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The role of ductility contrast and basement architecture in the structural evolution of the Crystal Creek block, Mount Isa Inlier, NW Queensland, Australia

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Abstract—The Leichhardt River Fault Trough of the Mount Isa Inlier comprises fault blocks which exhibit different local deformational histories and structural orientations. Many structural patterns in the stratigraphically highest cover sequences do not occur in adjacent fault blocks that expose older and mechanically stronger rocks. Within the Mount Isa Group sediments of the Crystal Creek block for example, tight E-trending upright folds appear to be at odds with the surrounding north–south regional trends. In this paper it is proposed that an inherited extensional fault geometry played a significant role in controlling the structural patterns developed during later shortening. Through the integration of detailed surface mapping and forward magnetic modelling, an inverted half-graben was identified beneath the Crystal Creek block, exposing the underlying origin of local structural complexities. Structural inversion and buttressing against pre-existing faults simultaneously removed extensional displacement across pre-rift rocks and induced folds and faults in overlying sag-phase sediments. This led to the development of two structural levels characterized by different deformational styles and apparently distinct deformational histories.

INTRODUCTION

The map pattern of the Leichhardt River Fault Trough of the Mount Isa Inlier has intrigued geologists for many years (e.g. Dunnet 1976, Glikson *et al.* 1976, Blake 1980, Derrick 1982, Bell 1983). The structural associations of the Leichhardt River Fault Trough are diverse (Figs. 1 and 2), and taken collectively, do not fit neatly into any 'type' terrane (i.e. wrenching, thrusting or extensional). For example, there are features which have been caused by an early history of rifting (Glikson *et al.* 1976, Derrick 1982, Blake 1987), while many other features can be explained by thrusting (Bell 1983, Connors *et al.* 1992, Bain *et al.* 1992, Nijman *et al.* 1992). Equally, many elements of Mount Isa geology can best be explained in terms of large-scale transpressional wrenching (Lister *et al.* 1987).

Controversy surrounding the structural development of the Leichhardt River Fault Trough is largely due to difficulties in determining the kinematic relationship between fault blocks which exhibit different structural orientations and deformational histories. Part of the reason for this difficulty may lie in the fact that a pre-existing fault geometry played a large role in controlling the structural patterns during later shortening. The structures developed during the shortening of previously extended regions are expected to be much more variable than those found in classical thrust belts which deform a layer-cake stratigraphy (McClay & Buchanan 1992). Buttressing against variably trending basement faults can partition deformation and lead to the development of separate structural levels characterized by different deformational styles.

This paper describes the development of tectonic fabric elements within and bounding the Crystal Creek block of the Leichhardt River Fault Trough (Fig. 2). We address some of the problems of correlation which have arisen due to the difficulties in tracing structures from the Crystal Creek block into adjacent fault blocks. A tectonic model is proposed which uses structural inversion to resolve the apparent disparity between the kinematics implied by many map-scale relations and those inferred from detailed fieldwork. This model eliminates the need to account for all large stratigraphic contrasts in terms of classical thrust tectonics, while still allowing for significant horizontal shortening. Finally, we describe how the integration of geophysical data with surface observations can be used to help constrain the kinematic linkage between basement and cover rocks at the various structural levels currently exposed.

GEOLOGICAL SETTING

The Proterozoic Mount Isa Inlier is situated in NW Queensland, Australia. It consists of three dominant, N-trending structural belts that display distinctive geophysical trends (Wellman 1992) and are separated by major transcurrent fault zones (Blake & Stewart 1992) (Fig. 1). The Kalkadoon–Leichhardt Block forms the central belt of the inlier exposing basement rocks deformed and metamorphosed during the Barramundi Orogeny (1900–1875 Ma) (Etheridge *et al.* 1987). Younger rocks in the Kalkadoon–Leichhardt Block consist of felsic Leichhardt Volcanics and coeval granites of the Kalkadoon Batholith (1870–1850 Ma) (Page 1988). This block is thought to have formed a topographic high throughout the ensuing depositional history and shed

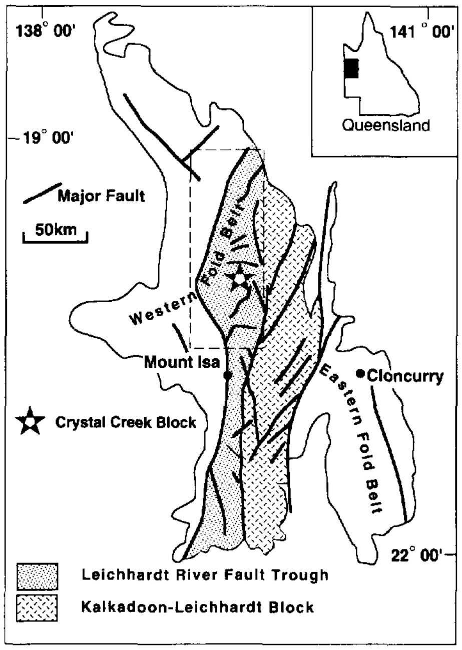

Fig. 1. Simplified map of the Mount Isa Inlier showing the dominant N-trending structural belts (after Blake 1987) and the location of the Crystal Creek block. Dashed box refers to the location of Fig. 2.

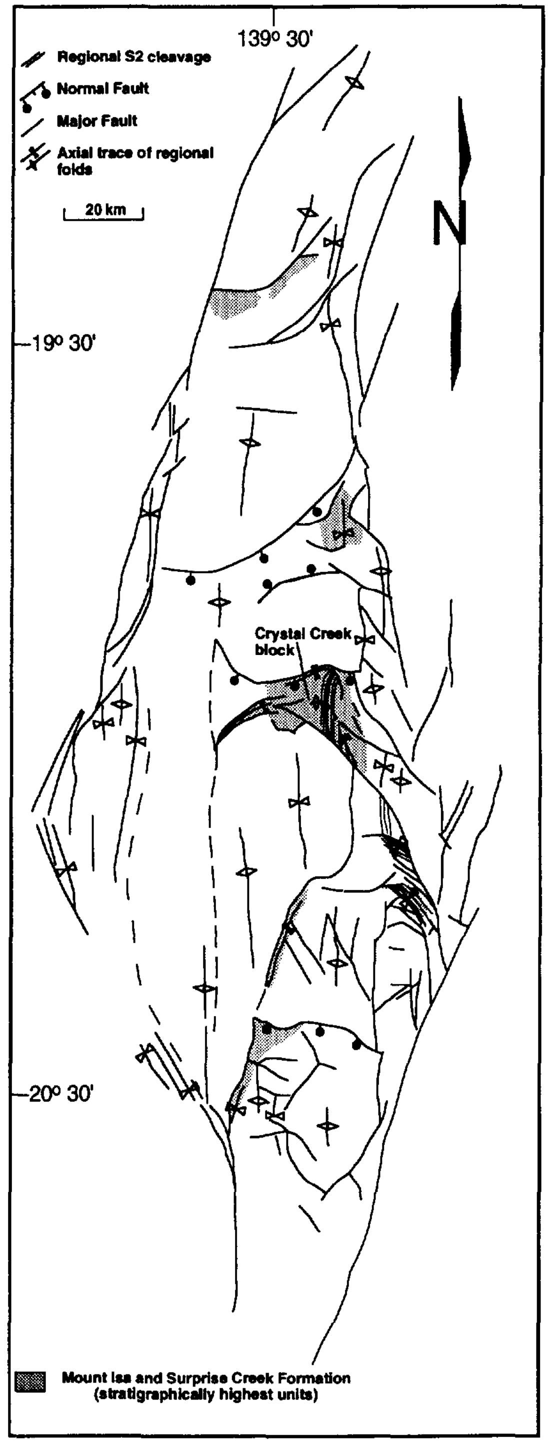

Fig. 2. Generalized geological map of the Leichhardt River Fault Trough, showing major faults, axial surfaces as well as the form surface trace of S_2 cleavage along part of its eastern margin. Location of Crystal Creek block is indicated.

detritus into flanking sedimentary basins on either side (Carter *et al.* 1961, Blake 1980). To the west, 10–12 km of continental tholeiites, volcanogenic sediments, felsic volcanics, thickly bedded arenites, coarse clastics, dolomites and minor pelites were deposited. To the east lies the more highly deformed and metamorphosed Eastern Fold Belt. The Mount Isa Inlier was intensely deformed and regionally metamorphosed to greenschist and amphibolite grade during one more more major tectonic events termed the Isan orogeny (1610–1510 Ma) (Blake 1980, Page & Bell 1986).

The Leichhardt River Fault Trough (Glikson *et al.* 1976, Derrick 1982) is a tectonic subdivision of the Western Fold Belt (Figs. 1 and 2). It is defined largely on the basis of a distinctive N-trending gravity and magnetic high associated with the distribution of continental tholeiites (Eastern Creek Volcanics). These basalts are interpreted to have been deposited in an intracontinental margin rift, although the location of its original boundaries are still a topic of much debate.

The eastern boundary of the Leichhardt River Fault Trough is defined by the Gorge Creek–Quilalar Fault Zone. Based on both geophysical and sedimentological evidence, this fault zone appears to have been long lived. It is now thought to represent a major tectonic boundary roughly coinciding with an ancient rift shoulder (Derrick 1982). Geophysically, this fault coincides with long wavelength magnetic and gravity anomalies, indicative of a deeply biting crustal structure (Wellman 1992). Sedimentologically, lateral facies changes towards this fault show an increase in conglomerate abundance suggesting proximity to a fault-controlled source area to the east (Derrick 1982). At present the western boundary of the Leichhardt River Fault Trough is poorly constrained and arbitrarily assigned to the Mount Gordon Fault Zone.

The tightly folded low-grade metamorphic rocks of the Leichhardt River Fault Trough belong to the uppermost two of the three cover sequences defined for the Mount Isa Inlier (Blake 1987). Deposition spanned ~150 Ma and was associated with repeated cycles of rifting and post-rift thermal subsidence.

Cover sequence 2, deposited between 1800 Ma and 1740 Ma (Derrick 1982), comprises a thick sequence

(~8–10 km) of syn-rift arenites and volcanics which consist of, from oldest to youngest: Mount Guide Quartzite, Eastern Creek Volcanics and Myally Subgroup. This sequence is capped by the sag-phase transgressive–regressive quartz–carbonate Quilalar Formation (Jackson *et al.* 1990).

Cover sequence 3 is ~60 Ma younger than cover sequence 2 and is thought to have been deposited during a separate basin-forming event (Blake *et al.* 1990). It was deposited between 1680 Ma and 1650 Ma and consists of rift-related Bigie Formation and Fiery Creek Volcanics, overlain by sag-phase arenites, siltstones and shales of the Surprise Creek Formation and Mount Isa Group. Uniform REE geochemical results from the siltstones of these upper units reflect tectonic stability during deposition and support this sag-phase interpretation (Eriksson *et al.* 1992). Figure 3 depicts the inferred rift geometry of the Leichhardt River Fault Trough following the deposition of the Mount Isa Group.

The Crystal Creek block is situated roughly 50 km north of Mount Isa town (Fig. 1) and is one of the largest exposures of Mount Isa Group sediments in the Leichhardt River Fault Trough (Fig. 2). Along the eastern margin of the Crystal Creek block, the Mount Isa Group conformably overlies the Surprise Creek Formation. In the western half of the Crystal Creek block however, it unconformably overlies the older Eastern Creek Volcanics and Myally subgroup, indicating that these underlying units must have been tilted prior to the deposition of the Mount Isa Group. The stratigraphic omission of the Surprise Creek Formation in this region implies that this unit probably thinned towards the west or northwest. This depositional juxtaposition is consistent with extensional block faulting, wherein syn-rift sediments onlap the hanging wall of a half graben (Fig. 3). As the eastern margin of the Crystal Creek block was subsiding and accumulating a thick succession of syn-rift sediments, the western margin was being uplifted, deeply eroded, and finally unconformably overlain by sag-phase sediments of the Mount Isa Group. This angular

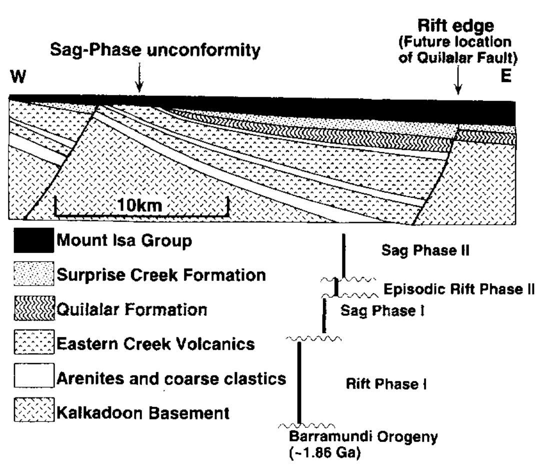

Fig. 3. Postulated geometry of the Leichhardt River Fault Trough following the deposition of the Mount Isa Group. A large tilt block has formed elevating the central domain, while the former rift shoulder has subsided. Mount Isa Group sediment are conformable with underlying Surprise Creek Formation to the east, but lie unconformably to the west on the uplifted footwall.

unconformity is quite pronounced and is now offset down the centre of the Leichhardt River Fault Trough, across E-striking, S-dipping normal faults.

Dunnet (1976) assumed this unconformity was originally a regionally continuous surface, which could be used as a marker horizon for reconstruction. However, using a more modern rift analogy, such as the Bass Strait off the southeastern coast of Australia (e.g. Etheridge 1986), it is likely that this unconformity developed in isolated, en échelon half-grabens separated by steeply-dipping transfer faults. If this were the case, many of the E-striking faults which record post regional D_2 normal displacement, may have originated as transfer faults, relaying extensional displacement between large tilt blocks.

Some of the prominent geometrical features of the Leichhardt River Fault Trough include: (a) a complex distribution of fault blocks; (b) repetition of the central anticline strata across E-trending faults; (c) east–west synclines associated with these east–west faults; (d) the association of upright regional D_2 synclines with sub-horizontal fold axes on either side of a regional antiform which plunges predominantly to the north.

Bell (1983, 1992) proposed a mega-duplex hypothesis to account for many of the geometric features listed above. In this model, an S-directed imbricate stack, bounded by a floor thrust and a roof thrust, formed during D_1. Subsequent east–west compression folded the duplex, producing regional N-trending F_2 folds. The repetition of strata across east–west faults and the association of tight synclines with these faults seemed to be adequately explained by Bell's model. However, at the core of this hypothesis was the assumption that orientation alone could be used as a means of correlating deformational fabrics across tens of kilometres. This implied a one-to-one correlation between local structural generations and regional deformation events (cf. Tobisch & Paterson 1988, Holcombe & Stewart 1992). While it is quite reasonable to presume that reverse faults were associated with compressional deformation in the Mount Isa Inlier, a mega-duplex, of the type proposed by Bell (1993), is inconsistent with other field evidence (e.g. Dunnet 1976, Nijman *et al.* 1992, Stewart 1992) and ignores the inherent complexity and mechanical influence of the original basin geometry.

Similarly, Lister (1986) proposed a transpressional wrenching model which attempted to explain the existence of correlative tectonic fabrics within apparently contrasting structural domains. In this model, much of structural complexity of the Leichhardt River Fault Trough was interpreted to have formed late (rather than early) in its deformational history due to the reorientation of earlier formed structures. For example, near the southern end of the Lake Julius Fault, an originally N-trending syncline has been tightened and reoriented counterclockwise due to movement on an adjacent strike-slip fault.

Despite these attempts at synthesis, inlier-wide tectonic models fall short because they invoke a single mode of deformation (e.g. thrusting or wrenching) to explain genetically and geometrically distinct structures. In so doing, they fail to discriminate between and/or to synthesize the many disparate aspects of the deformational history. In this paper, we do not attempt to develop a region-wide model. Rather, we highlight some unresolved geometries and attempt to reinterpret them in the context of an inverted rift basin.

One of the most contentious features of the geology in the Leichhardt River Fault Trough is that the orientations and history of structures developed in the stratigraphically highest cover sequences are often quite different from those developed in the lower units which define the regional N–S trends. The Crystal Creek block is one such fault block which appears to be at odds with the surrounding grain. This contrast lends support to the belief that rocks within the Leichhardt River Fault Trough may have responded differently depending on their inherent strength, stratigraphic level and position relative to a pre-existing architecture. Different structural styles developed during the inversion of various parts of the basin fill.

STRUCTURAL GEOMETRY OF THE CRYSTAL CREEK BLOCK

The Crystal Creek block consists almost entirely of Mount Isa Group sediments and is surrounded by fault blocks which expose much older Eastern Creek Volcanics and Myally Subgroup rocks. It contains a large-scale fold interference pattern developed throughout its eastern portion (Fig. 4). Based on geometrical criteria, there is a chronology of fold development wherein the axial planes of E-trending folds are folded about N-trending axes and cross-cut by a regional N-trending cleavage. We describe the features of this geometry in terms of first and second phase structures and make use of numerical subscripts (D_1, F_1, S_1 etc.) in the description. However, this is not meant to imply that successive folding episodes were necessarily produced during disparate shortening events separated by a large time interval. On the contrary, it is probable (although not unequivocal) that the two structural generations were broadly coeval and produced during the same overall deformation, controlled by a pre-existing basement architecture.

Phase one structures

The earliest phase of shortening in the Crystal Creek block produced ~E-trending regional scale, open to tight, upright folds which appear to have developed synchronously with reverse faults (Fig. 4). The gross D_1 geometry of the Crystal Creek block consists of an E-trending syncline–anticline pair, the common limb of

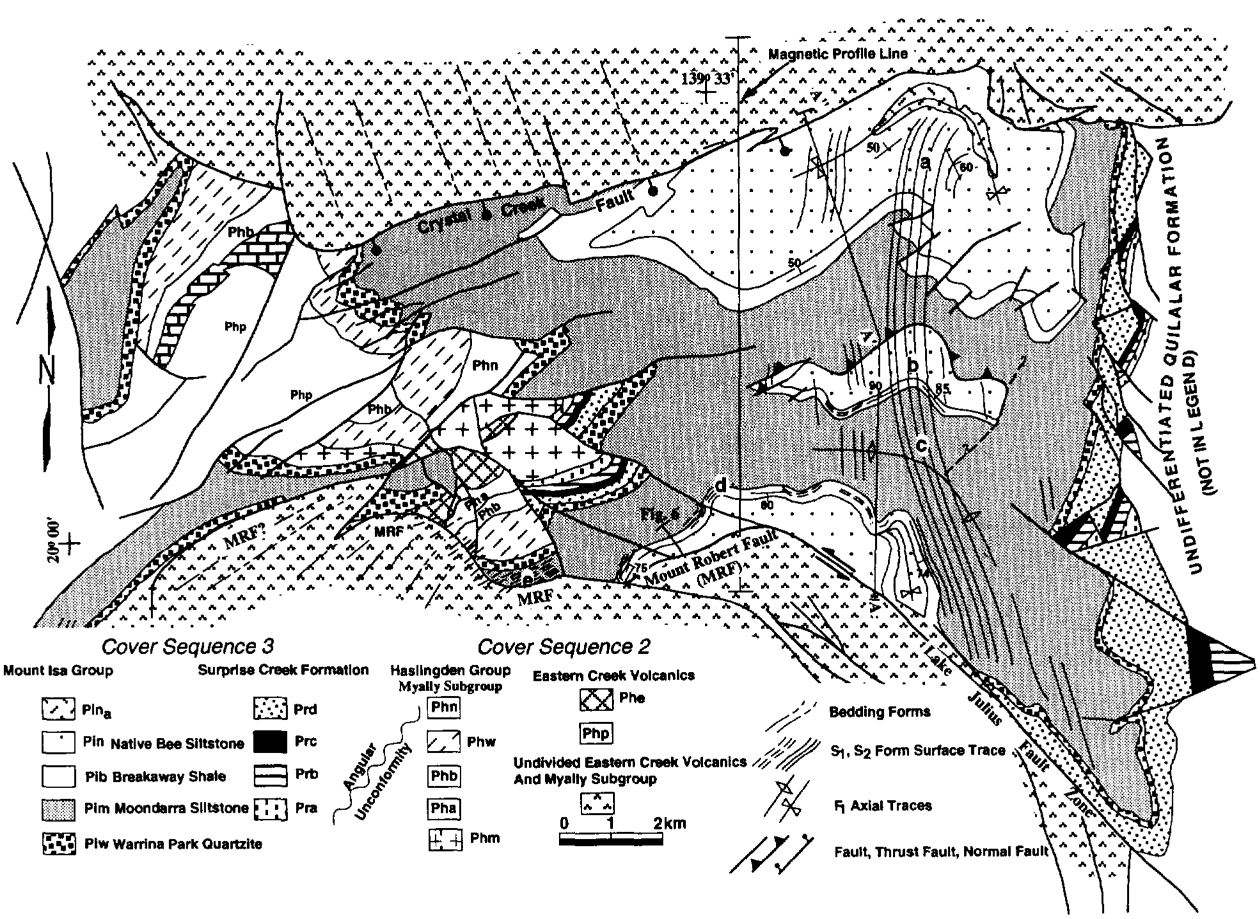

Fig. 4. Geological map compiled in part from the following BMR 1:100 000 maps—Prospector (1979), Alsace (1982), Myally (1984) and Kennedy Gap (1980). Structural data highlights domains of intense cleavage development (S_1 and S_2), folded axial surface traces, early thrusts and major bounding faults. Areas a–e refer to corresponding stereonet plots depicted in Fig. 7.

which is cut by a now steeply N-dipping, S-directed reverse fault (Fig. 5).

This early phase of shortening did not produce a regionally extensive first cleavage. The development of S_1 was controlled by fold tightness, and its distribution within folds was largely lithology dependent. S_1 is weakly-developed and patchy in the north where folds have interlimb angles of 80–90°. Dip-parallel slickensides observed on bedding planes are considered to reflect initial flexural slip folding. Towards the south, folds tighten and develop a weak to moderate, steeply-dipping, primary slaty cleavage within silty units. Despite weak cleavage development, small bedding–cleavage angles occur on the limbs of tight folds. This indicates that cleavage development commenced late in the folding history and was imposed on already steeply-dipping fold limbs. This may reflect a transition in folding mechanism from flexural slip to flattening presumably after fold limbs were no longer suitably oriented for bedding parallel slip (e.g. Gray & Willman 1991).

In the finest grained units, S_1 is defined by a continuous sub-parallel alignment of fine ($<10\,\mu$) syntectonic phyllosilicates and larger rotated detrital micas, which collectively dip roughly 10° steeper than bedding. In silty layers, S_1 has a slaty morphology defined by wavy discontinuous cleavage domains spaced at between 30–40 μ. Fine films of syntectonic white mica are aligned parallel to the cleavage domains and large detrital micas have an original bedding-parallel orientation which is often preserved within the microlithons. In places however, detrital grains appear to have been reoriented towards the cleavage through microfolding. Sutured grain boundaries, mica beards and apparent offsets across bedding all indicate a pressure solution origin for the cleavage, typical of sediments deformed at shallow crustal levels.

In the southwestern part of the Crystal Creek block, a zone of concentrated D_1 strain is localized adjacent to the Mount Robert Fault (Fig. 4, area e). In this area, S_1 is very well developed and the frequency and tightness of mesoscopic asymmetric F_1 folds increase, indicating an association between the accumulation of cleavage related strain and fault slip (cf. Marshak & Engelder 1985). These folds are first generation structures given the development of a primary axial planar cleavage and the absence of an earlier folded cleavage. Locally however, these rocks display a composite fabric wherein a spaced disjunctive cleavage developed in conjunction with the slaty cleavage. Spaced cleavage domains are ~1 mm apart but appear much more widely spaced in hand samples (0.5–2 cm). The two cleavages are approximately coplanar and generally parallel to the axial plane of mesoscopic folds, suggesting that both are related to the same overall folding event (cf. Gray 1981a). Microstructural evidence indicates that the spaced cleavage cross-cuts the slaty cleavage, providing a relative chronology between the two fabrics. Furthermore, while the spaced cleavage is axial planar to the folds in which it occurs, the slaty cleavage often transects the axial planes of these folds. Hinge migration related to fold flattening and reorientation adjacent to the Mount Robert Fault may explain the local transecting geometry of the slaty cleavage and overprinting nature of the spaced cleavage.

Along another segment of the Mount Robert Fault, local coaxial F_2 folds are developed. These folds contain a crenulation cleavage which has the same orientation and vergence as the regional S_1 (Fig. 6). This cleavage, however, is axial planar to crenulated bedding which does not display an earlier cleavage. It is postulated that the axial planes of some uncleaved F_1 folds may have locally been rotated into the shortening field adjacent to the Mount Robert Fault, resulting in coaxial refolding.

Phase two structures

North-trending second generation folds are open, have small wavelengths compared to F_1 folds, and display a regionally extensive N-trending vertical cleavage which is pervasive in both hand samples and thin sections (Fig. 4). Despite open fold profiles, widespread cleavage development indicates significant strain. This is considered to be a consequence of the mechanical difficulties associated with folding two non-parallel surfaces,

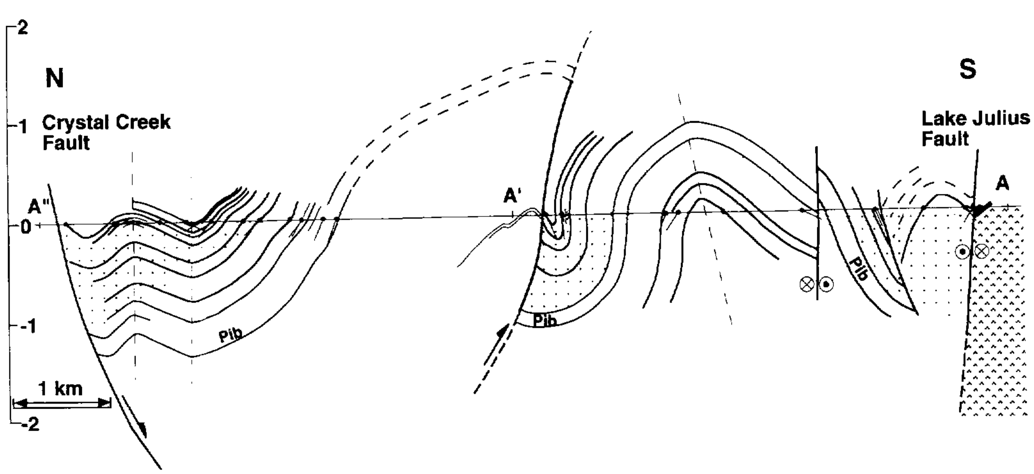

Fig. 5. Vertical N–S cross-section through the Crystal Creek block illustrating early fold and fault associations. This phase of deformation accomplished an estimated 30–35% shortening. Cross-section line is indicated on Fig. 4.

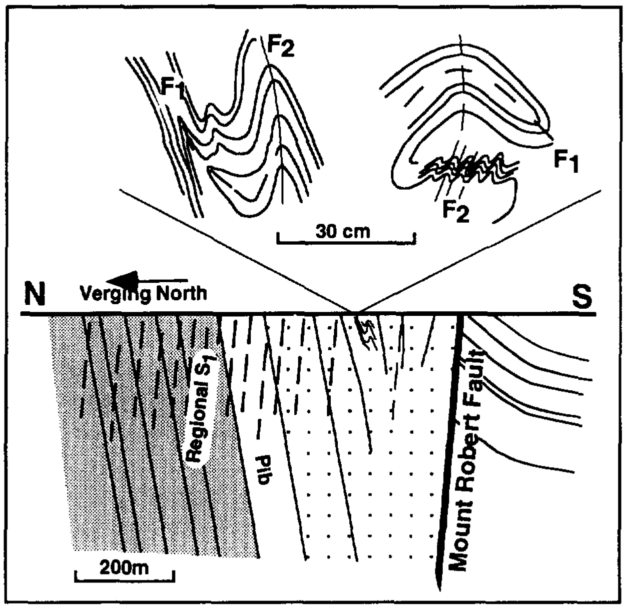

Fig. 6. Vertical cross-section illustrating the relationship between bedding, regional S_1 cleavage and coaxial refolding in the hangingwall of the Mount Robert Fault. The axial planes of some uncleaved F_1 folds may have locally been rotated into the shortening field adjacent to the Mount Robert Fault resulting in refolding. Location of cross-section is indicated on Fig. 4.

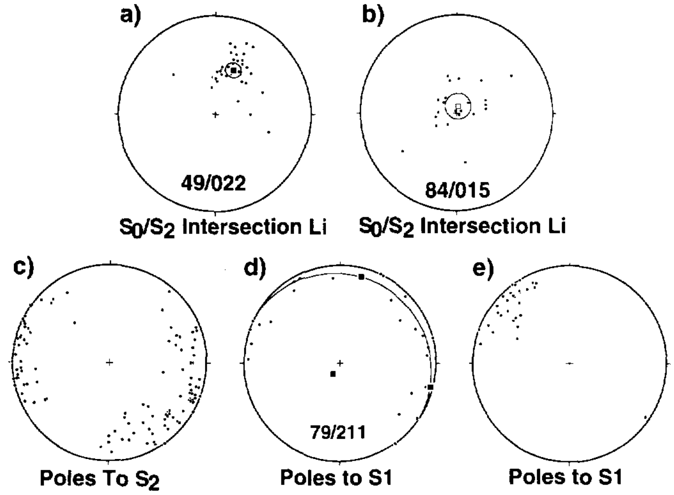

Fig. 7. Equal area stereonet plots (a)–(e) summarizing structural information at corresponding localities marked on Fig. 4; Li = lineation; values given for (a) & (b) represent the mean lineation.

such as pre-existing fold limbs, making flexural slip an unfavourable F_2 folding mechanism (e.g. Ramsay 1967, pp. 546–548, Ghosh 1974, Grujic 1993).

Since S_1 was only locally developed, the cleavage in most F_2 folds is a first generation fabric. However, by virtue of geometry, it is termed S_2. Depending on the rock type and structural position within F_2 folds, the morphology of S_2 varies from a spaced (~1 cm) stylolitic crenulation cleavage to a domainal slaty cleavage which has the same morphology as described for S_1. A 2 km wide N-trending corridor of intense S_2 cleavage is located in the eastern part of the Crystal Creek block. This cleavage appears to correlate with the regional N-trending folds developed north of the Crystal Creek block. Figure 7 summarizes the first and second phase structural features produced within the various domains of the Crystal Creek block.

FAULTING HISTORY

Southern bounding faults

The fault array which forms the southern bounding structure of the Crystal Creek block consists of several strands of intersecting fault segments of different ages. Contained within this array are: (a) fault breccias which are overprinted by and therefore predate S_1; (b) faults which were reactivated during the development of S_1 and belong to the Mount Robert Fault; and (c) faults which post-date S_2 and belong to the Lake Julius Fault Zone.

The Mount Robert Fault juxtaposes the Mount Isa Group to the north with the older Eastern Creek Volcanics to the south and displays a curved topographic trace with highly variable wallrock cut-off angles (between 0° and 90°). The easternmost section of the fault, which parallels bedding in the Mount Isa Group, dips steeply to the north and is pervasively silicified. Towards the fault, strain increases in the Mount Isa Group, marked by an intensification of the S_1 cleavage (Figs. 7e and 4, area e) and an increase in the frequency and tightness of mesoscopic F_1 folds.

Within fault rocks, the deformation of quartz-rich layers was dominated by intracrystalline mechanisms such as dynamic recrystallization, whereas phyllosilicate-rich horizons were dominated by pressure solution processes. Shear sense indicators are poorly developed and conflicting. Displacement-controlled curved fibres in pressure shadows imply a non-coaxial strain path, whereas zones of well-developed dynamically recrystallized conjugate shears suggest that faulting was associated with a large flattening component. Shallow to moderately plunging structures including fold axes, bedding–cleavage intersection lineations, and slickensides on the fault plane, all suggest a component of oblique-slip across this section of the fault.

Towards the west, the Mount Robert Fault changes orientation from ~E-striking to ~NW-striking leading to an abrupt increase in cut-off angle (~90°). In this region, highly silicified and chloritized fault breccias in the immediate wallrocks are cross-cut at ~30° by S_1. Thus, while bedding-parallel sections of the Mount Robert Fault indicate a synchroneity between fault slip and the accumulation of cleavage-related strain, sections such as this show evidence for the fault having existed before the development of S_1. Along the Mount Robert Fault, S_1 maintains a consistant orientation irrespective of fault strike and cut-off angle, indicating that the curved trace of the Mount Robert Fault must have been established no later than syn-S_1. We suggest, however, that the variations in cut-off angle along the Mount Robert Fault originated prior to S_1. For reasons outlined below, we propose that the Mount Robert

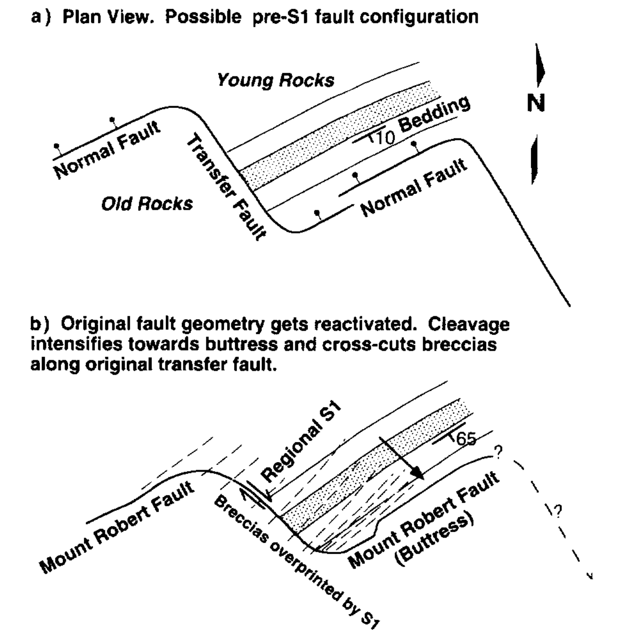

Fig. 8. (a) & (b) Schematic diagrams illustrating the relationship between the orientation of S_1 cleavage and the Mount Robert Fault (b) Along the Mount Robert Fault S_1 maintains a consistent orientation irrespective of fault strike and cut-off angle indicating that the curved trace of the Mount Robert Fault is not the result of later folding. We suggest that Mount Robert Fault was originally an extensional fault (a) that was reutilised during the development of S_1. The fault geometry, together with the stratigraphic separation and overprinted breccias, strongly support reverse-sense reactivation of an original normal fault.

Fault was originally an extensional fault which has been reutilized during the development of S_1 (Fig. 8).

The sense of stratigraphic separation across the Mount Robert Fault is inconsistent with reverse faulting, and shortening within the Mount Isa Group is incompatible with normal faulting. However, the emplacement of younger rocks in the hangingwall of faults which show evidence for horizontal shortening is admissible (but not unequivocal) evidence for structural inversion (Butler 1989). At upper crustal levels, extension commonly produces steeply-dipping normal faults which may terminate along strike against vertical transfer faults, resulting in contrasting wallrock cut-off angles (Etheridge 1986). Thus, the various segments of the Mount Robert Fault, with their associated changes in cut-off angles, may reflect an originally compound normal fault geometry.

It is proposed that during initial compression (local NW–SE?), bedding in the hangingwall of the Mount Robert Fault shortened against a relatively rigid footwall block belonging to a pre-existing extensional fault, generating upright folds and fault-parallel S_1 cleavage in the Mount Isa Group. The reactivation of the fault section associated with the large cut-off angles resulted in S_1 cross-cutting a pre-existing fault breccia at high angles (Fig. 8). While the stratigraphic separation across the Mount Robert Fault implies a net extension, it has clearly experienced substantial horizontal shortening. Based on cross-sections, for instance Fig. 5, first phase folds accomplished an estimated 30–35% shortening, during which time the Mount Robert Fault is interpreted to have remained active. However, due to the effects of superposed folding, the present F_1 fold configuration need not accurately reflect the original fold geometry (Grujic 1993), and estimates of percent shortening may be unreliable.

The Lake Julius Fault zone consists of a series of steeply-dipping, parallel, NW-striking faults. Movement on this fault system outlasted S_2 cleavage development and may represent the culmination of east–west shortening. This fault system extends for approximately 40 km southeast of the Crystal Creek block (Fig. 2) and displays similar timing relations with respect to S_2 cleavage along its entire length. The slip-sense across this fault is largely unconstrained. Axial zones of regional folds which are offset across this fault zone suggest that it is a left-lateral strike-slip fault which formed during a relatively late period of widespread wrenching, resulting in significant reorientation of pre-existing structures.

Northern bounding fault

The Crystal Creek Fault is the northern bounding structure of the Crystal Creek block (Fig. 4). It is an E-trending, steeply S-dipping (80°) brittle fault marked by a pervasively silicified fault breccia. The fault separates Mount Isa Group to the south from older Eastern Creek Volcanics to the north. This fault clearly cuts D_2 structures both within the Crystal Creek block and within neighbouring fault blocks. It is therefore interpreted to be a post-regional D_2 normal fault.

HETEROGENEOUS DEFORMATION AND PROBLEMS OF CORRELATION

The establishment of key localities, in which temporal relationships are both clear and informative, is an essential step in the process of structural correlation. This method has proved reasonably successful in well-exposed, unfaulted areas (Williams 1985). Within the Leichhardt River Fault Trough, the internal deformation of individual fault blocks can be determined using some of the established techniques of structural analysis (e.g. orientation, overprinting and style), but these methods become limited by the presence of faults, and variations in deformational response accompanied by lithological changes.

The Crystal Creek block is one such key locality because it contains structural orientations and generations which are not found in adjacent fault blocks and it has enough continuity for structural correlation. In much of the northern Crystal Creek block, F_1 folds are uncleaved, and N-trending S_2 is a first generation fabric and the only observable cleavage. Because of this, cleavage overprinting relationships are rarely developed. The fold interference pattern involves S_2 cleavage cutting across E-trending F_1 axial traces but is subparallel to N-trending F_1 axial traces (Fig. 4). In the N-trending domains, therefore, S_2 becomes indistinguishable from S_1 based on orientation and correlation is difficult because of the apparent axial plane orientation of the S_2 within F_1 folds. Despite the heterogeneous development of S_1, the consistent development of a first generation cleavage within F_2 folds is considered to suggest that F_1 and F_2 may have formed during the same overall deformation event.

Adjacent fault blocks do not record these fold interference patterns. They display ~N-trending regional-scale folds which are continuous for 10s of kilometres along their axial planes. The polyphase folding history of the Crystal Creek block, therefore, should not be used as a paradigm for that of the entire Leichhardt River Fault Trough. Its structural history (D_1, D_2 etc.) may carry little temporal significance on a regional scale since variations in deformational history between adjacent fault blocks may simply be due to heterogeneities in boundary conditions, rather than to different deformation events. In particular the correlation of cleavage forming events on the basis of their orientation has dubious value.

The mechanical behaviour of a stratigraphic sequence is governed not only by the intrinsic material properties of individual rock types, but by the relative strength of adjacent rocks. The manner, therefore, in which a stratigraphic sequence accommodates large plastic strains need not be consistent throughout. Within the Crystal Creek block, for example, there are domains which are characterized by contrasting deformation mechanisms. The eastern half consists of relatively ductile pelites and dolomitic siltstones, and is characterized by tight superposed folding and reverse faults. The western half of the Crystal Creek block consists of thickly-bedded arenites and volcanics and is dominated by widespread steep faulting and relatively minor folding.

Cleavage may also have influenced the mechanical properties of rocks within the Leichhardt River Fault Trough. For example, pressure solution associated with cleavage formation may actually be a stress relief mechanism at low pressures, reducing stress levels below the frictional strength of a rock and thus precluding faulting (Engelder & Marshak 1985). If this is were the case, then the mechanical properties of contrasting rock types in the Crystal Creek block may have been further affected by the development of cleavage. Stated otherwise, variations in lithology and associated cleavage formation will tend to enhance strain partititioning effects. For example, arenaceous rocks are generally low in clay content (<10%) and are therefore less inclined to form disjunctive cleavage at shallow crustal levels (Engelder & Marshak 1985). This, in addition to their inherent strength, makes them all the more likely to behave as stress guides and be prone to faulting. Pelites on the other hand, are generally more ductile which may be further enhanced by cleavage formation.

THE INTEGRATION OF STRUCTURAL GEOMETRY WITH MAGNETIC MODELLING

In the Crystal Creek block, the integration of surface observations with geophysical data may be used to help constrain the linkage between basement and cover rocks at the various structural levels currently exposed. Field relations suggest that the Mount Isa Group sediments deformed differently from the underlying strata, and magnetic modelling provides a relatively unbiased way of testing this hypothesis.

The Crystal Creek block exposes non-magnetic sediments of the Mount Isa Group and is surrounded almost entirely by much older, highly magnetic Eastern Creek Volcanics. Magnetic anomalies observed over the Mount Isa Group can therefore be interpreted to be related to the relief of the underlying magnetic basement. This makes it possible to model the geometry of the magnetic basement beneath the Crystal Creek block and determine if it is folded harmonically with the overlying sediments, or whether the two levels were decoupled during deformation.

An interactive $2\frac{1}{2}$-dimensional gravity/magnetic modelling package called *MacOnTrack* (Monash University 1994) was used for magnetic forward modelling. Magnetic profiles extracted from regional airborne datasets were imported and displayed above a drawing area. Rough geological cross-sections were drawn which were constrained by field mapping. Values for magnetic susceptibility were assigned to various rock units, and the magnetic response was calculated and displayed above the drawing area next to the imported profile. The rock properties and geometry of the cross-sections were then modified until a close match between actual and computed profiles was obtained.

The Crystal Creek block was modelled as a dipping prism which tapers towards the south and is truncated to the north by the Crystal Creek Fault (Figs. 9a & b). This prism of Mount Isa Group is surrounded laterally and below by Eastern Creek Volcanics. Magnetic susceptibilities of 0.003 and 0.0002 SI were assigned to the Eastern Creek Volcanics and the Mount Isa Group, respectively. These values are within the range of intrinsic susceptibilities for these rock types measured in other localities within the Leichhardt River Fault Trough (Leaman 1991). When the contact between the Mount Isa Group and the underlying Eastern Greek Volcanics is modelled as a shallowly N-dipping planar surface, the computed profile matches the actual one. This correlation is not significantly altered when any individual point along the interface is shifted less than ~150 vertical metres. Small changes (0.0001 SI) to the magnetic susceptibilities have a negligible effect on the correlation of the two profiles. However, if the contact is modelled as being tightly folded to match the cover geometry, the magnetic response does not agree with the actual profile. The geometry of this relatively planar interface is thus in marked contrast with the tight folds developed in the overlying Mount Isa Group.

The surface geology of the Crystal Creek block is

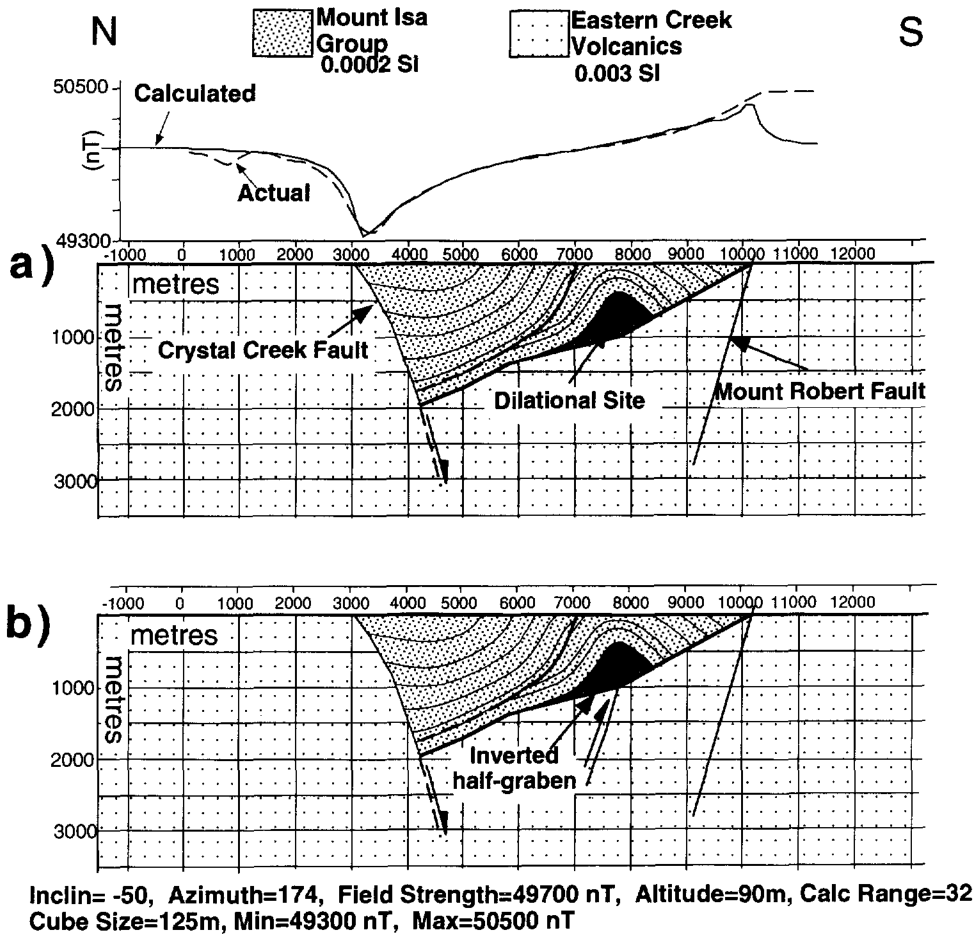

Fig. 9. Two structural interpretations of a north–south forward magnetic model across the Crystal Creek block. The interface between the Mount Isa Group and the Eastern Creek Volcanics is modelled as a shallowly N-dipping planar surface which is in marked contrast with the upright anticline in the overlying Mount Isa Group. The northern limb of this anticline flattens at depth while the southern limb remains at high angles to the interface. Model (a) introduces a large dilational site in the core of the anticline. Model (b) offers a structural interpretation based on inversion. Invoking an inverted half-graben in the core of the anticline resolves space problems and reconciles apparently conflicting geometrical relationships. The actual magnetic profile was extracted from an aeromagnetic survey which had a flight line spacing of 400 m. Location of this profile is indicated on Fig. 4.

characterised by a large upright syncline–anticline pair, whereas the magnetic interface is a relatively planar surface. When the surface geology is extrapolated to depth, apparently conflicting geometrical relations arise. Bedding on the southern limb of the anticline is at high angles to the interface implying a fault contact, whereas its northern limb becomes parallel to the interface suggesting a possible stratigraphic contact (Figs. 9a & b).

There are several ways of explaining the existence of upright folds above a planar interface. Firstly, the interface may be a fault which truncates and is genetically unrelated to the folds above it. This is considered unlikely since there is no field evidence in the Leichhardt River Fault Trough for shallow faults which postdate regional compressional structures. Secondly, the interface may be a syn-folding décollement horizon separating the Mount Isa Group from the underlying Eastern Creek Volcanics. A consequence of this model is that it requires the existence of a large dilational site in the core of the antiform and/or complex thrust geometries along the interface (Fig. 9a). This possibility is conceptually appealing and might have exploration potential. However, there is another explanation for the origin of this geometry which is consistent with that expected from the shortening of previously extended crust.

Structural inversion commonly produces the geometrical relations described above (e.g. Hayward & Graham 1989, Williams *et al.* 1989). During the inversion of a half-graben, much or all of the extensional displacement across pre-rift rocks is removed, causing the extrusion of the graben fill and the formation of an anticline in the overlying sag-phase sediments (Fig. 10). This geometrical model predicts the existence of an upright tapering anticline above an unfolded surface, and allows for large changes in bedding cut-off angles with the interface on either limb of the anticline. It is reasonable to infer therefore, that the core of the anticline in the Crystal Creek block contains the contents of an inverted half-graben (Fig. 9b). The rift phase which preceded the deposition of the Mount Isa Group produced many half-graben which were filled with detritus of the Surprise Creek Formation (as well as the red-beds and volcanics of the Bigie Formation). This is what we predict will be found to occupy the core of the anticline in the Crystal Creek block.

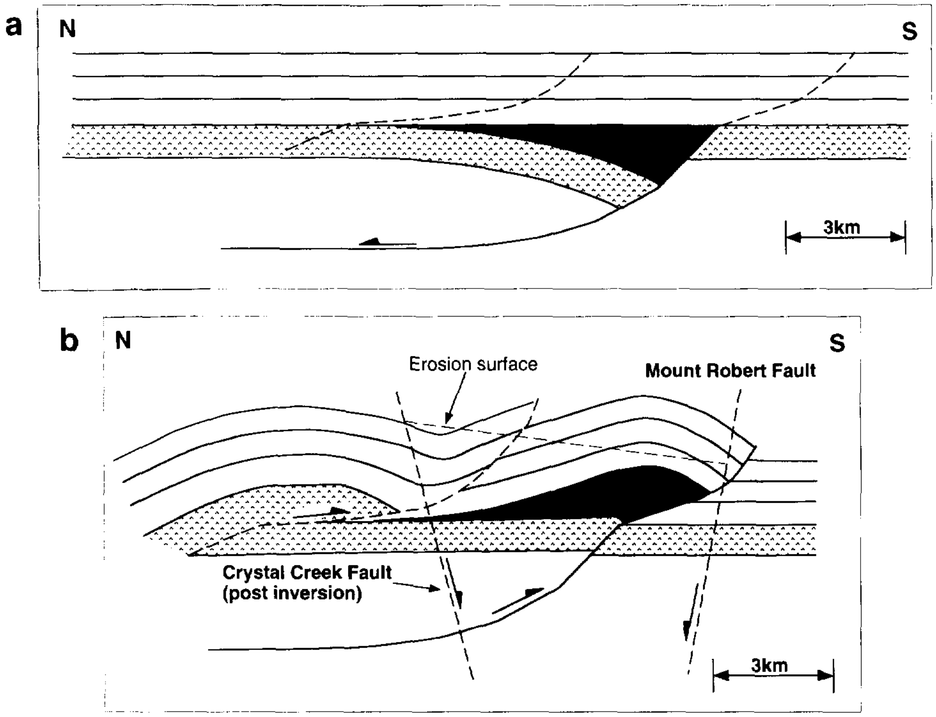

Fig. 10. (a) Development and (b) subsequent inversion of a half-graben. A 'classical' geometrical interpretation requires that the Mount Robert Fault be a normal fault postdating inversion. It also demands the development of a through going thrust, causing repetition of the Eastern Creek Volcanics. Field evidence for these requirements is lacking.

The inversion geometry depicted in Fig. 10 is a 'classical' interpretation based on principles of balanced cross-sections and chevron construction (e.g. Williams & Vann 1987). Half-graben are shown filled with Surprise Creek Formation and overlain by Mount Isa Group (Fig. 10). Thrusts, developed during later compression, are localised along pre-existing faults and lead to their reverse-sense reactivation. Although this technique can explain the gross geometry of the Crystal Creek block, it is limited by the assumptions that relate all hangingwall structure to footwall geometry. It does not offer a link between fault displacement and distributed strain, and it ignores the influence of rock composition on deformational style. In their implicit assumptions, balanced cross-sections are unable to handle the scenario developed in this paper.

An alternate inversion model that integrates fault slip, penetrative deformation and competency contrast is depicted in Fig. 11. This model reflects the variability in deformational style of the rocks within the Crystal Creek block, and exemplifies some of the relations presented in this paper. In this model, fault displacement is converted into distributed strain against the Mount Robert Fault buttress, and thrusting in the Mount Isa Group is related to localized buckling rather than a through going structure which soles out at greater depth.

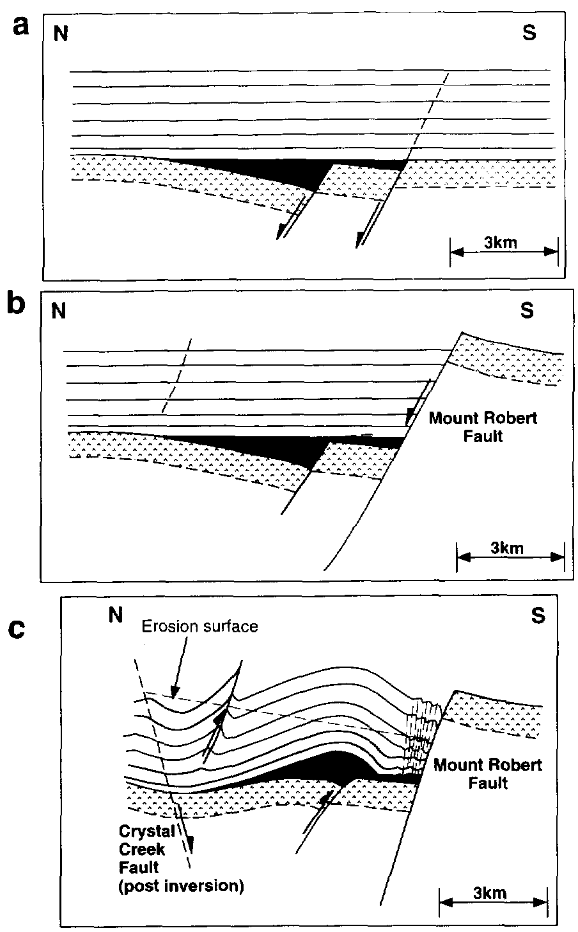

Fig. 11. (a) & (b) Development of and (c) subsequent inversion of a half-graben. This model is consistent with field relationships and better reflects the variability in deformational style of the rocks within the Crystal Creek block. Fault displacement is converted into distributed strain against the Mount Robert Fault, and thrusting in the Mount Isa Group is related to localised buckling.

DISCUSSION

Structural analysis and magnetic modelling within the Leichhardt River Fault Trough support inversion tectonics as the cause of some of the present variations in deformational style, structural orientation and stratigraphic associations. Furthermore, inversion neatly explains locally occurring structural complexities without having to introduce a regionally extensive décollement surface at the base of the Mount Isa Group. The features described above conform well to those found in highly inverted basins, and the deformational history resembles those presented for the Ketchika Trough of British Columbia (McClay *et al.* 1989) and for the margin of the French Alps (Gratier & Vialon 1980, de Graciansky *et al.* 1989, Butler 1989).

Recognizing the interaction between basin architecture and basin-fill rheology is essential to understanding why adjacent domains in the Leichhardt River Fault Trough recorded seemingly distinct deformational histories during shortening. Inversion models acknowledge this interaction and go a long way in explaining why many structural patterns developed in the stratigraphically highest cover sequences do not occur in adjacent fault blocks which expose older rock types. Inversion simultaneously removes extensional displacement across pre-rift rocks and induces folds and faults in overlying post-rift rocks. This leads to the development of two structural levels characterized by different deformational styles and apparently distinct deformational histories.

Variations in structural history between fault blocks which expose contrasting stratigraphic levels must reflect mechanical responses to the same deformation event since displacement across bounding faults has probably not juxtaposed rocks deformed at different crustal levels. In the Leichhardt River Fault Trough, Mount Isa Group rocks developed fold and thrust features associated with wide zones of distributed strain. These developed in conjunction with fault reactivation (and cleavage formation) at depth during the initial shortening of previously extended crust.

Any pre-existing fault geometry would have played a significant role in controlling the structural patterns during later shortening. The fact that fold interference patterns occur only in the stratigraphically highest sediments (Mount Isa Group), supports the fact that they were deposited on a complex pre-existing architecture. When subjected to a regional shortening event, this architecture reactivated to produce variably oriented folds in the overlying sediments. Buttressing against basement faults partitioned the deformation in the Mount Isa Group, producing locally developed corridors in which the cleavage orientation and intensity reflect the proximity to and orientation of the underlying structural architecture. In such a manner, a single phase of regional shortening (oriented NW–SE?), interacting with a pre-existing architecture, may be responsible for the observed deformational pattern. Local cleavage orientations therefore, need not represent regional shortening directions corresponding to discrete deformation events. Similarly, superposed folding may be a consequence of changes in the distribution of partitioned strain with time.

It is probable that the polyphase folding history of the Crystal Creek block resulted during a single regional deformation. Nevertheless, ongoing studies in other parts of the Leichhardt River Fault Trough may lend themselves well to a more classical interpretation wherein D_1 and D_2 structures can be considered to have formed during discrete regional events.

CONCLUSIONS

The structural interpretations we impose on the Leichhardt River Fault Trough are influenced greatly by our preconceptions of the original geometry and by the presumed tectonic class of deformation. While many map-scale relations can be rationalised in terms of thrusting and/or wrenching, both fail to explain fully the diversity of fault patterns and structural associations of the region.

Using the Crystal Creek block as an example, we demonstrated that some of the structural complexities developed in the Leichhardt River Fault Trough are due to structural inversion and buttressing against pre-existing basin bounding faults. Inversion predicts the development of upright folds above an unfolded surface, and illustrates how changes in deformational style with stratigraphic level can reflect a transition from reverse-fault reactivation at depth to distributed strain in higher level cover rocks.

Within the Crystal Creek block the earliest phase of shortening produced E-trending regional-scale folds locally accompanied by a first generation slaty cleavage. An increase in both the intensity of S_1 and the tightness of mesoscopic F_1 folds towards one segment of the Mount Robert Fault indicates a genetic relation between fault slip and early cleavage development. Abrupt changes in cut-off angles along this fault however, together with pre-S_1 fault breccias, hangingwall strain gradients, and the sense of stratigraphic separation are considered to reflect the reactivation of a pre-existing extensional fault. The integration of surface mapping with forward magnetic modelling supports the existence of an inverted half-graben beneath the Crystal Creek block. This helps explain why local upright E-trending folds only developed in high level cover rocks and not at deeper stratigraphic levels exposed in adjacent fault blocks.

Inversion tectonics relieves many of the problems of correlation since adjacent fault blocks which exposed different stratigraphic levels would not be expected to have developed the same family of structures. Furthermore, local cleavage orientations need not represent regional shortening directions. Variations in deformational history between adjacent fault blocks may have arisen from heterogeneities in boundary conditions rather than from different deformation events.

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