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Three-dimensional structure along the inverted Palaeoproterozoic Fiery Creek Fault System, Mount Isa terrane, Australia

Peter G. Betts*

Australian Crustal Research Centre, Department of Earth Sciences, Monash University, Melbourne 3168, Australia

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Abstract

The NW-dipping Fiery Creek Fault System, located in the northern Mount Isa terrane, comprises numerous sub-parallel faults that record multiple episodes of Palaeo- to Mesoproterozoic movement. Hanging wall wedge-shaped stratal geometries and marked stratal thickness variation across the fault system indicate that the earliest movement occurred during episodic intracontinental extension (Mount Isa Rift Event; ca. 1710–1655 Ma). Reactivation of the fault system during regional shortening and basin inversion associated with the Mesoproterozoic Isan Orogeny (ca. 1590–1500 Ma) resulted in complex three-dimensional hanging wall geometries and highly variable strain in the hanging wall strata along the fault system. This has resulted in the development of discrete hanging wall deformation compartments, that are characterised by different structural styles. High strain compartments are characterised by relatively intense folding and the development of break-back thrusts, whereas low strain compartments are only weakly folded. Variations in hanging wall strain are attributed to selective reactivation of normal fault segments, controlled by the pre-inversion fault dip and lithological contrasts across the faults. Variation of the pre-inversion fault dip is interpreted to have been caused by episodic tilt-block rotation during crustal extension. Moderately dipping faults active early in the Mount Isa Rift Event show the greatest degree of reactivation, whereas younger and steeper normal faults have behaved as buttresses during inversion with strain focussed in zones of upright folding in the hanging wall. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Fiery Creek Fault System; Intracontinental extension; Folding; Basin inversion; Fault reactivation; Isan orogeny; Reactivation

1. Introduction

Reactivation of normal faults in inverted extensional basins is an important consideration when analysing the geometry and evolution of poly-deformed terranes. Late reverse movement along normal faults commonly obscures the original normal displacement, leading to misinterpretation of kinematic histories. In extreme basin inversion, the pre-shortening history of a fault may be completely obliterated. Failure to identify the influence of a pre-existing structural template also leads to misinterpretation of the significance of local structural geometry and strain intensity, as well as regional shortening directions (see O'Dea and Lister, 1995).

Previous discussions of inverted fault systems have focused on fault geometry (Williams et al., 1989) and the orientation of the stress axes with respect to the fault orientation (e.g. Etheridge, 1986; Sibson, 1995). The effects of along-strike variations, fault segmentation, or the differences in the behaviour of normal fault segments on the three-dimensional geometry of basin inversion-related structures have recently been considered (e.g. Kelly et al., 1999). This variation in the three-dimensional geometry results because the outcrop traces of many normal faults are not always continuous, but rather faults are composed of discrete strands or segments (Willemse et al., 1996) that commonly have variations in dip and along-strike orientation. These segments may be separated by relay zones (Trudgill and Cartwright, 1994), fault step-overs and jogs (Stewart and Taylor, 1996; Willemse et al., 1996), and steeply dipping transfer or accommodation zones (Lister et al., 1986; Rosendahl et al., 1986; Gibbs, 1990).

This paper is based on field observations along the Fiery Creek Fault System, which is located in the Palaeo- to Mesoproterozoic northern Mount Isa terrane (Fig. 1a). Mesoproterozoic shortening during the Isan Orogeny (ca. 1590–1500 Ma) was relatively mild in this part of the terrane, making it an ideal locality to assess the early

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* Tel.: +61-3-9905-5761; fax: +61-3-9905-5062.
E-mail address: pbetts@mail.earth.monash.edu.au (P.G. Betts).

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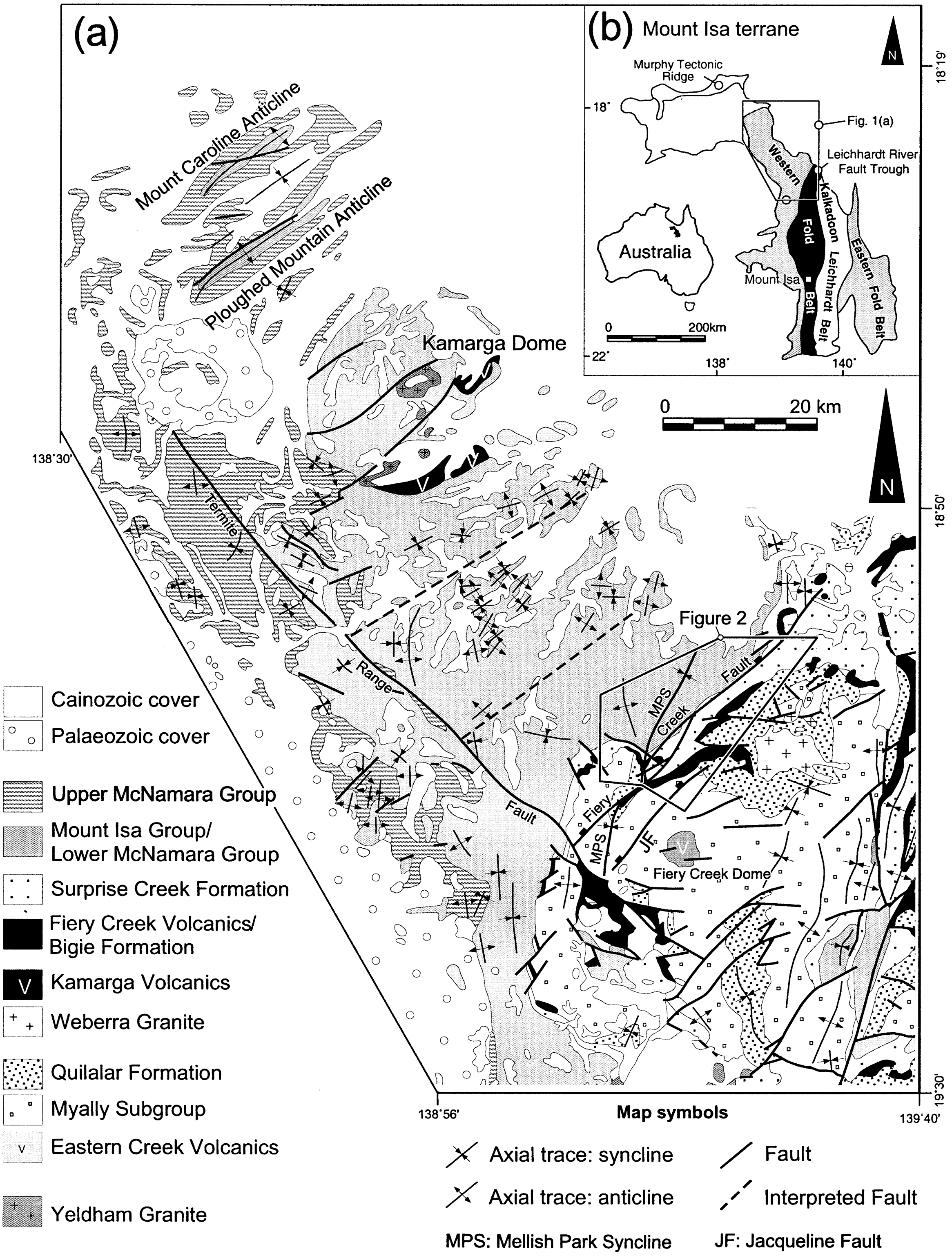


Fig. 1. (a) Map of the northern Mount Isa terrane showing the major stratigraphic divisions of the Isa Superbasin and Leichhardt Superbasin, and the architecture of extensional faults active during the Mount Isa Rift Event throughout the northern Mount Isa terrane and their spatial association with axial traces of major folds (adapted after Blake, 1987b). The location of the study area is shown. (b) Map of the major tectono-stratigraphic domains of the Mount Isa terrane.

extensional basin history and subsequent basin inversion (Betts et al., 1999). This paper illustrates the three-dimensional geometry and strike-parallel variations in structural style and strain intensity along the inverted Fiery Creek Fault System (Fig. 1a). These variations are related to the pre-shortening fault geometry, the way in which individual fault segments are linked and rheology contrasts across fault segments. These features developed in response to episodic development of half graben during the multistage evolution of the basin prior to inversion.

2. Geological setting

The NE-striking, NW-dipping Fiery Creek Fault system is located in the northern part of the Western Fold Belt of the Mount Isa terrane (Figs. 1 and 2). This part of the Mount Isa terrane records a protracted and episodic history of intra-cratonic basin development and subsequent basin inversion during the Isan Orogeny (Betts et al., 1998, 1999; Betts, 1999). Aspects of the extensional history (ca. 1800–1590 Ma) and its associated basin architecture are documented in Derrick (1982), O'Dea et al. (1997b), Betts et al. (1998, 1999), Scott et al. (1998) and Southgate et al. (1998). Supracrustal sequences were deposited onto metamorphic and granite basement during three major extensional episodes, resulting in the development of two unconformity-bounded basins (O'Dea et al., 1997b). These basins are termed the Leichhardt Superbasin (ca. 1800–1740 Ma) and the Isa Superbasin (ca. 1710–1590 Ma) (Scott et al., 1998; Betts et al., 1999; Southgate et al., 1998).

The Leichhardt Superbasin evolved during two superimposed extensional events. The Leichhardt Rift Event (ca.1800–1760 Ma) involved ~E–W directed extension resulting in the development of an elongate rift axis, the Leichhardt Rift (O'Dea et al., 1997b). A thick succession (up to 8 km) of continental tholeiitic basalt and clastic sediments was deposited (Eriksson et al., 1993). The Leichhardt Rift was overprinted by numerous E–W trending cross-rift normal faults during the Myally Rift Event (ca. 1760–1740 Ma) (O'Dea et al., 1997b). Clastic and dolomitic sequences were deposited into a south-tapering half graben. These were then overlain by sag-phase quartzite and carbonate sequences. A period of mild basin inversion then ensued, resulting in uplift and erosion of the Leichhardt Superbasin and localised folding (Betts, 1999).

Renewed crustal extension during the Mount Isa Rift Event (ca. 1710–1655 Ma: Betts et al., 1998, 1999) heralded the development of the Mount Isa Rift which was superimposed on the Leichhardt Rift. Fluvial and shallow marine syn-rift clastic sequences were deposited, and rift-related bimodal volcanic rocks erupted between ~1708 and 1694 Ma (Page and Sweet, 1998; Scott et al., 1998; Betts et al., 1999; Page et al., 2000). Multiple generations of normal faults formed at this time (Betts et al., 1999). First generation faults formed during deposition of basal, coarse clastic sequences and bimodal volcanism of the Bigie Formation and the Fiery Creek Volcanics, respectively (Fig. 3). Second generation faults were active during the deposition of shallow marine siltstone of the lower Gunpowder Creek Formation (Fig. 3) (Betts et al., 1999).

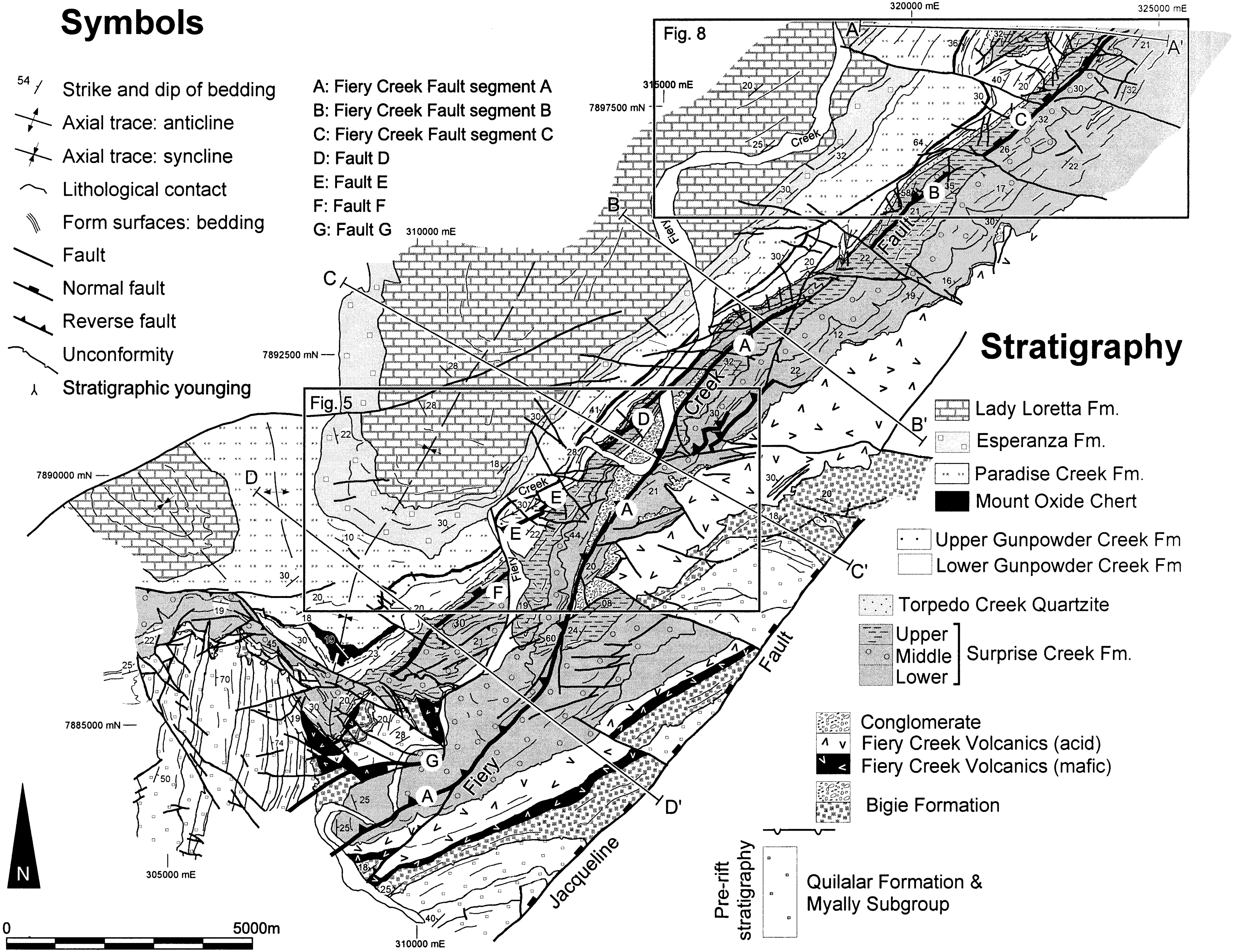
A depositional hiatus then ensued to the west of the Mount Isa Rift. This hiatus was caused by thermal uplift due to shallow level granite emplacement (Betts et al., 1998; Scott et al., 1998) combined with asthenospheric upwelling and mafic underplating associated with asymmetric lithospheric extension (Betts et al., 1998). At this time syn-rift sequences of the Bigie Formation and the Surprise Creek Formation continued to accumulate in the rift depocentre.

The post-rift depocentre (ca. 1650–1590 Ma) of the Isa Superbasin shifted from the Mount Isa Rift to the Lawn Hill Platform (Betts et al., 1998; Scott et al., 1998) and shallow marine carbonate (Dunster and McConachie, 1998), and deeper water clastic and carbonate sequences were deposited (Andrews, 1998) at this time. Reactivation of pre-existing extensional faults and volcanic activity continued episodically throughout the post-rift evolution of the Isa Superbasin (Andrews, 1998; Page and Sweet, 1998; Rohrlach et al., 1998; Scott et al., 1998).

Basin development was interrupted by the Isan Orogeny (ca. 1590–1500 Ma) (Bell, 1983; Blake, 1987a; O'Dea et al., 1997a; Lister et al., 1999). In the Leichhardt River Fault Trough (Fig. 1b), early E–W trending folds are overprinted by large-scale N–S oriented crustal-scale folds and associated cleavages (O'Dea et al., 1997b; Lister et al., 1999). Upper amphibolite facies metamorphism occurred in the southern and eastern parts of the terrane (Jacques et al., 1982; Rubenach and Barker, 1998; Giles, 2000) while sub-greenschist to lower amphibolite facies metamorphic conditions were prevalent in the western and northern parts of the terrane (Blake, 1987a). Strike-slip faulting dominated the late stages of the Isan Orogeny (O'Dea et al., 1997a; Lister et al., 1999). There are marked differences in strain intensity across the terrane. Shortening is mild in the northern Mount Isa terrane and increases to the south and east.

3. Palaeoproterozoic stratigraphy

The oldest rocks preserved in the study area (Figs. 1a and 2) are continental tholeiitic basalt and intercalated quartzite and sandstone of the Eastern Creek Volcanics (Fig. 3). Aeromagnetic modelling of this volcanic unit suggests it is ~2 km thick (Betts, 1997). The overlying Myally Subgroup (Fig. 3) is dominated by clastic sandstone and siltstone sequences that become increasingly dolomitic towards the top. The Myally Subgroup is approximately 2.5 km thick (Betts, 1997). The overlying Quilalar


Symbols
54 Strike and dip of bedding
Axial trace: anticline
Axial trace: syncline
Lithological contact
Form surfaces: bedding
Fault
Normal fault
Reverse fault
Unconformity
Stratigraphic younging
A: Fiery Creek Fault segment A
B: Fiery Creek Fault segment B
C: Fiery Creek Fault segment C
D: Fault D
E: Fault E
F: Fault F
G: Fault G
Stratigraphy
Lady Loretta Fm.
Esperanza Fm.
Paradise Creek Fm.
Mount Oxide Chert
Upper Gunpowder Creek Fm
Lower Gunpowder Creek Fm
Torpedo Creek Quartzite
Upper
Middle
Lower
Surprise Creek Fm.
Conglomerate
Fiery Creek Volcanics (acid)
Fiery Creek Volcanics (mafic)
Bigie Formation
Pre-rift stratigraphy
Quilalar Formation & Myally Subgroup
Fig. 8
Fig. 5
320000 mE
325000 mE
315000 mE
310000 mE
305000 mE
7897500 mN
7892500 mN
7890000 mN
7885000 mN
A
A'
B
B'
C
C'
D
D'
Fiery Creek Fault
Jacqueline Fault
Fiery
Creek
N
0
5000m

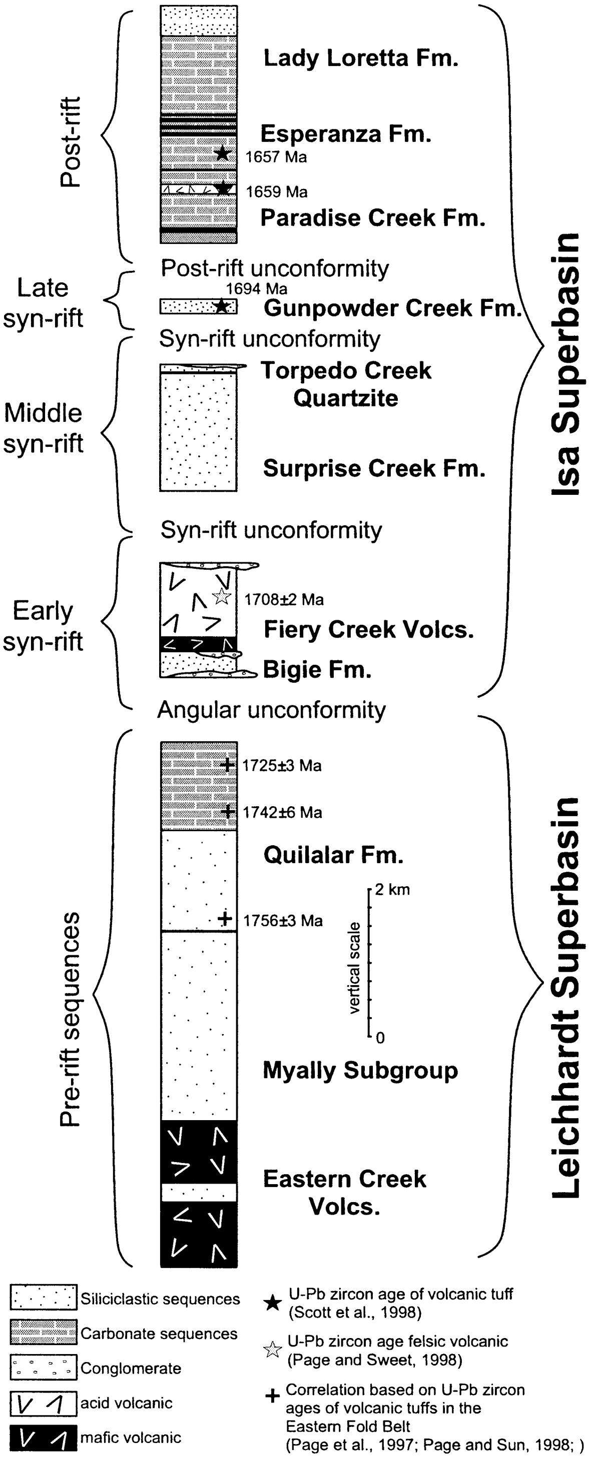


Fig. 3. Summary diagram of the stratigraphy in the vicinity of the Fiery Creek Fault System (adapted after Betts et al., 1999).

Formation is composed of a basal quartzite overlain by interbedded dolomitic siltstone and shale (Jackson et al., 1990), and is ~2.2 km thick (Fig. 3) (Betts et al., 1999). These formations were deposited into the Leichhardt Superbasin (Fig. 3) and form the pre-rift sequences to the Isa Superbasin.

Unconformably overlying sequences deposited into the Leichhardt Superbasin are the texturally and compositionally immature clastic sandstone and conglomerate of the Bigie Formation (Fig. 3), the basal formation of the Isa Superbasin. The exposed thickness of this formation varies up to 280 m, reflecting its wedge-shaped stratal geometry (Betts et al., 1999). The thickest accumulations are confined to the hanging wall of the Jacqueline Fault and the Fiery Creek Fault System (Fig. 2).

A relatively thick (750 m) accumulation of Fiery Creek Volcanics (Fig. 3) basalt flows and rhyolite breccia flows occur along the Fiery Creek Fault System. These are overlain by the Surprise Creek Formation (Fig. 3) which comprises interbedded micaceous sandstone and siltstone (lower member), quartzite, quartz sandstone (middle member), and interbedded siltstone and fine grained sandstone (upper member). Along the Fiery Creek Fault System the thickness of the Surprise Creek Formation ranges from 300 to 900 m. The overlying Torpedo Creek Quartzite is a relatively thin (<70 m) quartz sandstone and quartzite horizon (Fig. 3). This unit is confined to the hanging wall of the Fiery Creek Fault System and thins southward, where it becomes absent from the stratigraphy (Fig. 2), suggesting a period of uplift and erosion before deposition of the overlying Gunpowder Creek Formation.

The Gunpowder Creek Formation is the uppermost syn-rift sequence of the Isa Superbasin (Betts et al., 1999), comprising fine-grained sandstone and siltstone (Betts et al., 1999). The regional thickness of this formation is highly variable between 50 and 300 m, reflecting deposition into southeast thickening half-graben (Betts et al., 1999). Along the Fiery Creek Fault System the Gunpowder Creek Formation is ~100 m thick.

Outcrops of the dolomitic post-rift sequences of the Isa Superbasin are restricted to the hanging wall of the Fiery Creek Fault System and the core of the Mellish Park Syncline (Fig. 2). Post-rift sequences of the Paradise Creek Formation, Esperanza Formation, and Lady Loretta Formation comprise intercalated dolomitic sandstone, siltstone, and shale with abundant stromatolite and chert horizons (Fig. 3).

4. Fiery Creek Fault System

The Fiery Creek Fault System extends ~40 km northeast from the Termite Range Fault (Betts et al., 1998, 1999) to the exposed limit of the northern Mount Isa terrane (Fig. 1a). The master fault along the fault system is the Fiery Creek Fault. This fault comprises three sub-parallel segments (segments A, B, and C; Fig. 2) which are semi-continuous

Fig. 2. Geological map of the Fiery Creek Fault System and the Mellish Park Syncline. The map shows the distribution of fault segments and fault strands, and locations of major stratigraphic horizons (adapted after Betts, 1997). The location of cross-sections presented in Fig. 6 are also shown.

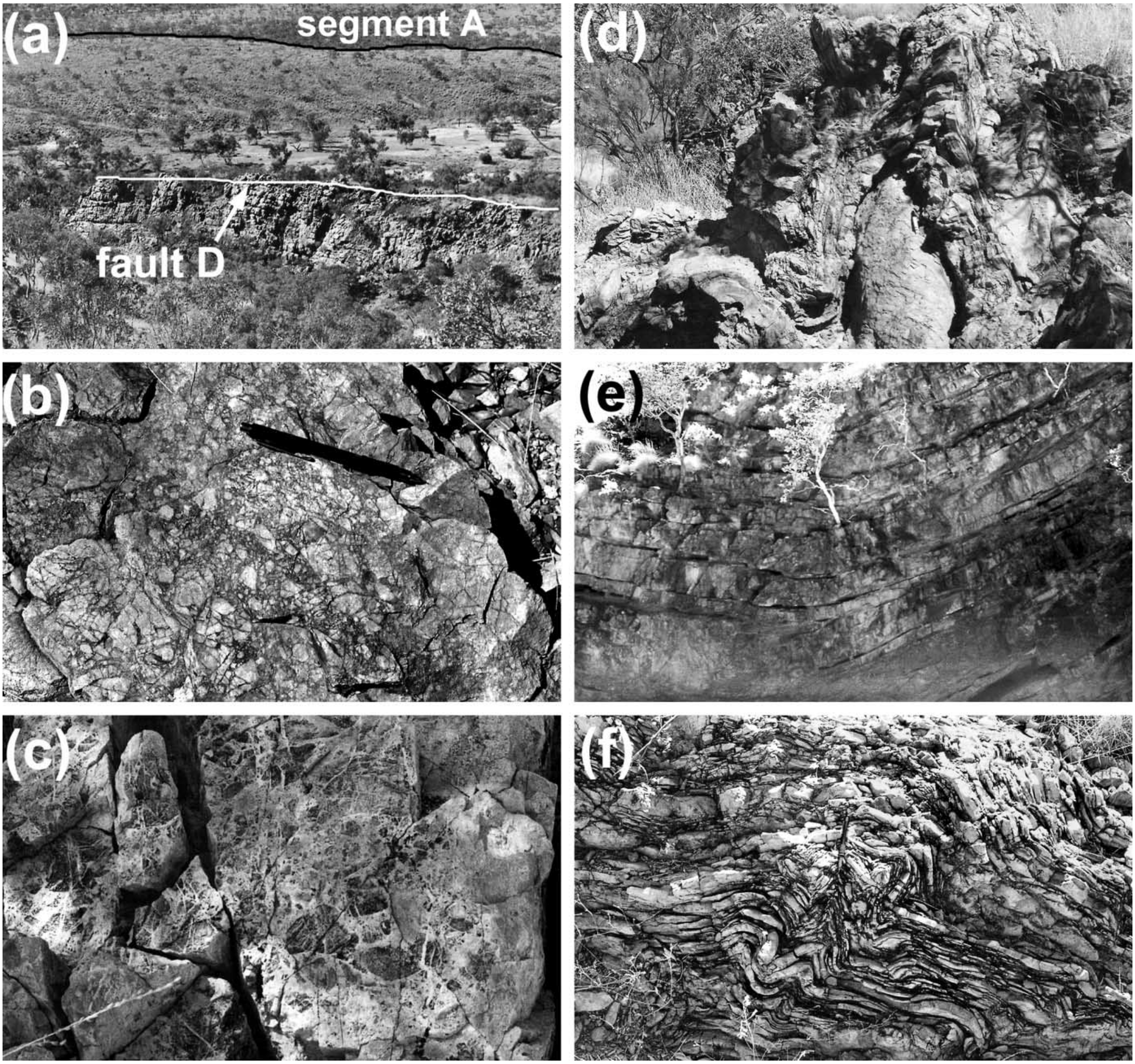


Fig. 4. (a) Photograph of fault D taken from the hanging wall looking to the east. The location of fault segment A is shown in the background. (b) Fault breccia at the margin of segment C. This breccia contains fragments of pre-existing silicified fault rock. (c) Brecciated fault zone containing fragments of arkose and siltstone from the surrounding country rock (fault D). (d) Disharmonic and non-cylindrical folds within siltstone in the immediate hanging wall of fault D. Photograph taken looking to the south. (e) Open fold developed within the Gunpowder Creek Formation in the hanging wall approximately 300 m from fault D. (f) Small-scale folds developed within the upper Surprise Creek Formation in the immediate hanging wall of fault segment C.

along strike but are separated by transverse faults. These segments have variable length between 1 and 12 km. A single fault segment C defines the northern part of the fault system (Fig. 2). To the south, the fault system widens to ~3 km and is defined by fault segment A and several sub-parallel synthetic fault strands which are preserved in the hanging wall of the master fault (Fig. 2). Fault strands have smaller strike lengths compared with the master fault but are nonetheless important because they preserve aspects of the fault movement history and have influenced the hanging wall structure during basin inversion. The dip and apparent sense of offset between the segments of the master fault and the subordinate fault strands changes along strike. Reverse offset is preserved along segment A. The sense of offset along segment B varies from normal in the south to reverse in the north, and normal offset is preserved along the entire length of segment C. Individual faults along the Fiery Creek Fault System dip between 65 and 85° to the northwest (Fig. 4a).

Several transverse faults have developed in the hanging wall and footwall of the fault system. Transverse faults have sub-vertical dips but vary in strike between 270 and 345°, although the majority are orthogonal to the Fiery Creek Fault System (Fig. 2). Several strands of the Fiery Creek Fault System terminate against transverse faults suggesting that transverse faults may have accommodated along-strike variations in normal fault nucleation (Betts et al., 1999). Other transverse faults abut normal fault strands (Fig. 2). These faults are interpreted to have allowed variation in throw along individual fault segments (Betts et al., 1999).

The fault system is eroded such that syn-rift sequences deposited during the Mount Isa Rift Event (Betts et al., 1998, 1999) are exposed in the hanging wall and footwall of the fault system. These sequences strike sub-parallel to the fault system (Fig. 2). Individual faults are commonly defined by white to grey silicified zones up to 10 m thick. Thin (<1 m) fault breccia, containing small angular fragments of quartz fault rock, quartzite, quartz sandstone, and siltstone, commonly define the outer margin of the faults (Fig. 4a and b). Kinematic indicators such as slickenside striations are not preserved due to brecciation and later silicification along the fault.

5. Movement history of the Fiery Creek Fault System

Mapping along the Fiery Creek Fault System reveals a long-lived Palaeo- to Mesoproterozoic movement history that spanned the Mount Isa Rift Event through to the Isan Orogeny.

5.1. Mount Isa Rift Event

The earliest preserved movements along the fault system occurred during episodic NW–SE directed extension associated with the Mount Isa Rift Event (O'Dea et al., 1997b; Betts et al., 1998, 1999). The Fiery Creek Fault System has been interpreted as a normal fault because of thickness variations of syn-rift sequences across components of the fault system; there is preserved normal offset along several fault segments and strands, and syn-rift unconformities are amalgamated in the distal hanging wall of the fault system (Betts et al., 1999).

The Fiery Creek Fault System preserves evidence for multiple normal fault generations, consistent with other parts of the northern Mount Isa terrane (Betts et al., 1999). Fault generations are geometrically similar suggesting that the bulk extension direction did not change significantly during the Mount Isa Rift Event (Betts et al., 1999).

5.1.1. Movement during the deposition of the Bigie Formation and Fiery Creek Volcanics

The earliest episode of movement along the Fiery Creek Fault system is indicated by marked thickness changes of conglomerate (Bigie Formation) across fault segment A (Betts et al., 1999). The exact amount of movement is unconstrained due to incomplete exposure of the conglomerate in the hanging wall. Conglomerate channels thicken from ~20 m in the footwall to a minimum of ~210 m in the immediate hanging wall (Figs. 5a and 6), suggesting a minimum of ~190 m normal offset during the Mount Isa Rift Event. The Bigie Formation also thins rapidly to the northwest, and has a wedge-shaped stratal geometry, indicating deposition into a half graben bounded by the Fiery Creek Fault System (Betts et al., 1999) (Fig. 5).

The thick accumulation (up to 800 m) of Fiery Creek Volcanics in the footwall (Fig. 2), and the presence of a volcanic dome along the fault plane to the north of the study area (Fig. 1a) has been interpreted to indicate that the fault system was a major magma conduit (Hutton and Wilson, 1984; Betts et al., 1999). To the south, in the distal hanging wall of the Fiery Creek Fault system, the Fiery Creek Volcanics are less than 100 m thick (Figs. 2 and 6). It is uncertain if these thickness changes are the result of movement along the fault during extension or whether they reflect increased distance from the eruptive centre to the north or east.

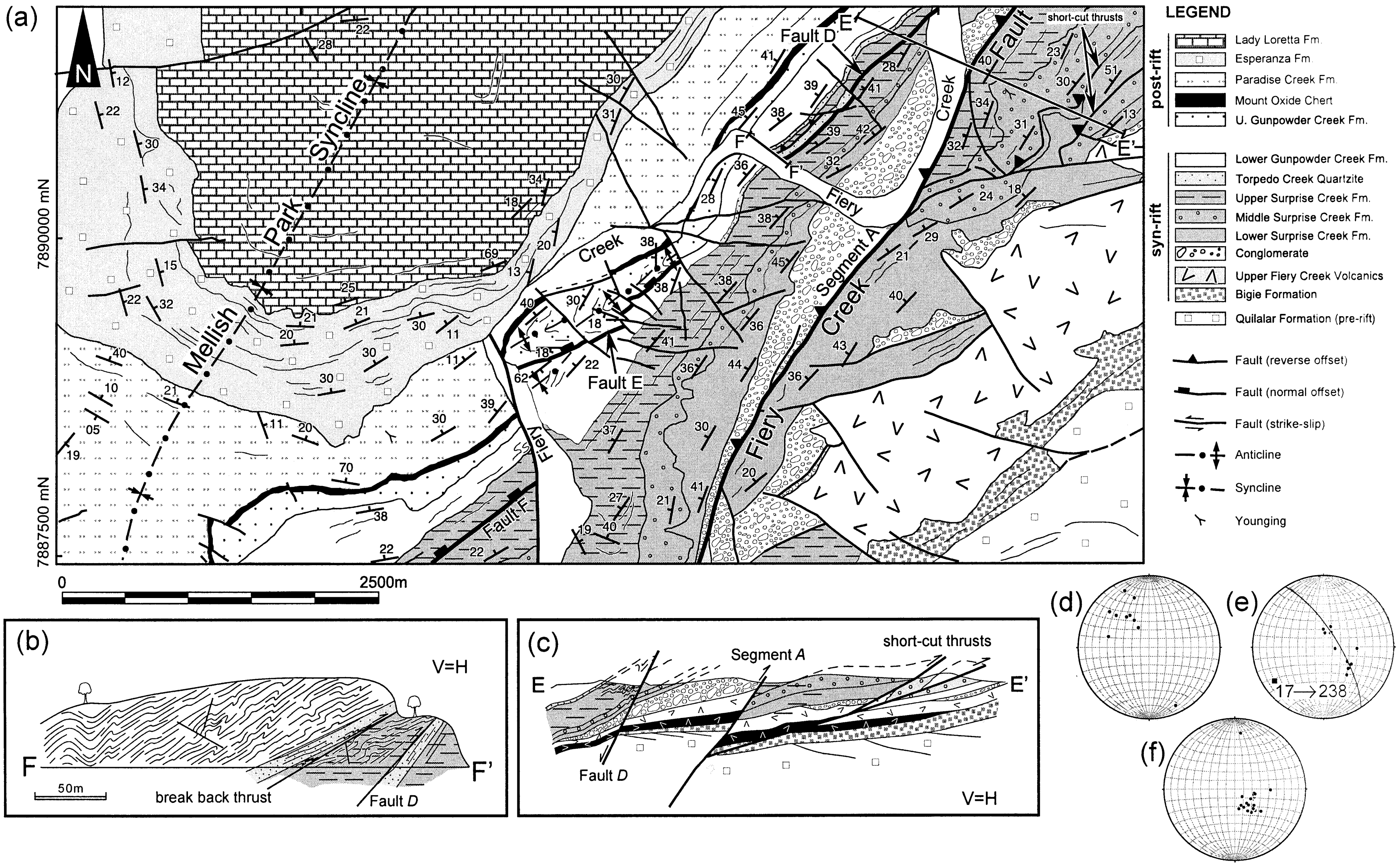
Syn-rift unconformities beneath the Bigie Formation and the Surprise Creek Formation (Betts et al., 1999) amalgamate approximately 6 km to the west of the fault system (Betts et al., 1999). This has been interpreted to indicate the position of the ancient uplifted tilt-block crest during the deposition of these sequences (O'Dea et al., 1997b; Betts et al., 1999).

5.1.2. Middle Mount Isa Rift Event (Surprise Creek Formation)

There is no direct evidence that indicates movement along the Fiery Creek Fault System during the deposition of the Surprise Creek Formation. Lack of a complete stratigraphic section in the hanging wall and footwall precludes assessment of any thickness changes across the fault system. There are marked thickness changes of the lower Surprise Creek Formation across several transverse faults indicating either continued fault activity at this time or passive deposition of the Surprise Creek Formation into remnant accommodation space created during the previous episode of rifting. This latter interpretation is consistent with thickness changes in the Bigie Formation and the Fiery Creek Volcanics, which occur across transverse faults in the hanging wall of the Jacqueline Fault (Betts et al., 1999).

5.1.3. Late Mount Isa Rift Event (Gunpowder Creek Formation)

Marked thickness changes of the Gunpowder Creek Formation across normal faults have been documented to the south of the study area (Betts et al., 1999). Along the Fiery Creek Fault system, thickness changes of the Gunpowder Creek Formation across transverse faults bounding faults E and F, as well as the transverse fault at


(a)
310000 mE
312500 mE
315000 mE
7890000 mN
7887500 mN
N
Mellish Park Syncline
Fiery Creek
Fault D
Fault E
Fault F
Fiery Creek Fault
Segment A
short-cut thrusts
E
E'
F
F'
0
2500m
LEGEND
post-rift
Lady Loretta Fm.
Esperanza Fm.
Paradise Creek Fm.
Mount Oxide Chert
U. Gunpowder Creek Fm.
syn-rift
Lower Gunpowder Creek Fm.
Torpedo Creek Quartzite
Upper Surprise Creek Fm.
Middle Surprise Creek Fm.
Lower Surprise Creek Fm.
Conglomerate
Upper Fiery Creek Volcanics
Bigie Formation
Quilalar Formation (pre-rift)
Fault (reverse offset)
Fault (normal offset)
Fault (strike-slip)
Anticline
Syncline
Younging
(b)
V=H
F
F'
50m
break back thrust
Fault D
(c)
Segment A
short-cut thrusts
E
E'
Fault D
V=H
(d)
(e)
17→238
(f)

the southern end of segment C (Fig. 2), suggest renewed extensional faulting during the Mount Isa Rift Event. The apparent normal offset of the Surprise Creek Formation and the Gunpowder Creek Formation across fault segments C and fault E is also consistent with fault activity at this time.

5.1.4. Post-Mount Isa Rift Event movements

Thickness variation of the post-rift sequences across the transverse faults and inconsistent fold-fault offset relationships across transverse faults indicate continued post-Mount Isa Rift Event fault activity. In the hanging wall of faults E and F, the thickness of the Paradise Creek Formation changes from ~110 to ~420 m across the transverse fault (Fig. 5a). Rocks to the north of this transverse fault are openly folded (Fig. 5e), whereas rocks in the hanging wall of fault F, to the south, are relatively undeformed, tilting ~15–50° northwest (Figs. 5a and f and 6d). The offset of post-rift sequences indicates apparent sinistral strike-slip displacement across the transverse fault (Fig. 7d), whereas shortening of the sequence in the hanging wall of fault E relative to sequences in the hanging wall of fault F should result in apparent dextral displacement. This inconsistency can be reconciled if there was a component of eastward tilting in the hanging wall of fault F relative to fault E, during the deposition of the Paradise Creek Formation (Fig. 7b), causing an apparent sinistral offset of the underlying units, and the abrupt thickness increase in the Paradise Creek Formation across the bounding transverse fault (Fig. 7b). The transverse fault terminates at the top of the Paradise Creek Formation suggesting activity ceased by this time (Fig. 5a).

Similar relations also occur in the hanging wall of fault segment C (Fig. 8a). Rocks to the north of the transverse fault are more tightly folded than rocks to the south. The map pattern shows apparent sinistral offset of the Mount Oxide chert (at the base of the Paradise Creek Formation) which is inconsistent with the relatively intense folding to the north of the transverse fault (Fig. 8a). Again, the difference between the apparent offset across the transverse fault and the shortening in the hanging wall blocks can be reconciled by eastward tilting of strata to the south of the transverse fault after the deposition of the Gunpowder Creek Formation (Fig. 7). Unlike the previous example, apparent thickness changes of post-rift stratigraphy do not occur across this transverse fault, suggesting that tilting may have occurred in the post-rift (rather than the syn-rift) history of the fault.

5.2. Isan Orogeny

Evidence for movement along the Fiery Creek Fault system during the Isan Orogeny can be seen at the outcrop scale and from the regional outcrop pattern (Derrick et al., 1983) (Fig. 2). The fault system had a favourable orientation for reactivation during either N–S or E–W regional shortening. Evidence for reactivation includes: (1) reverse offset across identified normal faults; (2) variable apparent offset along individual fault segments; and (3) perhaps a fault breccia containing pre-existing fault rock. There are also several faults along the system which have not been identified as reactivated normal faults, and may have formed during regional shortening (e.g. fault G; Fig. 2).

Repetition of syn-rift stratigraphy across several faults along the system indicate reverse reactivation during the Isan Orogeny. The Surprise Creek Formation and the conglomerate above the Fiery Creek Volcanics are repeated across fault segment A, and are juxtaposed with the upper member of the upper Surprise Creek Formation indicating a minimum of 300 m of dip-slip reactivation during the Isan Orogeny (Fig. 6c). The amount of reactivation may have been larger if there was movement along fault segment A during deposition of the Gunpowder Creek Formation. Stratigraphic repetition also occurs across fault segment B and fault D (Figs. 6a and 8a).

Fault segment B and fault D have variable offset along their strike. This is interpreted to indicate differential reverse reactivation. The northern part of fault segment B displays apparent reverse offset, whereas along the southern part of the segment there is little discernible offset. A similar relationship is observed along the strike length of fault D (Fig. 2).

The presence of pre-existing fault rock as breccia fragments along several fault segments (Fig. 4b) indicates brecciation of pre-existing silicified fault rock during fault reactivation. It is uncertain if normal fault reactivation occurred during episodic normal fault activity, or during the Isan Orogeny.

On a regional scale, the axial trace of the Mellish Park Syncline is offset by ~3–4 km across the Fiery Creek Fault, with an apparent dextral strike-slip sense of movement

Fig. 5. (a) Detailed map of part of the Fiery Creek Fault System (location of the map shown in Fig. 2). The map shows the compartmentalisation of deformation in the hanging walls of individual faults of the Fiery Creek Fault System. Open folds are developed in the hanging wall of fault E, whereas strata in the hanging wall of fault F are less intensely folded. These two faults are separated by a transverse structure that offsets the Mount Oxide Chert marker horizon with an apparent sinistral sense of displacement. The locations of cross-section F–F′ (b) and E–E′ (c) are shown. (b) Field sketch (cross-section F–F′) of the style of deformation in the hanging wall of fault segment D. There are several shallow dipping reverse faults. These are interpreted as break-back thrusts that formed during inversion of the Fiery Creek Fault System. (c) Cross-section (E–E′) showing the interpreted structure across the Fiery Creek Fault System. This section highlights the development of short-cut thrusts in the footwall of fault segment A. These short-cut thrusts are interpreted to have developed to facilitate continued shortening once fault segment A was rotated to an angle that could no longer be reactivated. (d) Equal area stereo-plot of the plunge and directions of non-cylindrical folds in the hanging wall of fault segment D. (e) Equal area stereo-plot of poles to bedding in the hanging wall of fault E. (f) Equal area stereo-plot of poles to bedding in the hanging wall of fault F.

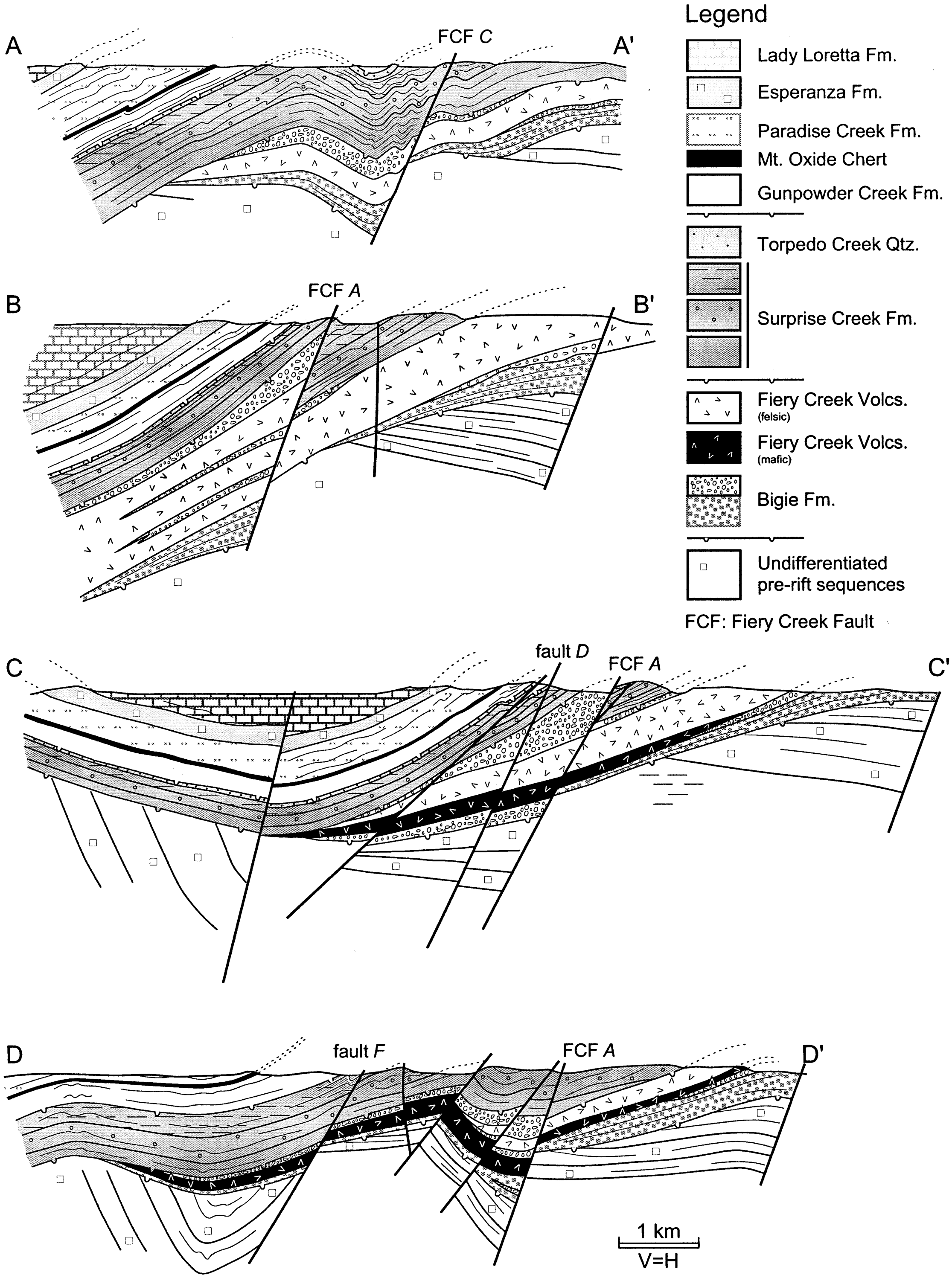


Fig. 6. (a–d) Cross-sections through the Fiery Creek Fault system. Locations of the cross-sections are shown in Fig. 2.

(Betts, 1999; Fig. 1a). The offset post-dates regional folding, suggesting that strike-slip movement occurred late in the Isan Orogeny (see Lister et al., 1999). The absence of stratigraphic pinning points along the fault system prevents assessment of the strike-slip component of displacement along the mapped section of the fault.

6. Inversion-related structures along the Fiery Creek Fault System

Structures developed during basin inversion are highly variable (Cooper and Williams, 1989). These variations result from differences in the underlying fault and

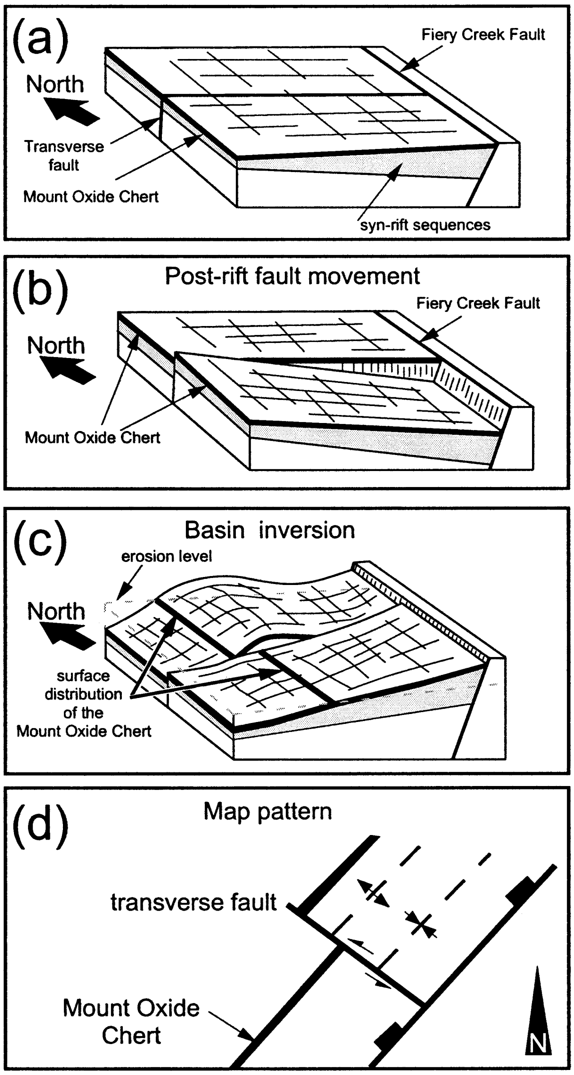


Fig. 7. Cartoon illustrating the sequential movement along a transverse fault, and the compartmentalisation of deformation in the hanging wall of a normal fault. (a) Configuration of the hanging wall divided into two deformation compartments separated by a transverse fault. (b) Renewed normal fault activity. Differential movement along the normal fault results in greater tilt block rotation in the southern compartment. (c) Inversion of the fault system resulting in the differential reactivation of the hanging wall compartments. The northern compartment is folded, whereas inversion of the southern compartment is facilitated by reverse reactivation. This schematic evolution explains apparent disparity between the offset along transverse faults and the greater shortening in the northern hanging wall compartment. This relationship is schematically illustrated in (d). (d) Schematic map view of the apparent sinistral sense of stratigraphic offset of post-rift units across a transverse fault and the compartmentalisation of deformation.

unconformity architecture (Hayward and Graham, 1989; Williams et al., 1989) and the fault orientation with respect to the principal stress axes (Etheridge, 1986; Sibson, 1995). The dip of the fault also contributes to the style of deformation during inversion. A shallow fault will tend to reactivate, whereas where faults are steeper, shortening may occur by buckling in the hanging wall or by the development of new faults, with kinematically favourable trajectories (McClay, 1989).

The recorded movement history of the Fiery Creek Fault system involved episodic normal fault activity during the Mount Isa Rift Event, post-rift movements, and reactivation during the Isan Orogeny. This has resulted in the development of highly variable strain patterns, fault offsets, and deformation styles in the hanging walls of the component faults of the system. Many of these component faults display a variety of inversion-related structures that are documented in well-studied inversion tectonic environments (Hayward and Graham, 1989; Williams et al., 1989; Welbon and Butler, 1992). These characteristics include reverse offset along identified normal fault segments, areas of relatively high hanging wall strain identified by fold intensity, and variations in the apparent offset along individual faults. Later gently dipping thrusts and reverse faults are also developed in the hanging wall and footwall of the fault system.

6.1. Short-cut thrusts

Several gently to moderately (30–35°) NW-dipping thrusts with strike lengths of ~1.5 km are developed approximately 1 and 1.2 km in the footwall of fault segment A. (Fig. 5a and c). The westernmost thrust displays a relatively small offset, exposing the middle parts of the Surprise Creek Formation in the hanging wall and footwall (Fig. 5c). The easternmost thrust displays larger offset. Here, the lower Surprise Creek Formation is exposed in the hanging wall and the middle Surprise Creek Formation is exposed in the immediate footwall (Fig. 5c). Another footwall thrust is interpreted to occur further to the north and truncates the Fiery Creek Volcanics (Fig. 2). These thrusts are interpreted to be footwall short-cut thrusts that developed when reactivation along fault segment A could no longer take place (Hayward and Graham, 1989; McClay, 1989).

6.2. Break-back thrust or reverse faults

There are numerous hanging wall faults/thrusts that developed during regional shortening of the Isan Orogeny. These structures are interpreted to be analogous to break-back thrusts or reverse faults (Coward et al., 1991; Welbon and Butler, 1992). Examples of break-back thrusts occur in the hanging wall of fault D (Fig. 5a and b) and in the hanging wall of Fiery Creek Fault segment A (Figs. 2 and 6d). Their influence on the overall geometry along the Fiery Creek Fault System is minimal, but movement along these structures has resulted in stratigraphic repetition (Fig. 6d). Fault G may be a larger scale example of a break-back thrust. The orientation of break-back thrusts varies from NE to ENE, with dip-slip offsets ranging from several metres to ~100 m.

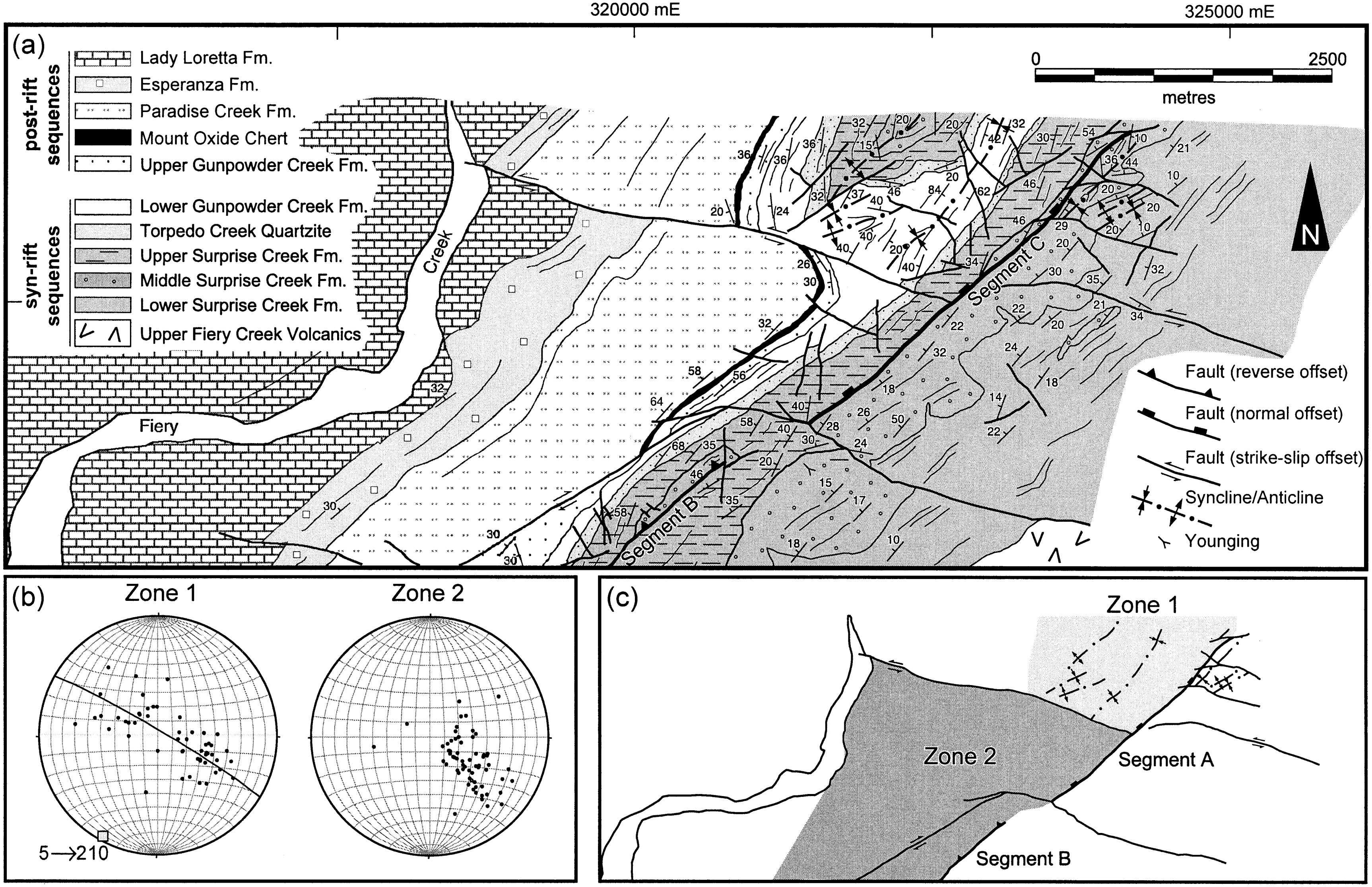


Fig. 8. (a) Detailed lithological and structural map along segment C of the Fiery Creek Fault illustrating the different structural styles associated with basin inversion. The hanging wall strain is heterogeneous and partitioned into individual compartments bounded by a NW-striking transverse fault. To the north of the transverse fault the hanging wall sequences are folded indicating buttressing against the footwall of the Fiery Creek Fault. To the south of the transverse fault the hanging wall sequences are less folded. Reverse reactivation appears to have facilitated basin inversion along this part of the fault segment. (b) Equal area stereo-plot of poles to bedding in the hanging wall of the fault C. Zone 1 stereo-plots show that folds in the northern compartment plunge shallowly to the south. Zone 2 stereo-plots show bedding data in the southern compartment. (c) Simplified map showing Zones 1 and 2.

6.3. *Offset variation*

Inverted faults commonly change from apparent reverse to normal in map view (Williams et al., 1989). The semi-continuous fault segments (A, B and C) of the Fiery Creek Fault System show a gradual change in the amount and sense of offset over the length of the fault. The upper member of the Surprise Creek Formation is exposed in the hanging wall of fault segment C, whereas the middle and lower members are exposed in the footwall. This indicates that fault segment C preserves a component of its original normal displacement (Fig. 2). The amount of net normal offset decreases southward along the entire Fiery Creek Fault. Along fault segment B, the upper Surprise Creek Formation occurs in the footwall and a small sliver of middle Surprise Creek Formation is exposed in the immediate hanging wall, indicating a small component of net reverse offset (Figs. 2 and 8a). This small offset suggests that reverse displacement during reactivation was slightly greater than the original normal offset (Figs. 2 and 8a). Fault segment A displays apparent reverse offset along its entire mapped strike length (Fig. 2). In the hanging wall, a conglomerate of the Bigie Formation is placed against the upper Surprise Creek Formation. The thickness of the Surprise Creek Formation in the hanging wall is ~500 m (Fig. 6b), providing a minimum estimate of the reverse displacement on the fault. Apparent changes from normal to reverse offset along strike also occur within individual fault segments (e.g. fault segment B and fault D).

6.4. *Buttressing*

In the hanging wall of inverted normal faults, strain increases with proximity to the fault plane, implying that the fault acted as a buttress during shortening (Hayward and Graham, 1989). This phenomenon is common along many parts of the Fiery Creek Fault System (Fig. 4d–f). Folds distal to the fault are gentle and upright (Figs. 4e and 5b) (e.g. Mellish Park Syncline: Betts, 1999). With increasing proximity to the fault system, strain intensifies, fold axial traces become parallel to the fault system, and variation in style and incidence of folding increases (Fig. 4d and f). This style of deformation is most intense in the hanging wall of fault segment C, and faults D and E, although folding occurs, to some degree, in the hanging walls of all fault segments.

Within individual hanging wall blocks, the style and intensity of folding is variable. For example, along the north part of fault D, meso-folds in the immediate hanging wall are non-cylindrical with strongly curved fold axial surfaces (Figs. 4d and 5d). Folds are disharmonic with highly irregular fold plunges, variable on a centimetre scale (Figs. 4d and 5d). Further to the south, shallowly north-plunging hanging wall folds, whilst remaining highly irregular, display moderate to tight interlimb angles (100–30°), suggesting less strain. Distal to the fault, folds are typically upright with a 'parallel' fold style (Figs. 4e and 5b). Proximal to the fault plane, kinking and a 'box-shaped' fold style are more common (Figs. 5b and 4f). These folds are best developed in the less competent siltstone and fine sandstone beds, whereas adjacent sandstone beds are often not folded, suggesting bedding-parallel flexural slip.

6.5. *Transverse faults*

Transverse faults active during the Mount Isa Rift Event also had a significant role in the style of deformation and hanging wall geometry produced during basin inversion. Transverse faults often bound hanging wall blocks characterised by different structural styles. Examples of this occur in the hanging wall of fault segment C (Fig. 8a) and at the shared boundary of faults E and F (Fig. 5a). In both examples the blocks to the north of the transverse fault are characterised by open, shallowly plunging folds,

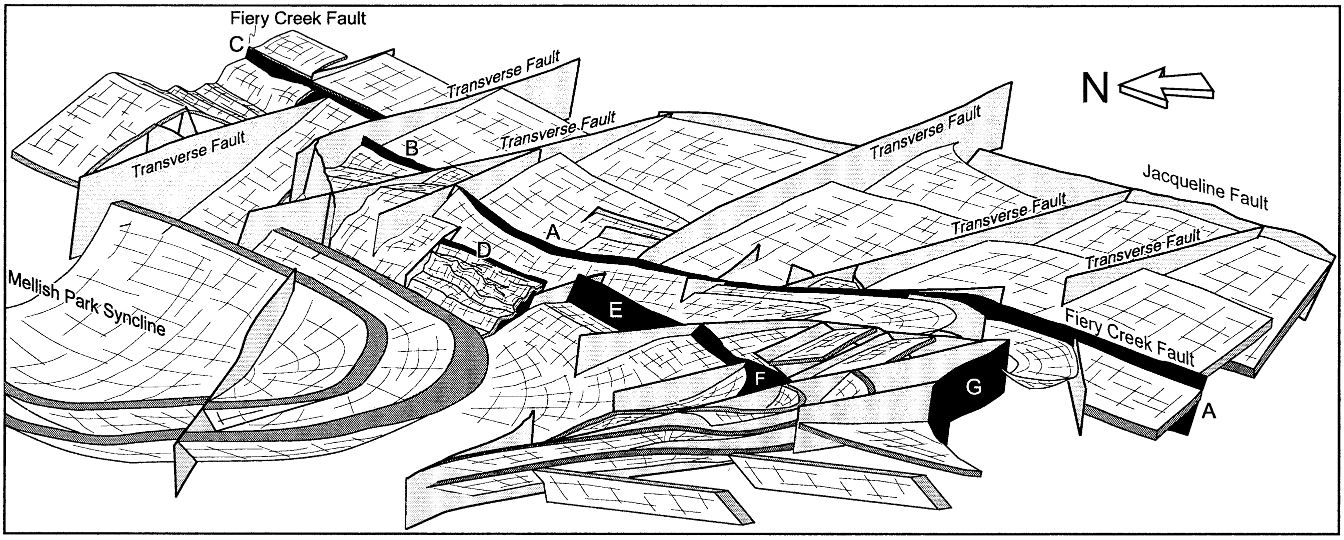


Fig. 9. Schematic three-dimensional cartoon of the geometry along the Fiery Creek Fault and surrounding areas.

whereas the block to the south is relatively undeformed (Figs. 5a and 8a). It thus appears that transverse faults separated the hanging wall blocks into discrete deformation compartments that deformed independently during basin inversion.

7. Deformation compartments in the hanging wall of the fault system

The compartmentalisation of discrete hanging wall blocks with distinct styles of deformation and the variations in basin inversion structures along the Fiery Creek Fault System has resulted in a diverse strain pattern and three-dimensional geometry in the hanging wall of the fault system (Figs. 5a, 8a and 9). This is best illustrated in the hanging wall of the Fiery Creek Fault segment C (Fig. 8a) and across the transverse fault bounding faults E and F (Fig. 5a). In these parts of the fault system there are marked changes in deformation style and strain, indicated by intensity of folding, across transverse faults. These are described in detail below.

7.1. Hanging wall of fault segment C

The amount of stratigraphic offset along the fault segment C is variable (Figs. 2 and 8a). The Surprise Creek Formation in the footwall typically dips to the west between 20 and 30°, although there are several open, shallowly south-plunging folds in the northern footwall of the fault segment (Figs. 6a and 8a). The immediate hanging wall of the fault segment contains sequences of the upper Surprise Creek Formation and the Torpedo Creek Quartzite (Fig. 3).

The hanging wall can be divided into two discrete compartments separated by a WNW-striking transverse fault. Sequences in the southern compartment (Zone 2 in Fig. 8c) dip moderately to steeply west (Fig. 6b). Dip variations are attributed to minor down-dip warping of the strata. Normal sense of displacement is preserved along this part of the fault system. The upper Surprise Creek Formation is exposed in the immediate hanging wall and this is placed against the middle Surprise Creek Formation in the immediate footwall. Assuming an average stratal thickness of the middle and upper members of the Surprise Creek Formation, $\sim$200–400 m offset is estimated.

The southern and northern compartments are separated by a WNW-striking transverse fault that abuts fault segment C (Fig. 6a). Stratigraphic offset across this fault indicates apparent sinistral displacement. The Torpedo Creek Quartzite is offset by approximately 50 m whereas the Esperanza Formation, farther to the west, is offset by approximately 1 km.

Deformation in the hanging wall compartment to the north of the transverse fault (Zone 1 in Fig. 8c) is characterised by a zone of relatively intense folding that extends approximately 2.5 km west of the Fiery Creek Fault (Figs. 5a and 6a). Folds are open with an inter-limb angle of 120–135° and dominantly plunge shallowly to the south (Fig. 8b), although numerous parasitic folds plunge shallowly north (Fig. 8a). Parasitic folds are pervasive in the less competent fine-grained sandstone and siltstone of the upper member of the Surprise Creek Formation and Lower Gunpowder Creek Formation but are not developed in the competent Torpedo Creek Quartzite.

The preserved offset along fault segment C in the southern compartment is less than that preserved in the northern compartment. The middle member of the Surprise Creek Formation is exposed in both the immediate hanging wall and footwall of the Fiery Creek Fault, suggesting that reverse dip-slip reactivation counteracted the original normal offset.

7.2. Faults E and F

The NNW-striking transverse structure dividing faults E and F (Fig. 8a) defines the boundary between the two hanging wall blocks characterised by different structural styles. The transverse fault bounding faults E and F is poorly exposed but is inferred from the apparent dextral offset of the Mount Oxide Chert marker horizon and the thickness changes of the Paradise Creek Formation across it. The transverse fault differs from the previous example in that it transects two distinct faults that are not continuous across the transverse fault. Approximately 900 m sinistral offset of fault F from fault E occurs across the transverse fault (Fig. 5a).

In many other ways the compartmentalisation of deformation is comparable with the previous example. Fault E occurs to the north of the transverse fault and separates the fine-grained sandstone and siltstone of the Lower Gunpowder Creek Formation in the footwall from carbonate sequences of the upper Gunpowder Creek Formation in the hanging wall. Footwall strata generally dip moderately to shallowly to the west (Fig. 5a). A shallowly south-plunging syncline with a steeply east-dipping axial plane occurs in the immediate footwall of fault E. Carbonate sequences in the hanging wall are gently folded about a shallowly SSW-plunging anticline (Fig. 5a) which has been disrupted and overprinted by numerous WNW to NW-striking faults.

The footwall of fault F comprises shallowly to moderately west-dipping strata of the upper Surprise Creek Formation. Sequences in the hanging wall of fault F comprise fine sandstone and siltstone of the upper Surprise Creek Formation and Lower Gunpowder Creek Formation, and the post-rift carbonate sequences. These sequences dip shallowly to steeply to the west between 10 and 40° (Fig. 8a and d). Again, dip variations appear to be related to down-dip warping of the strata.

8. Discussion

The regional map pattern of the western Mount Isa terrane is dominated by structures that were formed or reactivated during the Isan Orogeny. Recently, the location of ancient extensional structures have been interpreted by recognising enigmatic fold patterns and anomalous strain gradients related to inversion tectonics (O'Dea and Lister, 1995; Potma, 1996), resulting in refinement of the basin architecture. The continuous exposure of the Fiery Creek Fault System enables assessment of the major mechanical and geometric factors that governed fault reactivation during basin inversion. These factors are discussed below.

The variation in the three-dimensional hanging wall strain patterns and reactivation of original fault segments along the Fiery Creek Fault System is attributed to the pre-shortening orientation of normal fault segments and perhaps the lithological competency contrast in the hanging wall and footwall of the fault system. The variation in inversion geometries is strongly influenced by the original orientation of the extensional fault before inversion. Gently dipping normal faults are in a mechanical and kinematically favourable orientation for reactivation as reverse faults during basin inversion (Etheridge, 1986; McClay, 1989; McClay and Buchanan, 1992; Kelly et al., 1999) (e.g. fault segment A). The trajectories of steep faults restrict large reverse movement during inversion. Instead, basin inversion occurs by either buttressing and strain concentration in their hanging walls (Hayward and Graham, 1989; McClay, 1989) (e.g. Fault segment C, faults D and E), by strike-slip movement (Deeks and Thomas, 1995; Cloetingh et al., 1996), or by the development of new faults with kinematically favourable trajectories (Hayward and Graham, 1989; McClay, 1989) (e.g. fault segments A and D).

Episodic extensional events have been shown to have a major influence on the orientation of normal fault generations. Tilt block rotation during renewed extension caused older normal faults to rotate to shallower dips (Etheridge, 1986; Lister et al., 1991). At least two generations of Mount Isa Rift Event-aged normal faults have been identified (Betts et al., 1999). The older generation was active during deposition of the basal syn-rift sequences while the second generation was active during deposition of the uppermost syn-rift sequences (Betts et al., 1999). The present dip of the individual fault segments and strands along the Fiery Creek Fault system are not necessarily a good indicator of the pre-shortening orientation. Fault rotation during regional shortening will result in the steepening of faults until they are in a kinematically unfavourable trajectory for reactivation. Qualitative estimates of the pre-shortening fault dips can be made by how they behaved during inversion. For example, reverse reactivation is greatest along fault segment A suggesting that it may have been relatively shallow before regional shortening. Faults that display greater hanging wall strain such as faults E and D may have been relatively steep and therefore behaved as a buttress during inversion.

Along the Fiery Creek Fault System there appears to be a relationship between the magnitude of reverse reactivation and the longevity of the fault during the rift stages of its history. The largest reverse reactivation occurred along faults that show unequivocal evidence for movement during the earliest stages of rifting (e.g. segment A). Short-cut thrusting in the footwall of fault segment A is interpreted to have occurred during the later stages of reactivation when the fault plane was rotated into a trajectory that could no longer facilitate reverse reactivation. In contrast, footwalls of younger normal faults have behaved as buttresses. These faults are interpreted to have been steeper than the early generation normal faults at the onset of shortening. Examples of these faults include segment C and faults D and E (Figs. 5a and 8a). The development of multiple fault generations and their influence on pre-inversion fault dip, and their subsequent reactivation is illustrated in Fig. 10.

Another important control on the style of inversion structures along the Fiery Creek Fault System is competency contrasts between lithologies in the hanging wall and the footwall. Faults that exhibit appreciable competency differences across them (i.e. siltstone in the hanging wall and sandstone in the footwall) commonly exhibit greater hanging wall deformation relative to faults that do not have a marked competency contrast. This is best illustrated across fault segment C and fault D, where less competent siltstone exposed in the hanging wall has undergone a

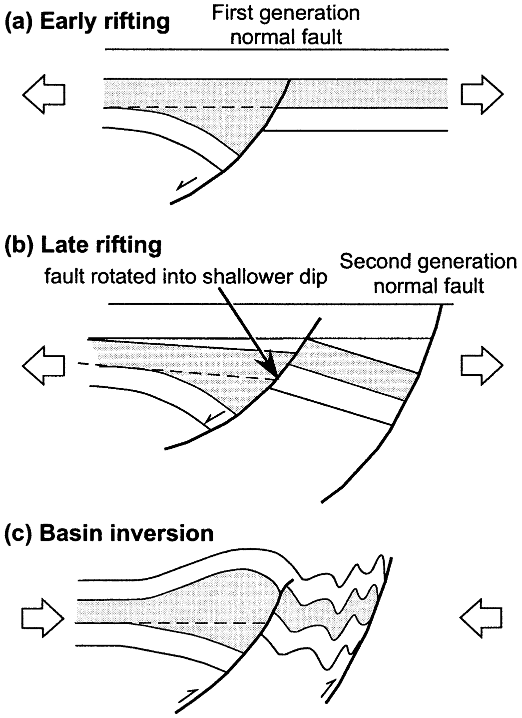


Fig. 10. Schematic cross-section depicting the influence of multiple generations of normal faults on the style of inversion. (a) Development of first generation extensional faults during the earliest stages of rifting. (b) During the development of a later normal fault generation, the pre-existing normal faults are rotated into a slightly shallower orientation. (c) During inversion, the shallower dipping, first generation normal faults are in a more favourable geometry for reactivation, whereas buttressing occurs in the hanging walls of steeper, second generation normal faults.

greater degree of folding compared with other parts of the fault system. Competent conglomerate units in the hanging wall of fault segment A are characterised by less strain. Fault reactivation appears to be the favoured mechanism for inversion if there are relatively competent units in the hanging wall and if units of similar competency occur across the fault segments.

The geometry of hanging wall sequences developed during inversion was also influenced by pre-existing transverse faults. Transverse faults mark boundaries in apparent movement sense (Fig. 8a), suggesting that they were re-utilised during basin inversion to facilitate differential reverse fault reactivation. The transverse faults also allowed hanging wall compartments to deform independently, resulting in variable geometries and deformation styles (Figs. 5a and 8a).

9. Conclusions

The Fiery Creek Fault System is an excellent example of an inverted normal fault system, allowing assessment of the three-dimensional geometry along its strike length. The fault system is composed of multiple segments and synthetic fault strands that preserve evidence of activity during the evolution of the Isa Superbasin, with subsequent fault reactivation occurring during the Isan Orogeny.

The hanging wall of the Fiery Creek Fault System contains several discrete deformation compartments characterised by variations in their geometry, strain intensity, and deformation style. This has resulted in a complex three-dimensional geometry and strain pattern along the fault system. This complexity is attributed to selective reactivation of individual fault components of the system, which is influenced by a combination of original fault dip and contrasting mechanical properties of the different rock types across the faults. Original fault dips are modified by rotation of pre-existing normal faults during episodic extensional fault development. Pre-existing extensional transverse structures played a major role in the partitioning of strain in the fault hanging wall, resulting in differential reverse movement along normal fault segments and heterogeneous hanging wall strain.

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