Brittle deformation of the Bathurst Batholith: A coeval behaviour with megakinking in the Lachlan Fold Belt, southeastern Australia.

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Abstract: The Bathurst Batholith is a post-kinematic granitic body in the northeastern Lachlan Fold Belt, west of Sydney. A survey of weathered granites in limited outcrops leads to the conclusion that the Bathurst Batholith has been penetratively deformed in a brittle manner. Typical deformation structures are subparallel joint/fault sets and fault gouges, which trend dominantly NNW to NE. Conjugate faults and feather fractures indicate north-south shortening. These brittle deformation structures can be interpreted as related to post-kinematic deformation during late Palaeozoic time, possibly including megakinking, in the Lachlan Fold Belt.

Key words: structural geology, granite, joint, fault, megakink.

INTRODUCTION

The Bathurst Batholith is a “subsequent bathylith” (Browne, 1931), or a post-kinematic granitic body (Valiance, 1969), which is located in the northeastern Lachlan Fold Belt (Fig.1). The batholith is made up of several types of granitoid, collectively termed the “Bathurst Granite”, all of which are massive and non-foliated (Valance, 1969). Because of their massive textures, extensive weathering and limited outcrops, deformation structures have not been studied in detail since the petrological investigation by Mackay (1964). This paper describes the brittle deformation structures such as joints and faults formed penetratively in the Bathurst Batholith and discusses their significance to north-south shortening, related to late Palaeozoic megakinking in the Lachlan Fold Belt.

One outcrop of the Davies Creek granite (Fig.1), just south of the Bathurst Batholith, is also discussed here because of its important fractures. The Davies Creek granite is considered to have intruded into the Rockley district in the “?Early Carboniferous” (Fowler, 1989; Fowler & Lennox, 1992) or in the Devonian (Shaw et al., 1982).

GEOLOGIC SETTING

The Bathurst Batholith, about 100 kilometres long in the WNW-ESE direction, intruded discordantly across the generally N-S trending, folded Ordovician to Late Devonian strata (Brunker and Rose, 1969), after the Kanimblan Orogeny (Stevens, 1974) (Fig.1). Its K-Ar ages were reported as 300 and 308 Ma (biotite: Evernden and Richards, 1962) or 301±6Ma to 318±17Ma (biotite or whole rock: Facer, 1978). Its Rb-Sr ages are from 340 to 312 Ma (Shaw & Flood, 1993), indicating late Early/early Late Carboniferous age of intrusion. The Bathurst Batholith is composed of coarse-grained (biotite-) granite with orthoclase megacrysts or coarse-grained biotite granite and hornblende-biotite granodiorite without megacrysts. The Granite contains quartz veins, microgranite dykes, and also contains mafic enclaves (Branagan, 1972).

The Bathurst Batholith and the enclosing country rocks are nonconformably overlain by the Shoalhaven Group which forms the basal part of the western Sydney Basin. The Shoalhaven Group resting on the Bathurst Batholith is uppermost Early Permian (upper Artinskian or Kungurian) (Branagan et al., 1976: Briggs, 1991).

The Bathurst Batholith is situated along a zone of east-southeasterly trending lineaments through Orange (Fig.1) which constitutes the northern edge of the 50 kilometres-wide Lachlan River lineament (Scheibner & Stevens, 1974). The latter is interpreted as a large megakink band with 25 kilometres dextral offset of the Late Devonian strata (Powell et al., 1985).
The Bathurst Batholith generally forms a low-relief surface and is topographically lower than the surrounding annulus of regionally-metamorphosed sedimentary rocks. It displays similar granite landforms to those elsewhere in the Lachlan Fold Belt (Branagan, 1972). Outcrops of Bathurst Batholith are limited and are extensively weathered. One hundred and eighty-five outcrops have been examined along roads, railway cuttings and creeks (Fig.2). Measurement faces of outcrops are
Deformation structures as indicators of palaeostress axes directions

Two sets of conjugate faults have been recognized in the eastern area of the batholith (Fig. 7: G.R.437639 and 279876: Fig.3f), based on opposite sense of displacements and cross-cutting relations. Displacements along each fault vary from one centimetre to 25 centimetres. They show $o_3$ (minimum principal stress) axes gently plunging E or W, and $o_1$ (maximum principal stress) axes gently plunging N or S. The half shear angles are about 25° and about 20° (Fig.8a, b).

Two feather fractures have been recognized in the western area and in the Davies Creek Granite (Fig.7: G.R.269042, 432794: Fig.6e). Rotational axes of drag folding and disposition of principal stress axes are inferred stereographically (Fig.8c, d). Both sets of feather fractures show a 3 axes gently plunging E to ESE, and $o_1$ axes moderately plunging SSW. The half shear angles are 15°, 23°, and 25° to 30°.

The direction and sense of displacement can be determined for seven high-angle faults in the western and eastern areas (Fig.7: G.R.307069, 319957, and 617863) using a combination of striations on slickensides and displaced markers. The principal stress directions are computed stereographically (Ramsay & Huber, 1987, p.607):

1. $c_2$ (intermediate principal stress) lies on the fault plane oriented at 90° to the striations.
2. $o_1$ is situated in a plane (great circle with pole a 2) at half shear angles.
3. $o_3$ is constructed by finding a point on the great circle with pole $o_2$ at an angle of 90° - x° (x=half-shear-angle) from the slip direction on the opposite side of the fault. As the half shear angle is about 15° (minimum) to 30° (maximum), $o_3$ axes plunge gently or moderately easterly and $o_1$ axes plunge gently or moderately northerly or southerly (Fig.8e).

Graphical determination of principal stress directions for slickensides populations using "M-planes" (Aleksandrowski, 1985) shows gently plunging $o_1$ and $o_3$ axes and subvertically or steeply-plunging $o_2$ axis, though the directions of $o_1$ and $o_3$ axes are not determined.

**DISCUSSION**

Deformation styles of the Bathurst Batholith

Deformation structures in the Bathurst Batholith are composed of joints and faults, all of which were formed by fracturing or brittle deformation. Folds of layered structures also show brittle behaviour. Fractures without gouges appear like joints and are not recognizable as faults unless there are displaced markers, striations, or drag folds. However, most fractures in the Bathurst Batholith are probably faults and not joints. No ductile deformation structures are developed in the Bathurst Batholith, rig.3. (Opposite Page)

Photographs of representative outcrops. The length of the hammer in photographs is 26 centimetres. Localities are indicated by grid references (G.R.'s) of 1:100,000 National Topographic Map Series; Blayney 8730, Orange 8731, Oberon 8830, Bathurst 8831, and Katoomba 8930.

(a) Subvertical subparallel joints/faults (arrows) (G.R.329817, 9 kilometres south of Lithgow).
(b) Ten subparallel fractures (a to j) displaced by a fault. The left-separation is about tens centimetres (G.R.307874, 5 kilometres southwest of Lithgow).
(c) Drag folding of quartz veins (G.R.617863: See Fig.7 for locality). (Outcrop sketch in Fig.6b).
(d) A minor thrust (G.R.319957: See Fig.7 for locality). Millimetres-spaced subparallel fractures are formed densely in the foot wall. Note the displaced orthoclase (Outcrop sketch in Fig.6a).
(e) Kink fold of a fractured granite (G.R.687813: See Fig.7 for locality).
(f) Conjugate minor faults displacing a quartz vein (G.R.279876: See Fig.7 for locality. Wulff net in Fig.8b).

**Representative deformation structures**

Sets of high-angle subparallel joints/faults, most of which dip subvertically, are formed penetratively in the batholith (Fig.3a). They extend from the bottom to top of outcrops. Spacing varies from centimetres to metres (Fig.4a), and orientations range within about 20° for each set (Fig.4b). The Bathurst Batholith can be tentatively divided into western and eastern areas based on the general trends of these joints/faults (Fig.5). The boundary is close to the junction of two separate granite phases identified by Stevens (1973). The main trends are NNW to NNE with subordinate E trend in the western area, while N to NE trends occur in the eastern area (Fig.5, upper right).

Displacements along these joints/faults are recognizable even in massive granite by displaced markers, such as coarse-grained granitic textures, orthoclase megacrysts, enclaves, veins/dykes, or joints/faults. When joints/faults are used as markers, at least three joints/faults should be systematically displaced, or other evidence of displacement should be recognized (Fig.3b). Striated surfaces in granite are also evidence of faults along which displacement has occurred, though striations are obscure in many places due to weathering. About 40% of the measured 365 joints/faults show striations, most of which plunge 0° to 30°S on northerly-trending subvertical fracture surfaces (Grid Reference (G.R.)290867, Fig.4c). Striations have been used only to note directions of displacement as it is difficult in the weathered Bathurst Granite to deduce with confidence the sense of displacement from striations alone. Zones of fault breccia and gouge are easily recognizable in outcrops. They are centimetres to a metre in width and lack primary cohesion. They are made up of breccias and decomposed mineral grains of granite.

Each set of joints/faults shows evidence of displacement, mainly slickensides and subordinately displaced markers and fault breccias/gouges (e.g., Fig.4c). Thirty-six percent of the measured 134 sets of joints/faults show evidence of displacement. Intense brittle deformation zones are formed in places where sets of closely spaced subparallel joints/faults of varying orientations intersect with each other. Granite is fractured to form slabs and blocks of various sizes (Fig.6a). Displaced markers, striated surfaces and gouges indicate that many slabs and blocks moved relative to one another. When veins/dykes are used as displacement markers, relative movements between slabs and blocks can be clearly established (Fig.6b). Layered structures such as subparallel fractures or veins/dykes show drag folding (Fig.3c). Densely spaced fractures may also be folded directly adjacent to the minor gouge zones, particularly where they bifurcate or terminate (Fig.6c). Gouge zones with sliced and displaced megacrysts are formed in some places (Fig.6d). They are generally bounded on both sides by planar fracture surfaces. Subparallel fractures are spaced less than a centimetre apart, and serve as evidence of displacement by millimetres or more, as shown by displacement markers.

Feather fractures associated with fault gouges are another type of intense brittle deformation. Feather fractures are striated and folded along gouge zones (Fig.6e). Gouge zones are composed of dense subparallel slip surfaces, irregularly oriented fractures, and scaly clays.

Low-angle subparallel faults occur locally in the batholith (Fig.7: G.R.319957, 687811, 374843). They have reverse components of displacement, with centimetres to tens of centimetres magnitude, as shown by displaced markers (Fig.3d). Striations and displaced markers show oblique-slip movements on the faults. Closely-spaced fractures are developed parallel to faults in zones a few metres wide adjacent to main faults, indicating a brittle deformation.

The Bathurst Granite was capable of being folded, in an analogue way to that reported by Davies and Pollard (1986), as it has planar structures such as subparallel fractures and veins/dykes in many places. Drag folds associated with faults provide evidence of the nature of the displacement along fractures. Slabs of subparallel-jointed granites are displaced across fault surfaces to produce open kink folds at some localities (Fig.7: G.R.302025, 246844, 687813: Fig.3e), though no kink bands have been observed.
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Firstly, $\sigma^2$ (intermediate principal stress) lies on the fault plane oriented at 90° to the striations. Secondly, $\sigma^1$ is situated in a plane (great circle with pole $\sigma^2$) at half shear angles. Lastly, $\sigma^3$ is constructed by finding a point on the great circle with pole $\sigma^2$ at an angle of 90° - $\theta$ (x=half-shear-angle) from the slip direction on the opposite side of the fault. As the half shear angle is about 15° (minimum) to 30° (maximum), $\sigma^3$ axes plunge gently or moderately easterly and $\sigma^1$ axes plunge gently or moderately northerly or southerly (Fig.8e). Graphical determination of principal stress directions for slickensides populations using “M-planes” (Aleksandrowski, 1985) shows gently plunging $\sigma^1$ and $\sigma^3$ axes and subvertically or steeply-plunging $\sigma^2$ axis, though the directions of $\sigma^1$ and $\sigma^3$ axes are not determined.

**DISCUSSION**

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Brittle Deformation of the Bathurst Batholith

(a) Joint/fault spacing

(b) Contoured pole density diagram of joints/faults

(c) Plan view of joints/faults along the route. Spacing between joints/faults ranges from several centimetres to 0.2 metre.

(d) Plastic deformation of a quartz vein.

(e) Kink fold axis

(f) Quartz vein and faulting.
except for some drag folds of brittle-ductile transitional behaviour. Even biotite grains, the most plastic mineral in the Bathurst Granite, show no signs of plastic deformation. This phenomenon is in contrast to nearby Silurian/Devonian syntectonic or pre-tectonic meridional granitoids, such as the Wyangala Batholith (Morand, 1988: Paterson et al., 1990), the Barry Granite (Lennox et al., 1991), and the Wollogorang Batholith (Shaw et al., 1982) (Fig.1), in which some biotite grains are warped and kinked even in non-foliated I-type granitoids (Vernon and Flood, 1988). The Bathurst Batholith is considered to have attained high level in the crust and a part of the Batholith apparently crystallized under quite shallow cover (Vallance, 1969). The half shear angles of about 15° to 30° suggest that the conjugate faults and feather fractures were formed under limited overburden. Therefore, the batholith is considered to have been deformed under low confining pressure/temperature which enables only brittle deformation.

Fig. 4. An example of a set of subvertical subparallel joints/faults (G.R. 290867, 6 kms southwest of Lithgow).
(a) Plan view of joints/faults along the route. Spacing between joints/faults ranges from several centimetres to 0.2 metre.
(b) Contoured pole density diagram of the joints/faults (equal area projection; lower hemisphere). The general attitude indicates the average strike and dip measured by “sighting-method” (Davis, 1984).
(c) Frequency of striation plunge. Most striations plunge shallowly southward.

Stress and strain
All the deformation structures used as indicators of palaeostress axes directions show northerly oriented σ1 axes and easterly oriented σ3 axes. It is probable that other penetrative fractures were also formed, at least in part, under a stress system with north-trending σ1 axis and east-trending σ3 axis.

The NNW- and NE-trending subparallel fractures are also likely to have been formed under the influence of north-south trending σ1 axis (Fig.8a to d), and possibly contributed to north-south shortening. In intense brittle deformation zones in the Bathurst Batholith, a stress analysis is impossible because of anisotropy due to fracturing and the later complex strain history affecting the Sydney Basin (Branagan, 1985: Lohe and McLennan, 1991).

Deformation history
The present surface of the Bathurst Batholith is considered to have been near the earth’s surface without substantial overburden since early Cainozoic for the following reasons: (1) Tertiary basaltic lava flows lie nonconformably on the Bathurst Granite to the southwest of Bathurst and also lie unconformably on the country rocks just to the northeast, west and south of the Bathurst Batholith (Fig.1). (2) The Middle Shoalhaven Plain, 150 to 200 kilometres south of Bathurst, is a dissected peneplain of Ordovician strata, partly covered with Late Eocene basaltic lava flows and Early to Middle Eocene alluvial sediments. It is considered likely to date back to the Mesozoic (Ruxton & Taylor, 1982). (3) Near the Middle Shoalhaven Plain at Sassafras, a Middle Eocene basaltic lava flow overlies a plateau capping and its adjacent valleys, indicating that the early Tertiary landscape has been preserved (Young & McDougall, 1985). Pre-Cainozoic periods are the only possible times when the present surface of Bathurst Batholith was subject to certain overburden. These periods are considered to be: (1) before the uppermost part of the Bathurst Batholith was eroded preceding the formation of a nonconformity, i.e., Late Carboniferous or early Early Permian, and (2) during the time when a possible western continuation of Permian/Triassic strata of the Sydney Basin nonconformably lay on the Bathurst Batholith, i.e., Late Permian to early Cainozoic. Possibility (2) is of minor significance because the western continuation of the Sydney Basin onto the Bathurst Granite is estimated to have been much less than 1,500 metres; the sum of “about 500 metres” (=the present thickness of strata at the...
western edge of Sydney Basin) and "a thickness much less than 1,000 metres" (=thickness of the eroded strata in the Sydney Basin; Branagan, 1983). The thickness of sedimentary cover is estimated to have been about 300 metres maximum for the Permian and Mesozoic strata on the Ordovician to Devonian strata and a Carboniferous granite around Capertee, about 50 kilometres northeast of Bathurst (Branagan, 1972). Thus, case (1) is much more probable.

Fig. 5. Distribution of subvertical subparallel joints/faults in the Bathurst Batholith. Upper right: Contoured pole density diagrams of sets of joints/faults. Each point represents the general attitude of each set.

Fig. 7. Locality and type of representative deformation structures of the Bathurst Granite. Faults, feather fractures, and kink folds are represented by schematical drawings. (Six numbers: grid references).
Fig. 6. Sketches of intensely deformed granites.
(a) Intense brittle deformation zone made up of dense fractures of various orientations (G.R.319957: See Fig.7 for locality).
(b) Folded and displaced granite (G.R.617863: See Fig.7 for locality). Drag folding of quartz veins is well exposed on the subvertical southern wall of the railway cutting. Displaced quartz veins are well exposed on the subvertical northern wall of the railway cutting, which is shown on the plan view in the lower left of this figure.
(c) Millimetres-spaced fractures. Note displacements of quartz veins along fractures and rotation of fractures (G.R.277876, 8 kilometres west-southwest of Lithgow). Enlargement: Minor fold of densely fractured granite associated with minor fault.
(d) Sliced and displaced megacrysts of orthoclase in a gouge zone (G.R.228817, 25 kilometres southwest of Bathurst).
(e) Feather fracture, associated with a gouge zone (Plan view) (G.R.269042: See Fig.7 for locality. Wulff net in Fig.8c).

Fig.8. (Opposite Page)
Disposition of principal stress axes. (a, b, d, e: Wulff net, lower hemisphere. c: Schmidt net, lower hemisphere).
(a), (b) Deduced from conjugate faults.
(c), (d) Deduced from feather fractures.
(e) Deduced from single faults.
The Intrusion of the Bathurst Batholith is considered to have taken place at the time of deformation possibly related to the early Tertiary activity of the Sydney region, in Engineering Geology of the Sydney Region, pp.3-46. P.

The north-south shortening characterized by this deformation structures in the Bathurst Batholith, where fractures similar to those reported here are described in brittle shear zones, and which "could be contemporaneous with..." (Begg et al., 1987).

The north-south shortening is preserved and is possibly related genetically to post-Late Devonian activity of the Lachlan River lineament in the Lapstone Structural Complex at the eastern lineaments (Scheibner & Stevens, 1974) or is also possibly related to the early Tertiary activity of the Sydney region, in Engineering Geology of the Sydney Region, pp.3-46. P.

Such brittle deformation of the Bathurst Batholith are attained in a brittle manner in several areas. The north-south shortening was detected in the Cann Valley Granitoids in Victoria, well south of the Lachlan Fold Belt during the Late Carboniferous or early Early Permian. The northwest to southeast shortening, which predates the north to south shortening, is possibly related to the Early to Middle Devonian Cann zones, which "developed 310°-0° dextral brittle shear zones", and which "could be contemporaneous with..." (Begg et al., 1987).

As shown in some sketches (Fig.6), large strains could have possibly occurred in relation to the deformation, possibly involving east-west shortening (Hobbs and Hopwood, 1969). This is one of the possible times in the last deformation of Palaeozoic rocks on the South Coast and possibly postdating the Early Devonian activity of the Lachlan River lineament in the Lapstone Structural Complex at the eastern lineaments (Scheibner & Stevens, 1974) or is also possibly related to the Early to Middle Devonian Cann zones, which "could be contemporaneous with..." (Begg et al., 1987).

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The Bathurst Batholith has been fractured densely and extensively to represent a major phase of brittle deformation. Evidence of which, through displaced markers and striatums, the brittle deformation is considered to have been responsible for the east-west shortening (Hobbs and Hopwood, 1969). This is one of the possible times in the last deformation of Palaeozoic rocks on the South Coast and possibly postdating the Early Devonian activity of the Lachlan River lineament in the Lapstone Structural Complex at the eastern lineaments (Scheibner & Stevens, 1974) or is also possibly related to the Early to Middle Devonian Cann zones, which "could be contemporaneous with..." (Begg et al., 1987).

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Intrusion of the Bathurst Batholith is considered to have taken place at the time of deformation involving east-west shortening (Hobbs and Hopwood, 1969). This is one of the possible times for the east-west shortening responsible for low-angle thrust faults at G.R.319957 and 374843 (Fig.7), though other possibilities still remain.

As shown in some sketches (Fig.6), large strains are attained in a brittle manner in several areas. Such brittle deformation of the Bathurst Batholith is possibly related genetically to post-Late Devonian activity of the Lachlan River lineaments (Scheibner & Stevens, 1974) or is also possibly related to the early Tertiary activity of Lapstone Structural Complex at the eastern extension of the Lachlan River lineament in the Sydney Basin (Branagan and Pedram, 1990).

**Comparison with other areas**

A north-south compression is inferred from megakinks on the South Coast of New South Wales (Powell, 1983: Powell et al., 1985), where the inferred disposition of stress axes are N-S-trending for $\sigma_1$, vertical for $\sigma_2$, and E-W for $\sigma_3$. This stress system is considered to have been responsible for the last deformation of Palaeozoic rocks on the South Coast and possibly postdating the Early Carboniferous folding event (350±Ma) (Powell, 1983) and to have antedated the oldest sediments of the Sydney Basin. Because of coincidence of stress axes dispositions and timing of deformation, the north-south compression inferred from brittle deformation structures in the Bathurst Batholith could have possibly occurred in relation to the north-south compression responsible for the formation of these megakinks.

A north-south shortening was detected in the Cann Valley Granitoids in Victoria, well south of the Bathurst Batholith, where fractures similar to those reported here are described in brittle shear zones, which “developed 310°-0° dextral brittle shear zones associated with some 020°-050° sinistral zones”, and which “could be contemporaneous with the north to south compression documented in New South Wales by Powell (1984)” (Begg et al., 1987). The north-south shortening characterized by this investigation is therefore not just a local feature within the Bathurst Batholith, but could possibly be part of a wider regional pattern in the Lachlan Fold Belt during Late Carboniferous or early Early Permian. The northwest to southeast shortening, which predates the north to south shortening, is detected in the Early to Middle Devonian Cann Valley Granitoids by Begg et al. (1987), while an east-west shortening possibly occurred in the Bathurst Batholith.

**CONCLUSION**

The Bathurst Batholith has been fractured densely and locally deformed intensely in a brittle manner. The most penetrative features in the batholith are subvertically-dipping subparallel fractures, many of which, through displaced markers and striations, show movements along them. Fault gouges and folds of layered structures in granites are also representative of brittle deformations. Evidence of north-south shortening is preserved and is probably related to the deformation, possibly including megakinking in the Lachlan Fold Belt, during the Late Carboniferous or early Early Permian.

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