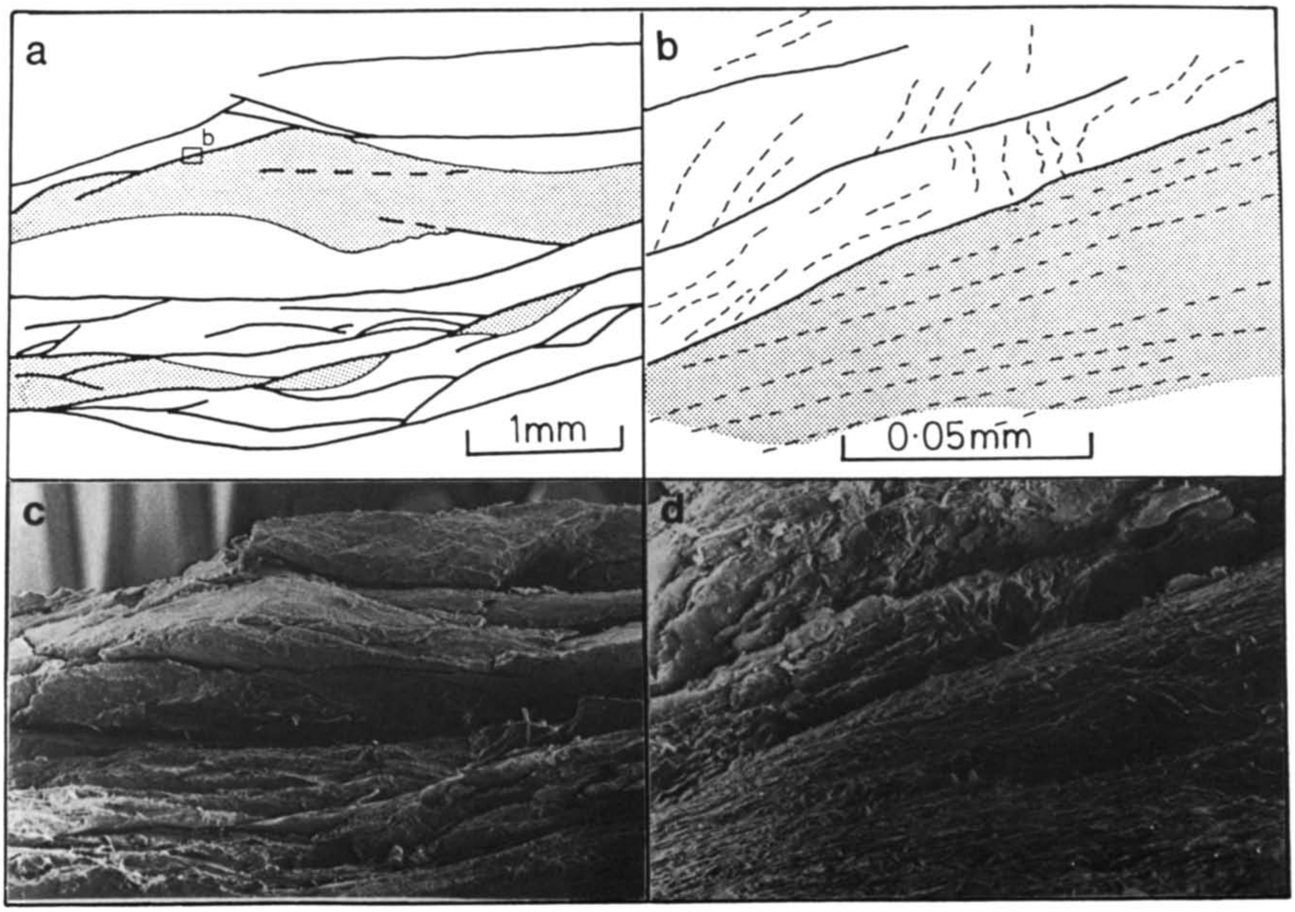


Fig. 6. Detailed structural relationship in the foliated cataclasite. (a) and (b) are line drawings from SEM photographs, (c) and (d), respectively. Thick lines are microfractures defining the spaced cleavage, thin lines are compositional layering, dashed lines are the basal cleavage of clay minerals and the stippled areas are silica-rich tuff. (a) & (c): phacoid of tuff, (b) & (d): sheared margin of phacoid.

faulting. In central Sulawesi, NW-striking wrench faults are closely associated with E-dipping thrusts (Djuri & Sudjatmiko 1974) which are interpreted as Miocene structures (Sukamto 1978, Silver & MacCaffrey 1983). A shallowly dipping (Fig. 3a) sequence of Cretaceous sediments crops out along the eastern margin of the basement complexes. These sediments unconformably overlie the basement rocks and the unconformity dips gently where it is exposed outside the major fault zones. The gross structure is relatively rigid blocks tilted to the E and bounded on three sides by large faults. The rigid blocks are 0.5–2 km wide and up to 10 km long. The faults are up to 500 m wide. The structures observed within the blocks are different from those within the fault zones.

An example of the structure within the core of the Barru Block is shown in Fig. 4. The area is composed of a series of *L/S* schists with a SE-dipping foliation and a S- to SW-trending lineation (Fig. 3b & c). The sequence of rock types is serpentinite, the lowest exposed unit, through quartz–mica schist to quartzite and chloritic phyllite. The small range in the orientation of the schistosity and the shallow dip of bedding in the Cretaceous sedimentary rocks demonstrate the limited Tertiary folding in these areas. In contrast the same fabric elements at Bantimala, in and near the major wrench faults, are strongly rotated (Fig. 3d, e & f). The most common strike direction of the schistosity at Bantimala is NW, roughly parallel to the faults (Fig. 3e). NW- to N-striking faults at Barru are sinistral while there are a large number of NE-striking dextral faults and less common SE-dipping thrusts. Cataclasite zones, up to 1 m wide, occur along NNW-striking wrench faults and SE-dipping thrusts. The Dengenge Fault Zone (Fig. 4) is composed of strongly deformed sediment but no sediments are exposed either side of this structure. It may have been formed as an intensely sheared synclinal core which has been reactivated as a dextral fault. The structural style in the core of the Barru Block involves extensive faulting with minor folding.

A Plio-Pleistocene sinistral fault zone is exposed at the junction of the Pangkajene and Pattetejang Rivers (Fig. 5). Within the fault zone, the strain is concentrated into discrete zones of cataclasite from 20 cm to 8 m wide. The cataclasites have a strong anastomosing cleavage with a spacing of 1–2 mm. The cataclasite splits very easily along this spaced cleavage into microlithons with an irregular elongate shape, about 2 cm long horizontally and 1 cm high. The cleavage surfaces are microfaults (Fig. 6a). Within the microlithons are relicts of compositional layering with phacoidal shapes. A weak slaty cleavage defined by the preferred orientation of illite is subparallel to this layering. Both the layering and the illite foliation are most commonly oriented at 160–175° to the microfaults, using the angular convention of Chester *et al.* (1985). Exceptions occur in areas of buckling of the illite foliation (Fig. 6b & d). The angular relations of the illite foliation to the microfractures and the phacoid shapes (Fig. 6a & c) support sinistral shear. In addition, within the microlithons the layering is consistently offset in a sinistral sense by microfractures.

Recrystallization is very limited in these cataclasites. Calcite grains and pyrite framboids act as rigid clasts. New grain growth along the microfaults is limited to rare calcite and illite grains. The illite foliation may be a modified bedding plane fabric.

Chester *et al.* (1985) have described foliated cataclasites from California. Despite substantial differences in mineralogy, most of the fabric elements they reported are recognizable in the foliated cataclasites from Sulawesi. They interpret the foliation formed at 160° to the main shear plane as the result of flattening without substantial crystal plasticity or diffusion and they conclude that cataclastic mechanisms are capable of producing a foliated material, such as that exposed in South Sulawesi.

Pebble-sized elongate clasts within the cataclasite zones have a strong preferred orientation plunging shallowly south (Fig. 7a) and approximately parallel to the long axes of the microlithons. They are perfectly aligned in the cleavage and have a symmetrical cleavage distribution. Half of the near equidimensional pebble-sized clasts, (length/width ratios <2) within the cataclasite have an asymmetrical cleavage distribution (Fig. 8). A sample of 45 clasts from three cataclasite zones contained 22 clasts where the clast was rotated anticlockwise with respect to the cleavage. Three clasts had the opposite sense of asymmetry and 20 clasts had no discernible asymmetry. Ghosh (1975, fig. 22a) predicted this drag pattern for sinistral shear where the foliation is parallel to the shear direction either initially or because of high shear strains. Ghosh & Ramberg (1976) proposed a model for rotation of clasts which predicted a stable orientation parallel to the shear direction for axial ratios greater than 2, if the strain rate ratio of pure shear to simple shear was greater than 0.7. While we have not attempted an exact survey of the axial ratios of clasts in this study, the presence of a range of clasts of variable axial ratios with symmetrical foliations indicates a substantial component of pure shear in the strain. Boulder-sized clasts within the foliated cataclasite occur as boudins and rounded blocks with their long axes approximately horizontal (Fig. 7a).

Between the foliated cataclasite zones are elongate blocks up to 200 m long and 10 m wide (Fig. 5). The tectonic fabric in these blocks is much weaker with local cleavage development, especially near the margins. For example, in a sandstone/siltstone sequence (Fig. 5, inset c) a weak cleavage strikes NE and is restricted to the margin of the block. There is a sharp change in foliation direction at the cataclasite boundary, but the orientation of the cleavage within its margin supports a sinistral component of shear. Other features of this margin are the numerous dextral faults which may be R2 Reidel shears (Sanderson & Marchini 1984). The sandstone in this area has pinch-and-swell structures with boudins subvertical, indicating horizontal extension. Common features within these blocks are conjugate dextral and sinistral faults symmetrically related to the layering (Fig. 5, inset b). Both normal and reverse faults occur with

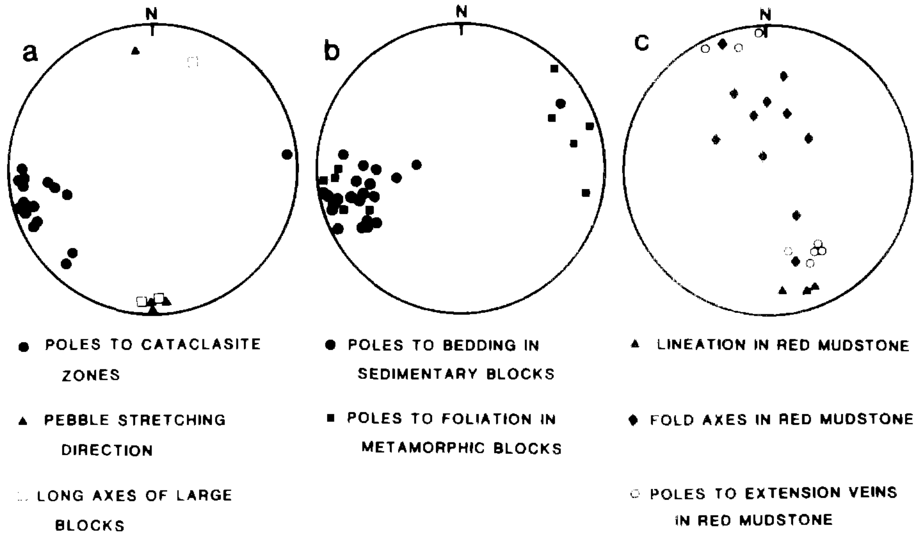


Fig. 7. Lower-hemisphere equal-area stereographic projection of structures within the NNW-striking fault zone: (a) fabric of cataclasite zones, (b) layering within large lenses and (c) fabric in red mudstone lenses.

strikes at a high angle to the NNW-striking cataclasite zone. The normal faults appear to be related to boudinage of blocks with a pre-existing plane of weakness.

Blocks of siliceous red mudstone contain a range of fabric elements. A weak stretching lineation is subparallel to the shear direction in the foliated cataclasite (Fig. 7c). Bedding is subparallel to the cataclasite zones which bound the block. Tight non-cylindrical folds are common with a range of steep to moderate plunges (Fig. 7c). Small extension fractures and quartz veins are widespread and are most commonly at 70° to the stretching lineation and perpendicular to the cataclasite zones. Burg & Harris (1982) have interpreted these types of extension fractures as Luders Bands.

In combination, all the fabric elements within these large blocks support a moderate N–S extension but there is limited evidence of rotational strain (non-cylindrical folds, lineated fabric) and no strong evidence for the sense of simple shear. However, the gross orientation of the large blocks is at 160–170° to the fault zone (Fig. 5). This asymmetry matches the orientation of relict layering in the cataclasites and is compatible with sinistral shear.

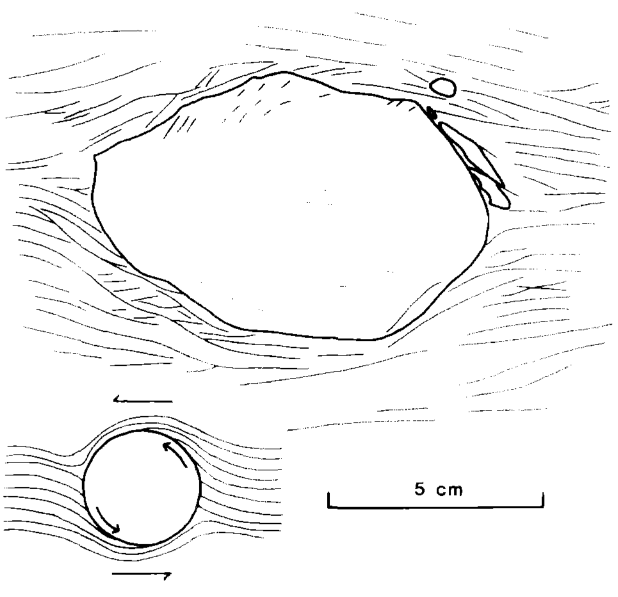


Fig. 8. Asymmetric cleavage distribution around near equidimensional clast in the foliated cataclasite. Inset shows cleavage relation predicted by Ghosh (1975) for this case.

The boundaries of the NNW-striking fault zone are transitional. Towards the blueschists to the E there is a gradual increase in the width of relatively undeformed material and a decrease in the width of foliated cataclasite zones. The deformation within the blocks is reduced and the orientation of layering and bedding is more variable.

The NW-striking shear zones have a similar style of deformation. For example, along the River Pattetejang there is a series of fault bounded blocks with strong extensional fabrics. Small blocks show conjugate sinistral and dextral faults, and have near horizontal fold axes. The blocks are separated by cataclasite zones in which elongate clasts have a subhorizontal preferred orientation. A feature common in this zone but not observed in the NNW-striking fault zones is the presence of blocks with curved antithetic faults. This difference may be related to lithological variation.

CONCLUSIONS

Sinistral wrench faulting has occurred at very low grades of metamorphism in South Sulawesi. The early stage of faulting was dominated by NW-striking wrench faults and E dipping thrusts. The second phase of faulting was dominated by NNW-striking wrench faults with the NW-striking wrench faults probably reactivated during this phase. The area is now composed of blocks up to 10 × 2 km separated by major fault zones 100–500 m wide.

Within the fault zones, the shear strain was concentrated into foliated cataclasite zones which anastomose around strongly rotated blocks of less deformed country rock about 10 m wide. Within the cataclasite, a strong spaced cleavage parallels the shear direction. The direction of shear is indicated by the long axes of microlithons and the long axes of pebble to boulder size clasts. The sense of movement is indicated by consistent microfaults and phacoids within the microlithons, the asymmetry of the cleavage around equidimensional clasts and locally the refraction of the foliation into adjacent less deformed blocks. A substantial pure shear component of the strain is suggested by the symmetrical cleavage distribution around clasts with axial ratios as small as 2.

In larger blocks within the shear zone the direction of shear is indicated by a range of structures but no unequivocal evidence for the sense of shear was observed. A lineation in siliceous mudstone, extensional veins and fractures, conjugate dextral and sinistral faults, and subvertical boudin axes all support horizontal extension. The evidence of a rotational strain history within the larger blocks, is limited to non-cylindrical folding and the lineated fabric in the mudstone. The obliquity of these blocks to the cataclasite zones supports the evidence for sinistral shear within the cataclasites.

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SHEAR CRITERIA IN ROCKS

Section II:

Sense of slip on faults