Geologie en Mijnbouw 65: 47–56, 1986

# Proterozoic deformation in the Duchess belt, Australia: A contribution to the BMR Mount Isa Regional Tectonic History Program

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Received 17 December 1985; accepted 27 February 1986

## Abstract

In medium to high grade metasediments of the Proterozoic Mt. Isa Inlier, Australia, at least three regional phases of deformation can be recognized. Early events of low angle brittle faulting at low grade conditions ($D_{1a}$), probably followed by localized transcurrent flow along a N-S ductile shearzone ($D_{1b}$) were overprinted by a phase of intense E-W shortening and vertical extension ($D_2$). During this phase, strain was accommodated without significant flow localization, i.e. without development of major shearzones. Important granite and gabbro intrusion occurred before and early during $D_2$. Crustal shortening values of up to 80% have been realized during $D_2$ leading to large-scale folding and the development of spectacular strain shadows around the major plutons. $D_3$ is characterised by strike-slip faults and minor accomodation structures.

## Introduction

The geology of the Mount Isa Proterozoic Inlier in Queensland, Australia is characterised by a pattern of N-S trending bands, 1–30 km wide and up to 150 km long, with contrasting stratigraphy and metamorphic history, that are separated by complex fault and shear zones. The area studied between Mt. Isa and Duchess covers 30 km² of two of these bands, the Kalkadoon-Leichhardt block and the Duchess belt, separated by the strongly deformed Shinfield zone (Fig. 1). The area consists mainly of metasediments in low pressure amphibolite facies, intruded by granite and gabbro plutons (Bultitude et al. 1982).

Granite intrusion and medium grade metamorphism in the Duchess belt outside the area studied have been dated between 1810–1550 M.a. (Blake 1980, Blake et al. 1984). Dating of the Myubee pluton in the area is in progress.

## Lithology

### *Kalkadoon-Leichhardt block*

The Kalkadoon-Leichhardt block is a narrow basement belt of various highly deformed granite plutons, acid metavolcanics and gneisses dated at 1810 M.a. or older (Page 1978; Wyborn & Page 1983), overlain by a consistent sequence of distinct formations in the following order (Blake et al. 1984): (1) Magna Lynn formation, mainly amphibolitised metabasalt with minor quartzites and felsic porphyry; (2) Argylla formation, mainly acid metavolcanics with minor felsic porphyry and amphibolite at the base, and arenitic sandstones, quartzite, felsic porphyry and minor amphibolite at the top; (3) Ballara formation, mainly homogeneous massive quartzite; (4) Corella formation, mainly banded calcsilicates, amphibolite and minor quartzite (Fig. 1).

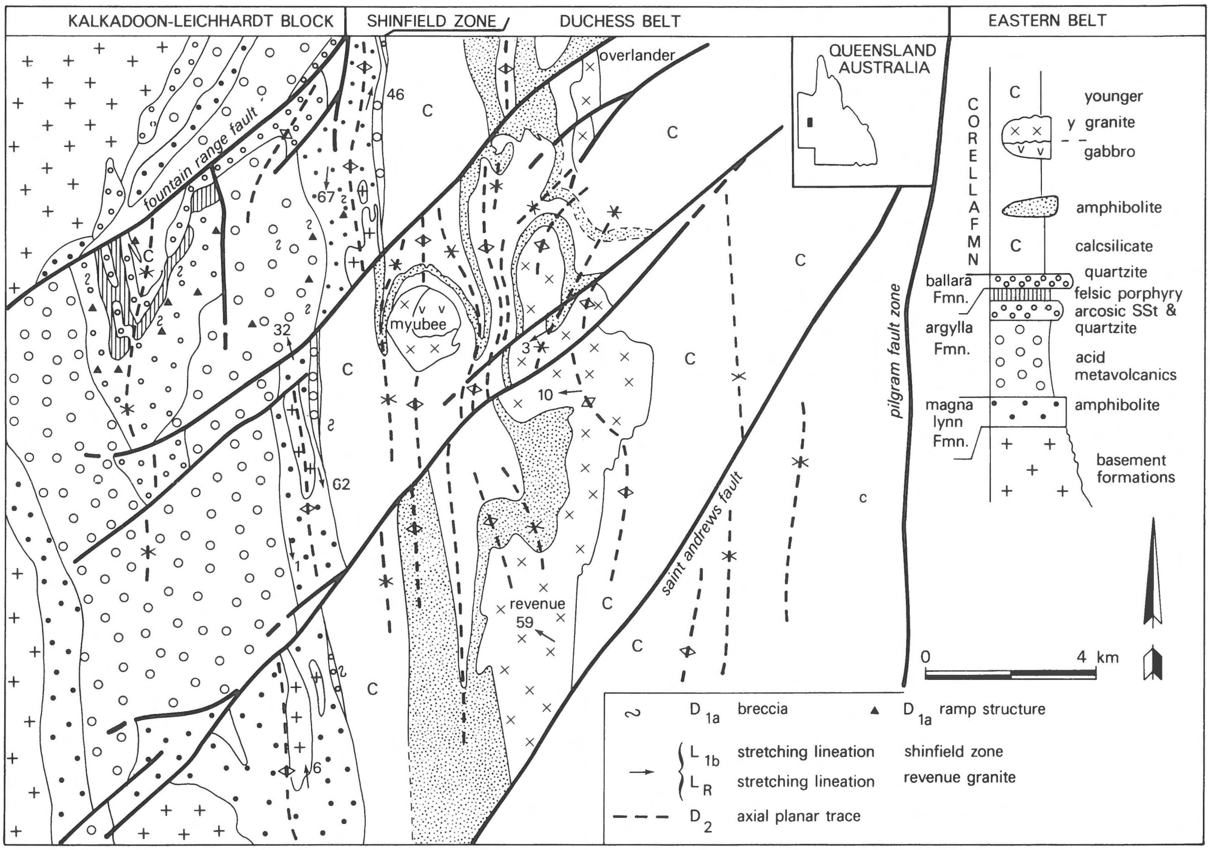

*Fig. 1.* Map of the central Mount Isa Inlier, Queensland

## *Duchess belt and Shinfield zone*

The Duchess belt in the area studied consists entirely of rocks attributed to the Corella formation. These rocks have been intruded by two plutons, the Revenue granite and the Myubee granite-gabbro pluton and by associated swarms of microgranite and dolerite dykes. Late granitic pegmatite and dolerite dykes transect the plutons and the metasediments (Fig. 2).

The Shinfield zone is a major anticlinal structure which contains strongly attenuated lenses of rocks from the Magna Lynn, Argylla, Ballara and Corella formations. It forms a link between the Duchess belt and the Kalkadoon-Leichhardt block. The total thickness of Argylla metavolcanics and Ballara quartzite changes dramatically over the Shinfield zone from 4 km in the west to maximal 200 m on the eastern side of the anticline (Fig. 1).

The Shinfield zone contains strongly deformed lenses of porphyritic biotite-granite and coarse grained leucogranite, together known as Bushy Park gneiss (Blake et al. 1981). They have sharp contacts with amphibolite and acid metavolcanics of the Magna Lynn and Argylla formations, but do not show clear intrusive relationships in any of these rocks. The sharp contacts may represent ancient fault planes or narrow shear zones, but overprinting by $D_{1b}$ and $D_2$ may have transposed such earlier structures along the contacts. The Bushy Park gneiss may be associated with the older granites in the basement of the Kalkadoon-Leichhardt block but has a chemical composition unlike any of those exposed further west (Blake, pers. comm.). Bushy Park Gneiss and Magna Lynn amphibolites are cut by microgranite (Fig. 3a) and pegmatite veins of unknown age which certainly predate the earliest ductile deformation event in the Shinfield

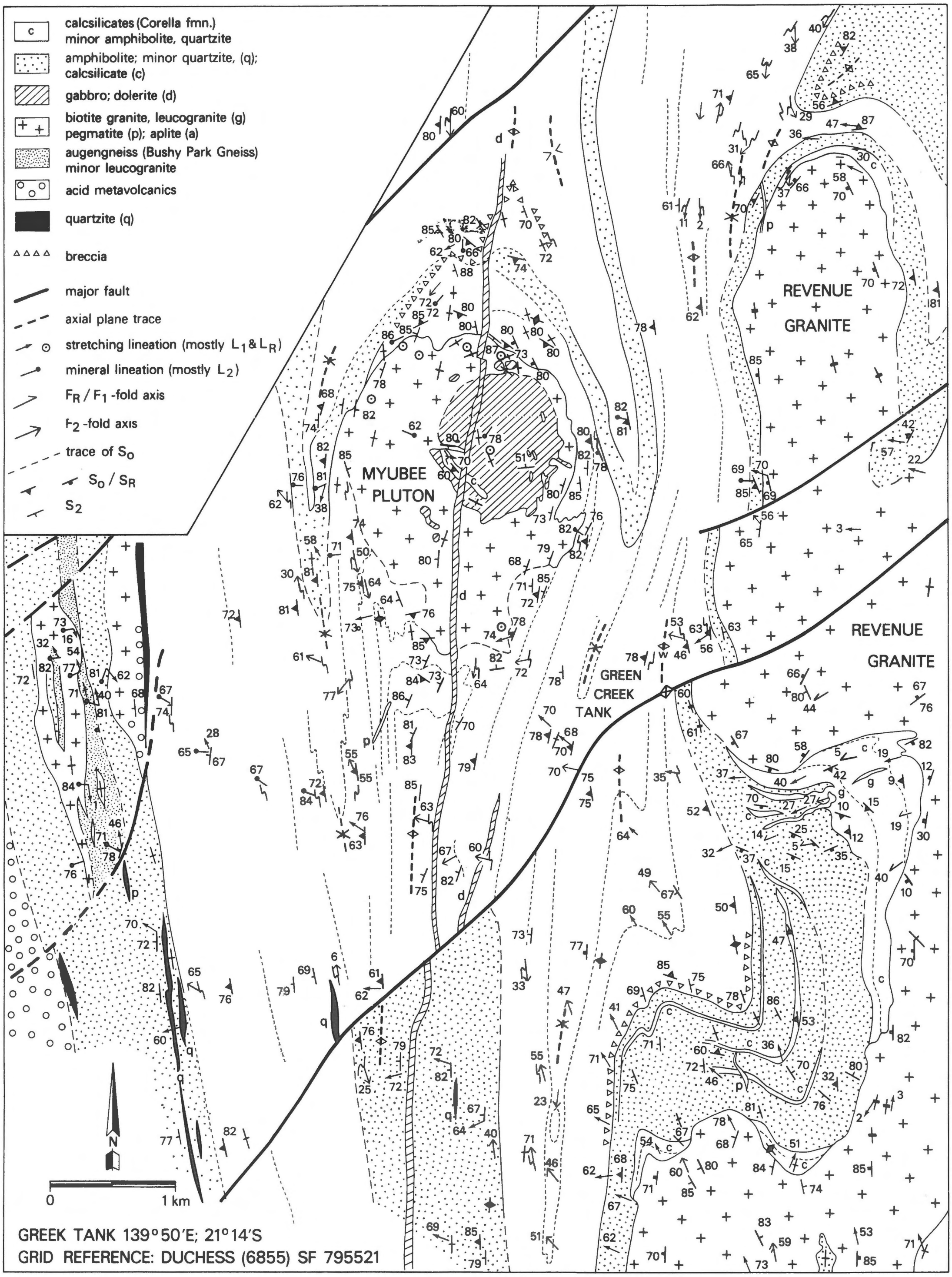

*Fig. 2.* Structural map of the central Duchess belt, Queensland

zone ($D_{1b}$). The veins are not offset along the contacts of Bushy Park gneiss and Argylla or Magna Lynn rocks, which means that these contacts, whether of intrusive or tectonic origin, predate the intrusion of the veins and $D_{1b}$.

### *Corella formation*

The Corella formation in the Duchess belt consists of at least 3000 m of alternating calcsilicates, banded amphibolite and massive amphibolite on a metre to kilometre scale (Blake et al. 1984; Fig. 2). Minor lenses of quartzite, acid metavolcanics and sillimanite-white mica schist are present. The calcsilicates consist of microcline, scapolite, carbonate, hornblende, diopside, grossular and allanite (cf. Carter et al. 1961). A distinct banding is defined by layers rich in carbonate and silicates respectively. Banded amphibolite differs from calcsilicate s.s. by a higher hornblende content and the presence of plagioclase.

### *Younger intrusive rocks*

The Revenue granite (Figs. 1 and 2) consists of a leucogranite rim, up to 300 m wide, and a core of homogeneous biotite granite. The contact between both granite compositions is usually gradual and probably not intrusive. The contact with Corella calcsilicates and amphibolites is clearly intrusive as indicated by truncated bedding and swarms of microgranite veins invading the metasediments. Xenoliths of calcsilicate and amphibolite, often affected by metasomatism, are common on a cm to 300 m scale but make up less than 5% of the outcrop surface of the pluton.

The Myubee pluton (Figs. 1 and 2) consists of an outer zone of coarse leucogranite surrounding a core of olivine gabbro. Xenoliths of banded calcsilicate represent up to 30% of the outcrop surface of the granite rim. Fragments of gabbro are common in the granite, but the reverse is also observed, suggesting that both magma types intruded synchronously. Similar relationships in the Myubee and others plutons in the Duchess belt have been described by Blake (1981) as net-veined complexes. The Myubee pluton shows clear intrusive relationships with Corella formation rocks, and microgranite and dolerite dykes invade the country rock.

## Deformation history

### *Early structures – $D_1$*

In the metasedimentary cover of the Kalkadoon-Leichhardt block and in the Shinfield zone, evidence exists for an early phase ($D_{1a}$: Passchier in prep) of low angle brittle faulting, comparable with structures first described by Bell (1983) north of Mt. Isa (Fig. 1). Quartzite and sandstone lenses are locally truncated by veins of breccia with a matrix rich in tourmaline, and cataclasite. The contact of the lenses with adjacent quartzite lenses or other lithologic units is usually sharp and commonly truncates the internal bedding sequence, producing ramp structures with hanging wall anticlines and footwall synclines. Breccia and cataclasite veins have been ductilely deformed during $D_2$, mainly by folding. Ramp structures are overprinted by $D_2$ shape fabric elements. Outside quartzite and sandstone units little evidence exists for an early brittle phase of deformation; bedding is less obvious and makes recognition of ramps difficult, and small scale brittle structures may have been erased by recrystallization during $D_2$.

Due to uncertainties about the stratigraphic sequence in the area, and strong overprint by $D_2$, no coherent model can sofar be made for the early brittle structures. Nevertheless, the available geometrical arguments seem to favour an extensional brittle regime rather than thrust faulting as proposed by Bell (1983) further to the north (Passchier in prep); (1) in individual quartzite lenses obliqueness of bedding to the outer contacts often persists throughout the lens as described for extensional detachments (Davis & Hardy 1981). Short distinct ramp structures, which seem to be common in constrictional horses (Butler 1982) are less common; (2) the intersection angle between faults and bedding in quartzite lenses seems to have been high prior to $D_2$ overprint, often exceeding 50° (cf. Davis & Hardy 1981); (3) certain lithologic units, e.g. cordierite-anthophyllite rock in the transition from

Argylla to Ballara formations (Blake et al. 1984) is locally cut out along strike by faults, while evidence for tectonically produced repetition of stratigraphy, typical for constrictional fault belts (cf. Butler 1982) is absent.

In the Shinfield zone and in the westernmost kilometre of the Duchess belt a N-S plunging linear shape fabric has been developed, especially in Bushy Park Gneiss but also locally in Argylla acid metavolcanics, microgranite dykes, Magna Lynn metabasalt, quartzite and calcsilicates (Fig. 3b). The plunge varies strongly along strike in the zone on a 10 m scale but is usually rather shallow (Fig. 2). A $D_2$-mineral lineation defined by the preferred orientation of biotite or hornblende (Fig. 3b), and in quartzite a second stretching lineation is usually present in the same outcrops with a consistent subvertical or steeply W-plunging orientation (Fig. 2). The variable orientation of the first lineation is interpreted as an effect of overprinting by $D_2$, which formed the mineral lineations. Similar sets of lineations have been found in the Wonga belt 70 km further north, which seems to the lateral equivalent of the Shinfield zone.

The relative age of brittle structures in the west and linear shape fabric elements in the Shinfield zone is not clear. The occurrence of ramp-like structures in some of the quartzite lenses in the Shinfield zone which contain two overprinting lineations seems to indicate that a brittle phase predates the development of the early linear shape fabric. The early structures are therefore separated into an early brittle $D_{1a}$ phase and a younger (?) ductile $D_{1b}$.

### *$D_2$*

$D_2$ is a phase of ductile deformation which strongly affects all units in the studied area, and which has been recognized over large parts of the inlier (e.g. Bell 1983, Blake et al. 1984). In the Duchess belt it is synchronous with the peak of metamorphism, which reached amphibolite facies conditions in all the studied units. Extensive static recrystallization of scapolite, diopside, hornblende and biotite in calcsilicates indicates that these conditions outlasted $D_2$ at least in the Corella formation. $D_2$ produced folding of the calcsilicate and amphibolite with steeply W-dipping axial surfaces and a variable plunge of the foldaxes. In the calcsilicate the silicate-rich competent layers developed cm – 10 m scale folds, usually strongly disharmonic and non – cylindrical (Fig. 3c, d). Open folds are nearly parallel (Fig. 3c) but attenuated folds have more complex shapes (Fig. 3d). The orientation of the foldaxes is undulating gently without development into tight sheath folds (Fig. 2). Vergence mapping of parasitic folds of various orders revealed the existence of km-scale folds with N- and S-plunging foldaxes, which affect not only the calcsilicates, but also the amphibolites of the Corella formation, and the Revenue granite (Fig. 2). The Shinfield zone can also be interpreted as a $D_2$-anticline, and to the west, in the Kalkadoon-Leichhardt block, at least one major $D_2$-syncline has been recognized (Alligator syncline; Passchier in prep).

In the calcsilicates an $S_2$ foliation is locally developed in the competent, silicate-rich bands as a widely spaced (5–50 mm) cleavage along which relatively large hornblende and calcite crystals are concentrated. $S_2$ usually has a convergent fan geometry around fold closures, and seems to have formed relatively early in the deformation phase: in tight folds the banding is commonly displaced along $S_2$ planes indicating layer-parallel shortening (Fig. 3e) or boudinage (Fig. 3f). Locally, $S_2$ has been folded.

A steep $S_2$ foliation and subvertical $L_2$ lineation defined by a preferred orientation of hornblende and biotite is developed in amphibolite of the Corella and Magna Lynn formation. Planar and linear shape fabric elements of the same orientation occur in Argylla acid metavolcanics, porphyry and quartzites. Although the $D_2$ structure seems simple on a large scale, a number of complications arise when considered in detail.

The Myubee pluton contains weak and inhomogeneously distributed linear and planar shape fabric elements, mainly in the granite, but also locally in the gabbro (Fig. 2). Linear elements are always subvertical and planar elements have a variable steeply dipping orientation. Along the outer edge of the pluton, the planar shape fabric follows the contact with the country rock. The contact be-

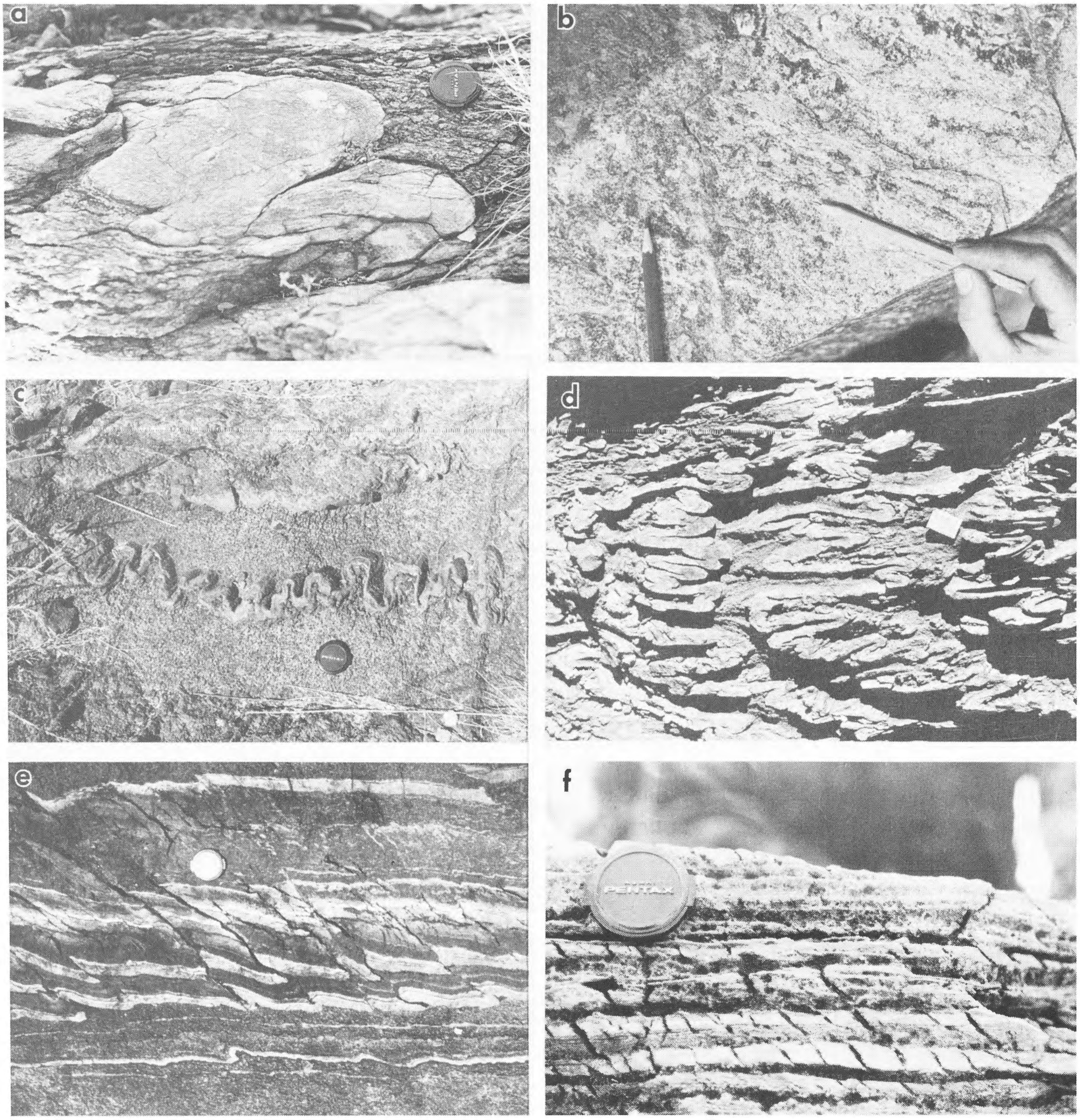

*Fig. 3.* (a) microgranite vein intruding Bushy Park gneiss folded during $D_2$. $S_2$ is well developed in both units; (b) stretching lineation ($L_{1b}$-gentle plunge) and mineral lineation of biotite ($L_2$-steep plunge) on a steep foliation plane in Bushy Park gneiss; (c) tight parallel $F_2$-folding of a silicate rich band in Corella calcsilicates; (d) isoclinally attenuated $F_2$-folding in the silicate-rich bands of Corella calcsilicates. Carbonate-rich matrix deformed passively; (e) spaced $S_2$ in Corella calcsilicates, reactivated by layer parallel shortening; (f) idem, reactivated by layer-parallel extension.

tween the granite and the gabbro is often deformed into 10 m scale steeply plunging mullion-like structures, gabbro being the competent phase with foliation development parallel to the contact. Microgranite and dolerite dykes which intrude the surrounding metasediments became buckle-folded or boudinaged (Fig. 3g, h) depending on their orientation with respect to the lines of no finite long-

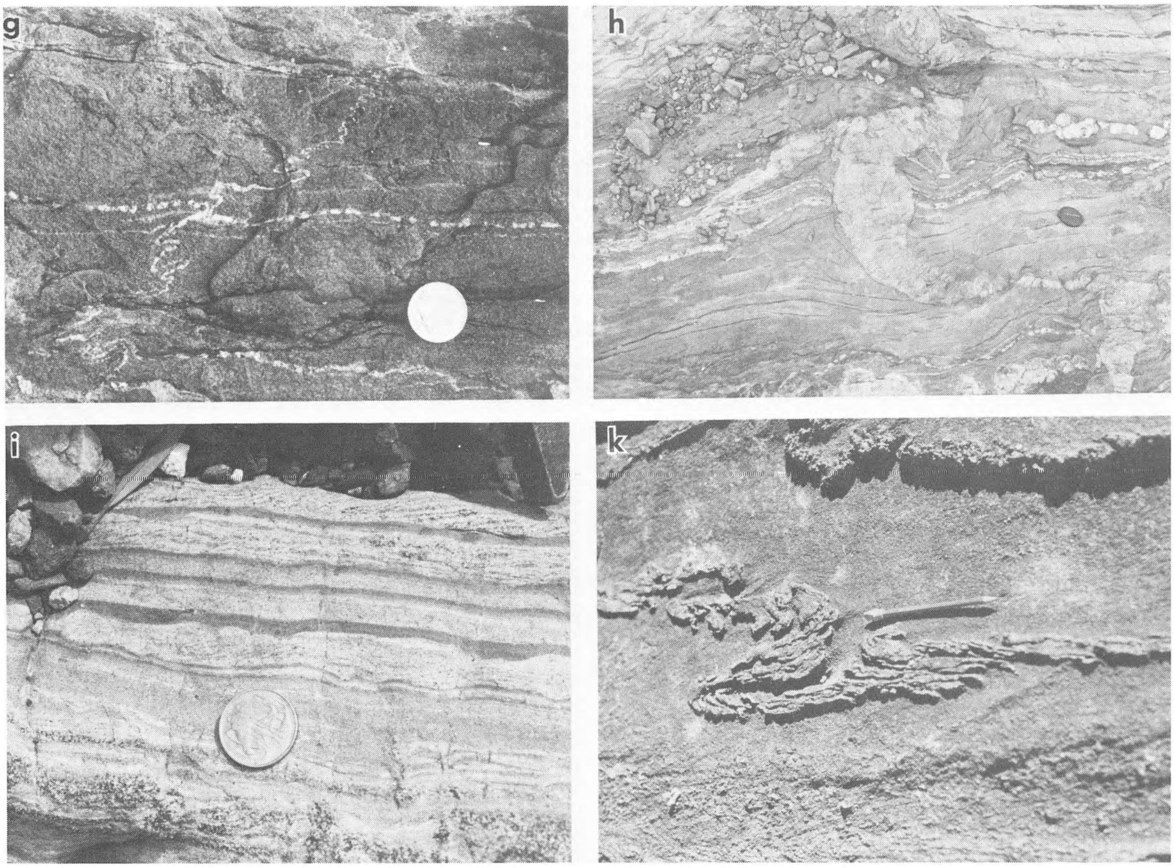

*Fig. 3.* continued. (g) $D_2$-folded and boudinaged microgranite veins in massive Corella calcsilicates adjacent to the Myubee pluton; (h) idem, with $S_2$ normal to the contacts in the folded granite vein – folding reoriented the central part of the vein and $S_2$; (i) ripple foresets in silicate-rich bands of Corella calcsilicate, near the northern margin of the Myubee pluton – dark laminae consist of hornblende-diopside; (k) spaced $S_2$ in silicate-rich layer in Corella calcsilicates, which has been refolded by late D2 structures

itudinal $D_2$-strain in outcrop surface (Talbot 1970). Internally, the dykes developed a subvertical linear shape fabric, and locally a steeply dipping planar shape fabric (Fig. 3h).

The Myubee pluton seems to have acted as a relatively strong domain in a more ductile matrix consisting mainly of calcsilicates: Major $F_2$-folds are clearly deflected around the pluton and the strain-intensity of $D_2$ varies in a regular way in the surrounding rocks (Fig. 2). To the west and east, strain intensity is very high as determined from deformed dykes, flattened layering in calcsilicates, and attenuated $F_2$-folds (Fig. 3d). To the north and south, however, areas of low strain intensity occur; these 'strain shadows' are the only sites where ripple lamination is still recognizable in the calcsilicates indicating that the banding is of sedimentary origin (Fig. 3i). In the southern strain shadow, the pluton is seen to cut through open $F_2$ folds and $S_2$, and granite offshoots intrude the metasediments along $S_2$ planes. Even in these locations though, the granite develops a planar and linear shape fabric as described above.

The relationship of the Myubee granite with structures in the country rock could be interpreted to mean that the granite intrude between two phases of deformation. However, the style and orientation of structures developed in calcsilicates and amphibolite before and after the intrusion are sufficiently similar to group them together. Overprinting relationships are rare and occur between structures of similar style (Fig. 3k); they are usually not datable with respect to each other or to the Myubee intrusion. In calcsilicates, $S_2$ seems to develop mainly at an early stage of $D_2$ and becomes folded in the limbs of some strongly flattened folds (Fig. 3k). Also, $S_2$ planes often act as incipient boudin necks or 'thrust planes' in the limbs of such tight folds (Fig. 3e, f). Considering the high competency contrast between bands in the calcsilicates and the disharmonic foldstyle, it is very well possible that early developed $S_2$ planes become deformed in this way during progressive deformation without major changes in the orientation of the bulk regional kinematic frame and metamorphic condition in the Duchess belt. While the instantaneous shortening axis was at a small angle to the bands, initial layer-parallel shortening may have generated $S_2$. Further shortening was accommodated mainly by rotation of fold limbs and more complex flow in the competent bands leading to rotation and deformation of the earlier formed $S_2$ planes. The Myubee pluton can therefore be described as syn-$D_2$, but must have developed soon after the onset of the deformation in order to explain the strain shadows of the pluton. It intruded into the core of an open, incipient $D_2$ anticline (Fig. 2).

### *The Revenue granite*

Contrary to the Myubee pluton, the Revenue granite does not seem to truncate early $D_2$ structures. The pluton contains an early shape fabric, usually planar ($S_r$) but locally with a linear component or even entirely linear ($L_r$). This shape fabric is everywhere parallel to the contact with the country rock (Fig. 2; Passchier in prep). The contact zone is locally mylonitized with dominant E-W or SE-NW trending stretching lineations. The mylonitic fabric usually has orthorhombic symmetry, but locally shear band cleavages (Lister & Snoke 1984) and foliation deflection indicate bulk non-coaxial flow. Sense of shear in these locations is variable over the pluton, and seems to indicate a relative uplift of the pluton with respect to the country rock (Passschier in prep).

The early fabric in the Revenue granite is overprinted by $F_2$ folding with steep N-S trending axial planes, and shallowly plunging foldaxes. Detailed mapping of parasitic folds in the Corella calcsilicates surrounding the pluton indicate that it lies in the core of a strongly attenuated $D_2$ anticline. The 'double fold' SE of Green creek tank on the western side of the pluton consists of a southern parasitic $F_2$ fold and a northern $F_r$ (pre-$D_2$) structure associated with the early ($S_r$-$L_r$) shape fabric in the granite (Passchier in prep). Pegmatite veins cut $F_2$ folds in and around the Revenue granite, but sometimes contain shape fabrics; they may be associated with the slightly younger Myubee pluton, or be of even later age.

### *$D_3$*

All structural elements mentioned sofar are truncated by SW-NE trending brittle transcurrent faults with dextral offset, usually recognizable as cataclasite zones up to 30 m wide (Fig. 2). The zones are rich in vein quartz which is often affected by the cataclasis. The country rock usually contains quartz veins up to several hundred metres away from the main faults. To the east, the faults run up to the brittle N-S trending Pilgrim fault (Fig. 1) which bounds the Duchess belt to the east. This fault is not offset by the SW-NE trending set and is therefore either synchronous with them, or younger. Minor N-S trending faults, usually filled with quartz or coarse calcite, some of which are associated with Cu-mineralization, are common throughout the area (Fig. 2). The age of $D_3$ faulting is unknown but postdates all igneous intrusions and general uplift from peak amphibolite facies metamorphism. The Pilgrim fault truncates Cambrian rocks.

## Discussion

The structural history of the Myubee area is quite clear for $D_2$ but less so for earlier events. After deposition of at least the Magna Lynn, Argylla and

Ballara formations a phase of brittle deformation affected the western part of the area, possibly due to extensional tectonics. The Corella formation may have been present, but may also have been deposited in a developing basin. It is tentative to attribute the dramatic thinning of the Argylla and Ballara formations from west to east over the Shinfield zone to an extensional tectonic phase, with a developing basin on the site of the Duchess belt. This could also explain the fact that the Duchess belt has at present a normal crustal thickness (Blake et al. 1984) while $D_2$ seems to have produced 50–80% horizontal shortening and vertical extension. Considering the observation that low pressure amphibolic facies rocks are at the surface at present, this seems to indicate that the crust was relatively thin at the onset of $D_2$.

The early linear shape fabric in the Shinfield zone cannot easily be fitted into such a model. The zone represents the deepest exposed level in the Duchess area and could at first sight be interpreted as an exhumed ductile shear zone associated with brittle low angle-fault tectonics in the top of the Kalkadoon-Leichhardt block; it could be even regarded as an extensional ductile shear zone associated with both the brittle event in the west and opening of a basin in which Corella type sediments were accumulating in the east. Such models, however would require development of NW-SE or SW-NE trending stretching lineations and and a gently dipping planar shape fabric. The absence of refolded foliations in the Shinfield zone indicates that either a N-S trending purely linear fabric existed before $D_2$, or that a steeply dipping planar shape fabric element was developed in addition. Gently dipping foliation elements and E-W trending lineations would have been refolded and steepened during $D_2$ and cannot be explained by the present orientation of fabric elements in the zone. Therefore, it seems more likely that the linear shape fabric in the Shinfield zone is associated with ductile transcurrent movement at the present exposure level of the Shinfield – Wonga zone along the lines suggested by Bell (1983). Such deformation cannot easily explain the dramatic thinning of the Argylla and Ballara formations from west to east over the Shinfield zone which occurs all along its strike (Fig. 1): a brittle phase of deformation ($D_{1a}$), possibly extensional, apparently predates ductile transcurrent movement along the zone ($D_{1b}$).

The early shape fabric ($S_r$-$L_r$) which is present in the Revenue granite, predates $D_2$ and developed subparallel to the contact, which is intrusive in the calcsilicates (Passchier in prep). Considering the sense of shear data from the contact zone, two models can be proposed for the development of this fabric: 1) doming of the granite in the Corella rocks and 2) megaboudinage of the granite in homogeneously stretching Corella calcsilicates. Both possibilities could be associated with inferred early extensional tectonics ($D_{1a}$) in the Kalkadoon-Leichhardt block. Further research on similar granite plutons in the Duchess belt is necessary to solve this problem.

$D_2$ caused extensive E-W shortening and vertical extension throughout the area and apparently thickened the sequence in a rather homogeneous way by bulk coaxial flow, without development of major shear zones. Even the Shinfield zone cannot be regarded as such since $D_2$ finite strain values in it do not seem to exceed those to the west and east; the lensoid internal structure of the Shinfield zone must have formed during $D_1$. $D_2$-finite strain values seem to increase gradually over the area from the Kalkadoon-Leichhardt block to the Duchess belt. In the Duchess belt, peaks in finite strain magnitude seem to be restricted to inhomogeneous strain around the relatively rigid granite plutons. No planar zones of high finite strain have been found, and monoclinic fabric elements of $D_2$ age are rare and of conflicting sense over the area. The strip – like appearance of the Duchess belt and Kalkadoon-Leichhardt block may have been present before the onset of $D_2$, but were certainly strongly attenuated by it.

The Revenue and Myubee plutons are clearly different in age and composition: the former is pre-$D_2$, contains contact-parallel shape fabrics and consists only of granitoid rocks; the latter is syn-$D_2$, contains only $D_2$ fabric elements and consists of a granite-gabbroic net-veined complex. Since other granite plutons in the Duchess belt either resemble the Revenue (e.g. Overlander granite) or Myubee (e.g. Mt. Erle pluton), two separate phases of magmatic activity seem to have been present. The Bushy Park Gneiss is either of the same age as the Revenue, or even older.

## Acknowledgements

Funding for this research project was given by the Schürmann fund (1984, 1985) and by the Royal Society of London (1983). Extensive logistic and financial support was obtained from BMR, Canberra, who organised the Mt. Isa Regional Tectonic History Project. I further wish to thank Gordon Lister, Dave Blake and Mike Etheridge who run the project. Ide van der Molen cooperated in the Myubee project during 1984.

## References

Bell, T.H. 1983 Thrusting and duplex formation at Mount Isa, Queensland, Australia – Nature 304: 493–497

Blake, D.H. 1980 The early geological history of the Proterozoic Mount Isa Inlier, NW Queensland: an alternative interpretation – BMR Journal of Australian Geology and Geophysics 5: 234–256

Blake, D.H. 1981 Intrusive felsic-mafic net-veined complexes in north Queensland – BMR Journal of Australian Geology and Geophysics 6: 95–99

Blake, D.H., R.J. Bultitude, P.J.T. Donchak, L.A.I. Wyborn & I.G. Hone 1984 Geology of the Duchess – Urandangi region, Mount Isa inlier, Queensland – BMR Bulletin 219

Bultitude, R.J., D.H. Blake & P.J.T. Donchak 1982 Duchess region, Queensland – 1: 100.000 Geological Map Commentary. Bureau of Mineral Resources, Australia

Butler, R.W.H. 1982 The terminology of structures in thrust belts – J. Struct. Geol. 4: 239–245

Carter, E.K., J.H. Brooks & K.R. Walker 1961 The Precambrian mineral belt of north-western Queensland – BMR Bulletin 51

Davis, G.H. & Hardy, J.J. 1981 The Eagle Pass detachment, southern Arizona: product of mid-Miocene listric (?) normal faulting in the southern Basin and Range – Bull. Geol. Soc. America 92: 749–762

Page, R.W. 1978 Response of U-Pb zircon and Rb-Sr total-rock and mineral systems to low grade regional metamorphism in Proterozoic igneous rocks, Mount Isa, Australia – J. Geol. Soc. Australia 25: 141–164

Talbot, C.J. 1970 The minimum strain ellipsoid using deformed quartz veins – Tectonophysics 9: 46–76

Wyborn, L.A. & R.W. Page 1983 The proterozoic Kalkadoon and Ewen Batholiths, Mount Isa Inlier, Queensland: source, chemistry, age and metamorphism – BMR Journal of Australian Geology and Geophysics 8: 53–69