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D. J. Och ^a; R. Offler ^b; H. Zwingmann ^c; J. Braybrooke ^d; I. T. Graham ^e

^a New South Wales Department of Primary Industries, Londonderry, NSW, Australia ^b Discipline of Earth Sciences, School of Environmental & Life Sciences, University of Newcastle, NSW, Australia ^c CSIRO Petroleum, Bentley, WA, Australia ^d Douglas Partners Pty Ltd, NSW, Australia ^e School of Biological, Sydney, NSW, Australia

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Timing of brittle faulting and thermal events, Sydney region: association with the early stages of extension of East Gondwana

D. J. OCH^{1*}, R. OFFLER², H. ZWINGMANN³, J. BRAYBROOKE⁴ AND I. T. GRAHAM⁵

¹New South Wales Department of Primary Industries, Geological Survey of New South Wales, Londonderry, NSW 2753, Australia.

²Discipline of Earth Sciences, School of Environmental & Life Sciences, University of Newcastle, NSW 2308, Australia.

³CSIRO Petroleum, PO 1130, Bentley, WA 6102, Australia.

⁴Douglas Partners Pty Ltd, 96 Hermitage Road, West Ryde, NSW 2114, Australia.

⁵School of Biological, Earth and Environmental Sciences, UNSW Sydney, NSW 2052 Australia and Australian Museum, 6 College Street, Sydney NSW 2010, Australia.

Structural studies in the Sydney region have revealed the presence of vertical to near-vertical, north-northeast-striking faults that are manifest as joint swarms and highly brecciated zones in which gouge of varying thickness is developed. Strike-slip movement accompanied by minor dip-slip, normal movement occurred on these faults. Timing of movement on these faults by K-Ar dating of illite and illite-smectite in fractions extracted from fault gouges, was attempted. These dates were compared with dates obtained from the host-rocks. K-Ar ages determined from the 2–10 µm to <0.1 µm fractions produced from the gouge and host-rocks, range from 159.5 ± 3.2 to 106.6 ± 2.1 Ma ($n=26$). In <0.5 µm fractions extracted from the gouges that are less contaminated by detrital phases, K-Ar ages vary from 138 ± 4.4 to 106.5 ± 2.1 Ma (mean 121 Ma; $n=6$) which are similar to ages obtained from host-rocks in the Sydney region. The similarity in age between the host rocks and gouge suggests that the K-Ar system has been reset. The resetting is attributed to a thermal event at ca 120 Ma related to the underplating of felsic intrusions associated with early stages of breakup of East Gondwana. Subsequent to this event, dykes of Early Eocene age (K-Ar whole-rock: 51.0 ± 1.1 Ma) exploited north-northeast-striking faults and subsequently developed brecciated margins. These observations and the fact that gouge formed before the thermal event suggests that movement took place on north-northeast-striking faults prior to 120 Ma and after 51 Ma.

KEY WORDS: dykes, faults, gouge, joints, potassium–argon dating, Sydney region.

INTRODUCTION

Absolute timing of fault movements has been investigated by isotopic-dating techniques since the early 1970s (Lyons & Snellenberg 1971). Rb-Sr and K-Ar, the most commonly used isotopic techniques, have been applied in studies of synkinematic illite (Kralik *et al.* 1987; Pevear *et al.* 1997; Vrolijk & van der Pluijm 1999; Choo & Chang 2000; Zwingmann *et al.* 2004; Zwingmann & Mancktelow 2004). Illite is a K-bearing clay suitable for dating by the conventional K-Ar method. Recently, a new development involving ^{40}Ar - ^{39}Ar dating of illite in fault gouge using a micro-encapsulation technique was applied to address and monitor ^{39}Ar recoil (van der Pluijm *et al.* 2001 and references therein).

Unfortunately, there are problems using the K-Ar technique to determine the age of K-bearing clays as contaminants such as detrital muscovite and illite, and other detrital K-bearing phases derived from the

host-rock may be present. These contaminants contribute radiogenic ^{40}Ar to the system and depending on their K content, can substantially change the total fusion age. To determine their presence, X-ray diffraction (XRD) and transmission electron microscopy (TEM) analyses are carried out on several fractions (<2–0.1 µm). Generally, it is found that the finest fractions are the least contaminated and provide the youngest ages (Clauer & Chaudhuri 1995). They are thus considered to be the best approximation to the age of the clay formation.

Burial history will also play a role in defining the age of K-bearing clays. For example, Środon *et al.* (2002) found that fast burial followed by slow burial results in much older mixed ages than those produced by slow burial followed by fast burial.

In the Sydney region, many studies have indicated the presence of different types of faults of varying orientation at a number of localities (Willan 1925; McIver 1979; Branagan 1985; Braybrooke 1985; Rickwood 1985;

*Corresponding author and present address: Parsons Brinckerhoff Australia Pty Ltd, PO Box 5394 Sydney NSW 2001, Australia (doch@pb.com.au).

Branagan *et al.* 1988; Mills *et al.* 1989; Speechley *et al.* 2004; Och *et al.* 2006). However, exposure of faults in this region is limited, particularly between the Parramatta and Georges Rivers (Figure 1) because of the residential concentration. This has made it difficult to produce a map showing the distribution and geometry of faults in the Sydney region, although Pells *et al.* (2004) produced a map featuring known faults across the Sydney CBD to make the geotechnical professionals aware of such features for planning and risk minimisation.

In this study, we have delineated four major north-northeast-striking faults named the Watsons Bay Fault Zone, Woolloomooloo Fault Zone, Luna Park Fault Zone and Homebush Bay Fault Zone plus the less well-developed Heathcote Road Fault Zone and ubiquitous thrust faults in the Triassic Narrabeen Group, Hawkesbury Sandstone and Wianamatta Group of the Sydney region (Figure 1). We have also carried out K-Ar analyses of the gouges associated with these faults in an attempt to ascertain their age of movement, as this aspect has not been examined previously. In addition, we have determined the age of the Great Sydney Dyke ('dyke LVI,' Pittman 1903; Rickwood 1985; Dale *et al.* 1997) and another at South Era Beach (Figure 1). Knowledge of the age of these dykes provides constraints on the timing of movement on the north-northeast-striking faults (see later discussion).

This study complements earlier studies by Zwingmann *et al.* (2004) of faults in Upper Permian sediments of the Sydney Basin at Burwood Beach, south of Newcastle.

GEOLOGICAL SETTING

The study area lies within the Sydney Basin, a north-northwest-trending foreland sedimentary basin ranging in age from Early Permian to Middle Triassic. Clastic sedimentary successions are interstratified with volcanic rocks (Campbell *et al.* 2001) and abundant coal seams of Late Permian age (Bamberry 1991; Little 1998). Within the study area, flat-lying, Lower Triassic sedimentary rocks of the Narrabeen Group (Hanlon *et al.* 1954; Herbert 1980a), Hawkesbury Sandstone (Woods 1883; Conaghan 1980) and Wianamatta Group (Woods 1884; Herbert 1980b), dominate. Various types of faults and joints are common, as are mafic dykes (Pittman 1903; Morrison 1904) (Figure 1). The faults and joints strike northwest, north-south and north-northeast, and the dykes strike northwest, north-northeast and northeast and generally dip vertically (Scheibner 1973; Branagan *et al.* 1988; Lohe *et al.* 1992). The dykes vary in width from tens of centimetres to several metres and commonly exploit joints and faults (Lohe *et al.* 1992). Although the orientation of the faults, joints and dykes is well documented, little is known of their age. Prior to this study, only the age of the dykes at Bondi (151 ± 3 Ma: Embleton *et al.* 1985) was known.

ANALYTICAL METHODS

Techniques

From examination of road-cuts, tunnels, cliff faces and building excavations, fault exposures were identified in

various locations within the Sydney region (Figure 1). Samples of ~ 500 g of fresh material were collected from the core zones of these fault zones and their host-rocks within and outside the damage zone of several of the north-northeast-striking faults (Table 1). To avoid possible contamination, samples were collected directly from the gouge zone ~ 0.3 m below the surface. The samples were reduced to chips by hammer with maximum dimension <10 mm and then gently disaggregated using a repetitive freezing and thawing technique to prevent artificial reduction in size of the rock constituents (Liewig *et al.* 1987). Then, <0.4 , <0.5 , $1-2$, <2 , $2-6$ and $2-10 \mu\text{m}$ fractions were separated in distilled water according to Stokes' Law and the efficiency of this separation was controlled by a laser granulometer. Additional grainsize fractions of <0.1 , <0.4 and $<0.5 \mu\text{m}$ were separated using a high-speed centrifuge.

Dating of the Great Sydney Dyke was determined from plagioclase separated from the sample. The sample was crushed and sieved, and the fraction containing grains of the same dimension as the plagioclase observed microscopically, was collected. It was then washed repeatedly in distilled water to remove any fines and dried. Separation of the plagioclase was carried out using a Frantz Isodynamic Separator by running the fraction repeatedly at increasing current. In most samples a purity of $>95\%$ was obtained.

X-ray diffraction

MICA POLYTYPES

X-ray diffraction (XRD) analyses were carried out on a Philips automated PW1732/10 X-ray diffractometer using $\text{CuK}\alpha$ radiation and graphite monochromator at $40 \text{ kV}/30 \text{ mA}$.

To ascertain the presence and quantity of detrital muscovite, two different preparation techniques were used to determine percentage 2M_1 polytype, one involving pipetting the sample onto a slide, the other packing the sample into a Robinson (1981) mount. The latter technique provided better defined peaks and was used for most samples. The percentage of 2M_1 muscovite relative to 1Md illite was determined from the method of Maxwell & Hower (1967) and the equations of Grathoff & Moore (1996) that involve polytype specific 2M_1 peaks at $2\theta = 23.8^\circ$, 25.5° , 27.8° , 29.8° and 32.1° . Integrated intensities (i.e. peak areas) were measured for these peaks using the Traces Version 5.0 program of Diffraction Technology. Peak heights were measured manually. Only the percentage of 2M_1 determined by the method of Maxwell & Hower (1967) and from the equation of Grathoff & Moore (1996) for the 32.1° peak are given in Table 2 as the latter was the best defined of all the reflections.

TRANSMISSION ELECTRON MICROSCOPY

A JEOL 2010 transmission electron microscope (TEM) was used for a detailed grain-by-grain characterisation of the $<0.4 \mu\text{m}$ clay mineral fractions and the $<2 \mu\text{m}$ fraction from samples 545, 549, 599, 630 and 631 respectively. One drop of clay solution was loaded on a micro carbon grid film and dried under air. Clay

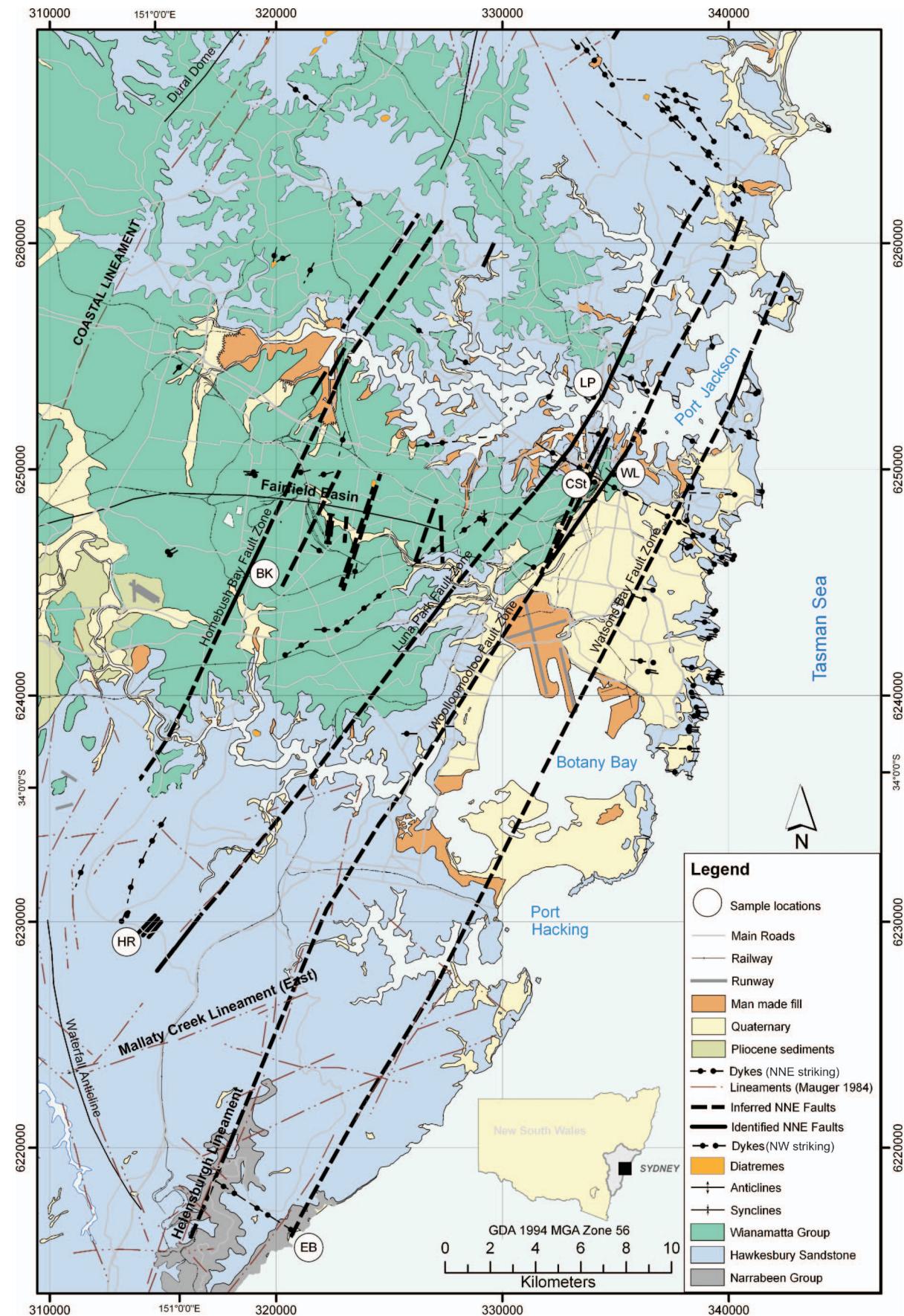


Figure 1 Simplified geology map of the study area showing location of main north-northeast-striking fault zones, dykes and sample locations (after Herbert 1983, Mauger *et al.* 1984; Stroud *et al.* 1985, Clark & Jones 1991). LP, Luna Park; WL, Woolloomooloo cross-city tunnel east; HR, Heathcote Road; CST, Cunningham Street; EB, South Era Beach; BK, Bankstown.

Table 1 K-Ar dates on fault gouge and host rocks.

Location	Coordinates ^a		Sample ID (μm)	K (%)	Rad ^{40}Ar (mol/g)	Rad ^{40}Ar (%)	Age (Ma)	Error (Ma)
	Easting	Northing						
LP1 < 0.5 μm (LP)	334461	6253153	545 < 0.5	7.0	1.3738E-09	92.64	110.4	2.3
LP1 0.5–1 μm (LP)	334461	6253153	546 0.5–1	6.2	1.3731E-09	79.30	124.1	2.5
LP1 1–2 μm (LP)	334461	6253153	547 1–2	5.4	1.3047E-09	83.15	133.2	2.7
LP1 > 2 μm (LP)	334461	6253153	548 > 2	5.2	1.2471E-09	80.02	134.2	2.7
LP3 < 0.5 μm (LP)	334461	6253153	549 < 0.5	6.5	1.2427E-09	87.37	106.5	2.1
LP3 0.5–1 μm (LP)	334461	6253153	550 0.5–1	6.1	1.2601E-09	86.19	115.2	2.3
LP3 1–2 μm (LP)	334461	6253153	551 1–2	4.7	1.0538E-09	83.21	125.6	2.5
LP3 2–10 μm (LP)	334461	6253153	552 2–10	1.6	3.7561E-10	92.73	127.4	2.6
Woolloomooloo cross-city tunnel (WL)	3351184	6250331	559 < 2	3.2	7.3236E-10	94.99	127.7	2.6
Woolloomooloo cross-city tunnel (WL)	3351184	6250331	559 2–6	2.8	6.7505E-10	97.49	134.4	2.7
Lucas Heights/Heathcote Road 1-HAF (HR)	314210	6229524	630 < 0.4	0.3	6.2825E-11	14.78	138.8	4.4
Lucas Heights/Heathcote Road 1-HAF (HR)	314210	6229524	630 < 2	0.5	1.1248E-10	25.75	132.2	3.0
Lucas Heights/Heathcote Road 1-HAF (HR)	314210	6229524	630 2–6	0.8	1.7136E-10	52.50	123.6	2.6
Lucas Heights/Heathcote Road 2-HAF (HR)	314210	6229524	631 < 2	1.6	3.8365E-10	76.19	130.1	2.6
Lucas Heights/Heathcote Road 2-HAF (HR)	314210	6229524	631 2–6	1.6	3.7398E-10	88.47	130.0	2.6
Lucas Heights/Heathcote Road-LAF (HR)	314210	6229524	632 < 0.4	3.7	7.7520E-10	79.86	115.7	2.3
Lucas Heights/Heathcote Road-LAF (HR)	314210	6229524	632 < 2	3.7	8.4138E-10	75.67	125.6	2.7
Lucas Heights/Heathcote Road-LAF (HR)	314210	6229524	632 2–6	3.5	8.9775E-10	84.64	141.0	3.3
Lucas Heights/Heathcote Road-B (HR)	314210	6229524	633 < 2	4.1	9.0372E-10	91.89	121.9	2.4
Lucas Heights/Heathcote Road-B (HR)	314210	6229524	633 2–6	3.9	9.2262E-10	94.86	131.8	2.6
LPC2 (LP)	334461	6253153	671 < 0.4	5.7	1.4036E-09	97.19	136.4	2.7
LPC2 (LP)	334461	6253153	671 < 2	5.2	1.5013E-09	98.66	159.5	3.2
CSC1, 2 Cunningham Street, Sydney (CSt)	334114	6249872	709 < 2	4.9	1.0436E-09	98.18	120.0	2.4
0306 Fault Gouge National Park (EB)	320674	6216113	839 < 0.1	4.0	8.6280E-10	85.75	120.6	2.4
0306 Fault Gouge National Park (EB)	320674	6216113	839 < 0.4	3.4	8.1917E-10	89.21	133.1	2.6
0306 Fault Gouge National Park (EB)	320674	6216113	839 < 2	2.6	6.8401E-10	89.48	147.8	2.9
Great Sydney Dyke (GSD)	333353	6250038	544 (plagioclase)	1.6	4.7644E-10	87.02	163.0	3.3
01/06 South Era Beach Basalt (EB) ^b	320670	6216117	884 (whole rock)	0.8	7.6135E-11	29.48	50.9	1.1

^aAGD 1994 MGA Zone 56.^bDR 17924 alkali basalt, South Era beach, Royal National Park, NSW (Australian Museum collection, Sydney). HAF, high-angle fault; LAF, low-angle fault; B, bedding. See Figure 1 for sample locations.

Table 2 Proportion of 2M₁ in various fractions extracted from hosts and gouges.

Sample no.	Location	2–6 µm	>2 µm	1–2 µm	0.5–1 µm
Centrifuged					
LP1	Luna Park Fault Zone (LP)	–	12, (21), 2	14, (26), 9	~13, (24), 5
LP3	Luna Park Fault Zone (LP)	–	–	28, (51), 16	–
599	Woolloomooloo Fault Zone (WL)	13, (23), 13	–	–	–
Sedimented					
<i>Gouge</i>					
LP1	Luna Park Fault Zone (LP)	–	17, (33), 14	–	10, (17), 21
LP3	Luna Park Fault Zone (LP)	95, (>100), 67	–	–	24, (40), 20
<i>Robinson mount</i>					
<i>Gouge</i>					
630	Heathcote Road Fault Zone (HR)	2, (0), 0	–	0 ^a	0 ^a
631	Heathcote Road Fault Zone (HR)	0 ^a	–	0 ^a	–
632	Heathcote Road Fault Zone (HR)	12, (18), 9	–	0	0
633	Heathcote Road Fault Zone (HR)	7, (12), 4	–	0	–
LP1	Luna Park Fault Zone (LP)	–	18, (33), 14	12, (21), 10	–
LP3	Luna Park Fault Zone (LP)	95 ^b , (100), 67	–	–	~23, (40), 19
599	Woolloomooloo Fault Zone (WL)	12, (24), 12	–	7, (15), 9	–
839	Watsons Bay Fault Zone (EB)	–	–	5–7 ^c	0
<i>Host</i>					
709–2	Cunningham Street Fault Zone (CSt)	–	–	13, (22), 10	–
LPC2	Luna Park Fault Zone (LP)	–	–	20, (25), 16	–

^a0, determination of % 2M₁ not possible: the presence of kaolinite causes low peak intensities of illite and 2M₁.

^bValue obtained from 2–10 µm fraction; 67, values in italics determined from height of 2.8 Å and 2.58 Å peaks; (10), values in brackets determined from peak area of 2.8 Å and 2.58 Å peaks (Grathoff & Moore 1996); 18, value determined by the Maxwell & Hower (1967) method.

^c2.8 Å peak absent: values based on peak heights of 3.21 Å and 3.0 Å.

particle morphologies were investigated as well as the grainsize distribution within the fractions. The presence of contaminants such as K feldspar was investigated and the composition of individual particles was determined by an attached EDS system.

STRUCTURE

In the Sydney region, our studies have revealed four main, high-angle, north-northeast-striking fault zones (Figure 1). Many other smaller fault zones exist between these faults (Chestnut 1983), for example, the Martin Place Joint Swarm, GPO Fault Zone (Pells *et al.* 2004) and Heathcote Road Fault Zone, but their lateral continuity has not been determined. Further, recent georectification of tunnel logs for the ‘City Tunnel’

(Metropolitan Water Sewerage & Drainage Board 1950) indicates that the fault zones shown in Figure 1 correlate with fracture zones in the tunnel. The logging also identified several other fracture zones lying between the Homebush Bay Fault Zone and Luna Park Fault Zone (Figure 1).

The major faults appear to be associated with prominent geomorphological features such as north-northeast-trending bays and valleys (Figure 1) and have zones of up to 3 m in width of brecciated or highly jointed material (Figures 2, 3) containing up to 2 m wide of fault gouge. At Haymarket, drillcore revealed that movement on a north-northeast-striking fault produced crushing and slickensiding of the west-northwest-striking Great Sydney Dyke (163.0 ± 3.3 Ma; K-Ar, plagioclase: Figure 1; Table 1). In some areas, these faults comprise closely spaced (<0.5 m), highly jointed

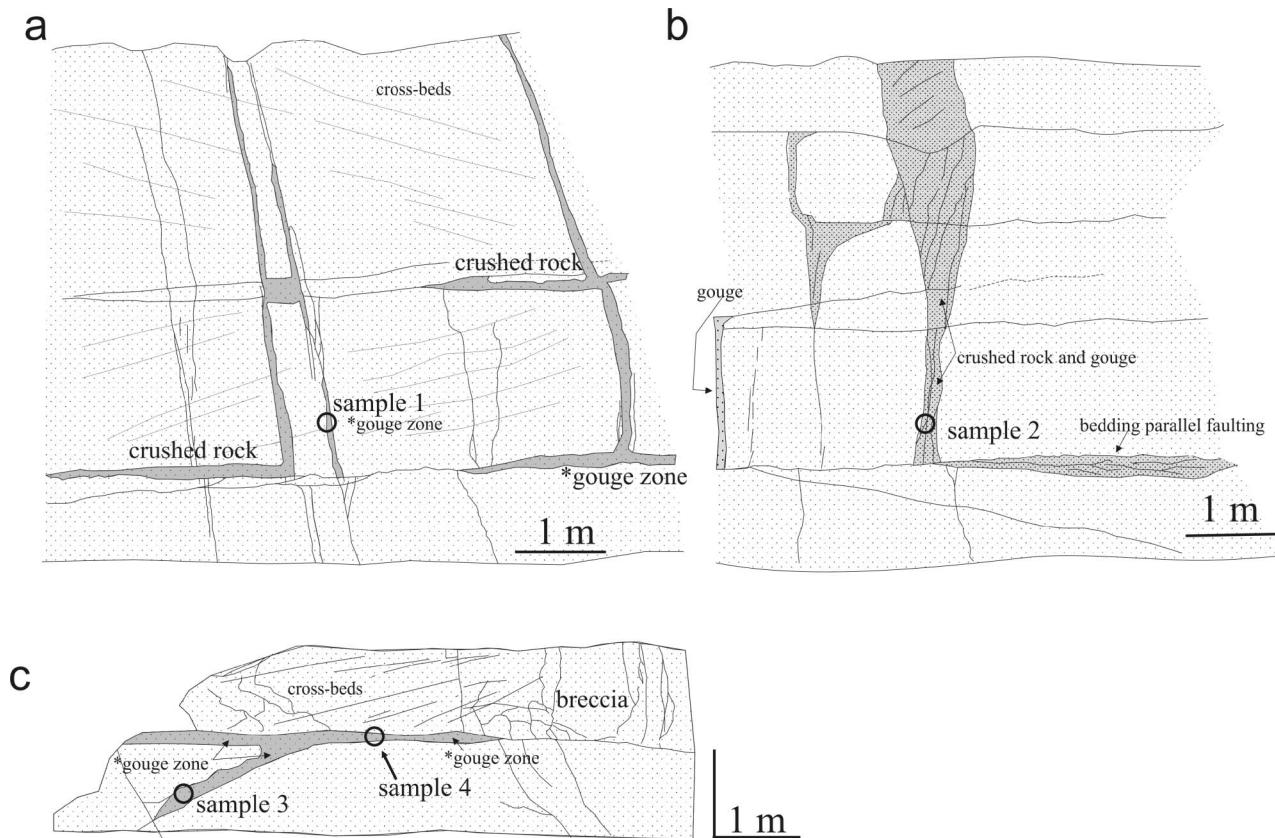


Figure 2 Features of fault zones at the Lucas Heights–Heathcote Road location (GR 314210E 6229524N MGA). Samples 1–4 correspond to sample ID 630–633 respectively in Table 1.

zones (especially in shale) up to 30–70 m in width. In other areas (e.g. Centro Bankstown), the faults have an *en échelon* pattern, with zones in between having accommodation normal and reverse faults. Hanging-walls associated with these reverse (thrust) faults are commonly identified by laterally extensive highly weathered and fractured rock (Figure 3c). The Heathcote Road Fault Zone occurs along a north-facing sandstone road cut 1 km west of the Luna Park Fault Zone and comprises several widely spaced discrete sheared joint zones, with gouge zones up to 200 mm wide. South of Sydney at South Era Beach (Figure 1), a basaltic dyke (50.9 ± 1.1 Ma; Table 1) intrudes a possible continuation of the Watsons Bay Fault Zone. Reactivation of this fault has resulted in the formation of veins within the dyke and gouge at the contact of the dyke with the host sandstone. These veins are displaced dextrally by faults striking 110° .

The direction and sense of movement on these north-northeast faults is difficult to determine owing to the general absence of lineations such as slickenlines. The few that do exist indicate strike-slip movement (sinistral: Centro Bankstown, Homebush Bay Fault Zone; dextral: Luna Park, Luna Park Fault Zone) (Figure 4) though displaced bedding in some excavations and road cuts indicate a dip-slip component of movement. Studies carried out by others on north-northeast-striking faults elsewhere in the Sydney Basin, show oblique-slip, strike-slip, normal and reverse movement (Lohe *et al.* 1992; Whitehouse & Branagan 1998; Nicol *et al.* 2002; Memarian & Fergusson 2003). Strike-slip movement

often follows normal fault movement (e.g. at Metropolitan Colliery, Southern Coalfield) according to Lohe *et al.* (1992).

MINERALOGY

XRD studies of various fractions show that most gouges consist dominantly of illite [$<10\%$ smectite (Sme—mineral abbreviation from Siivola & Schmid 2007)], quartz, kaolinite and less common dickite and halloysite in varying proportions (Offler *et al.* 2009). Smectite-chlorite is an additional phase in gouge formed adjacent to a basaltic dyke at South Era Beach (Figure 1) and illite in gouge from the Heathcote Road Fault Zone contains more interlayered smectite (30–38% Sme). Further, the XRD studies indicate that detrital muscovite is a contaminant in all but the finest fractions (Table 2). However, TEM studies reveal detrital illite and K-feldspar as minor contaminants in the $<0.5\text{ }\mu\text{m}$ fraction of 545 and 549 (Figure 5). They also reveal the distinctive lath-like shape of authigenic illite (Figure 5).

K-Ar DATING

Potassium contents of the samples were determined by atomic absorption using Cs for ionisation suppression. 100–200 mg sample aliquots were dissolved with HF and HNO_3 . The samples, once in solution, were diluted to 0.3–1.5 ppm K for the atomic absorption analysis. The

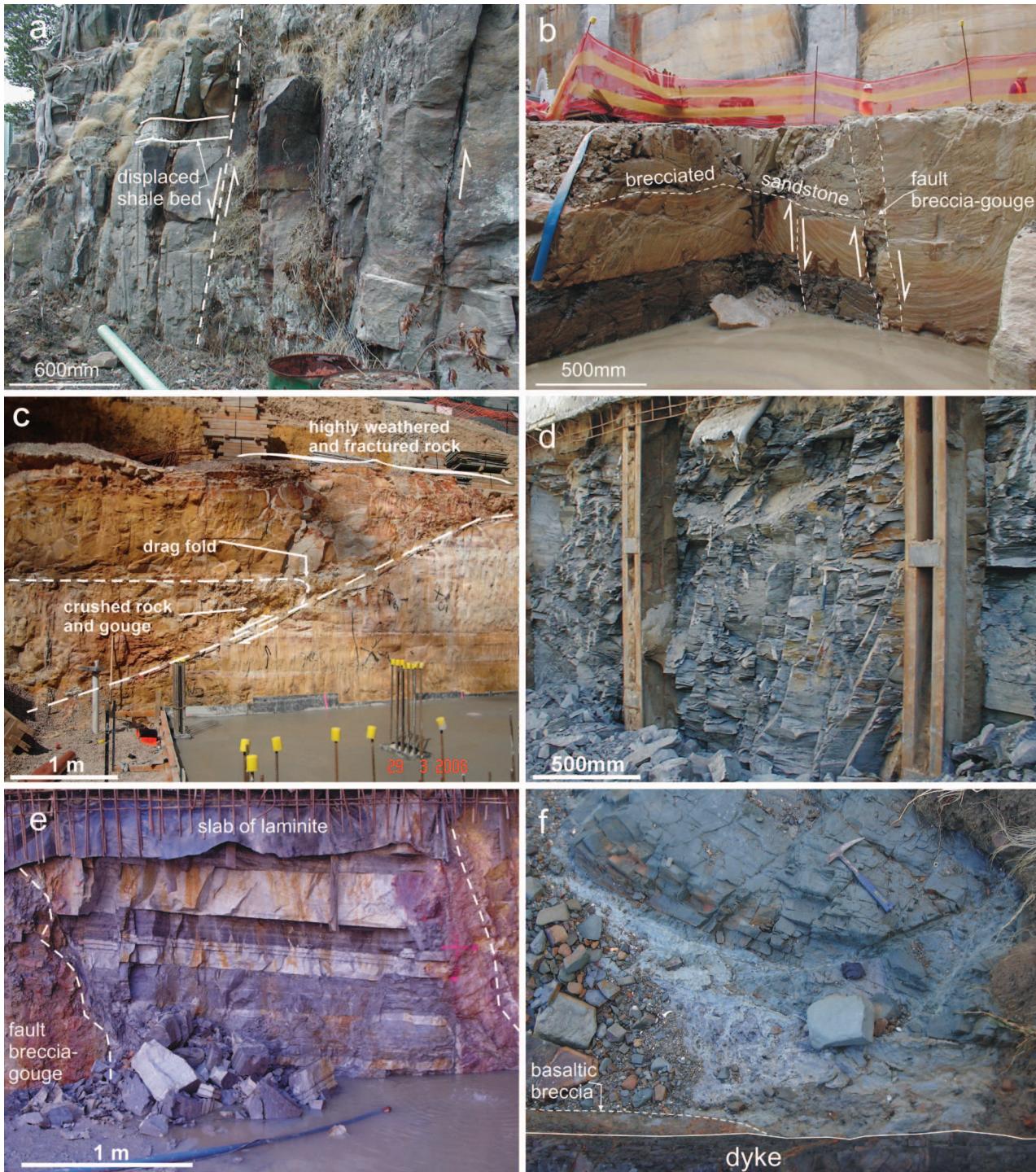


Figure 3 Features of the fault zones. (a) Western extent of Luna Park Fault Zone (GR 334430E 6253250N MGA). (b) Eastern extent of Luna Park Fault Zone (GR 334450E 6253180N MGA). (c) Thrust fault located west of Homebush Bay Fault Zone, Meadowbank (GR 323316E 6256321N MGA). (d) Homebush Bay Fault Zone at Rhodes (GR 322960E 6254440N MGA). (e) Slab of laminate entrained in Luna Park Fault Zone (GR 333750E 6252160N MGA). (f) Fault gouge at border of basaltic dyke, South Era Beach (GR 320680E 6216100N MGA).

pooled error of duplicate K determination on all samples and standards was ~2%. K-Ar isotopic determinations were performed using a procedure similar to that described by Bonhomme *et al.* (1975). Samples were preheated under vacuum at 80°C for several hours to reduce the amount of atmospheric Ar adsorbed onto the mineral surfaces during sample handling. Ar was

extracted from the separated mineral fractions by fusing samples within a vacuum line serviced by an online ^{38}Ar spike pipette. The isotopic composition of the spiked Ar was measured with a high sensitivity online VG3600 mass spectrometer. The ^{38}Ar spike was calibrated against standard biotite GA1550 (McDougall & Roksandic 1974). After fusion of the sample in a low-blank Heine

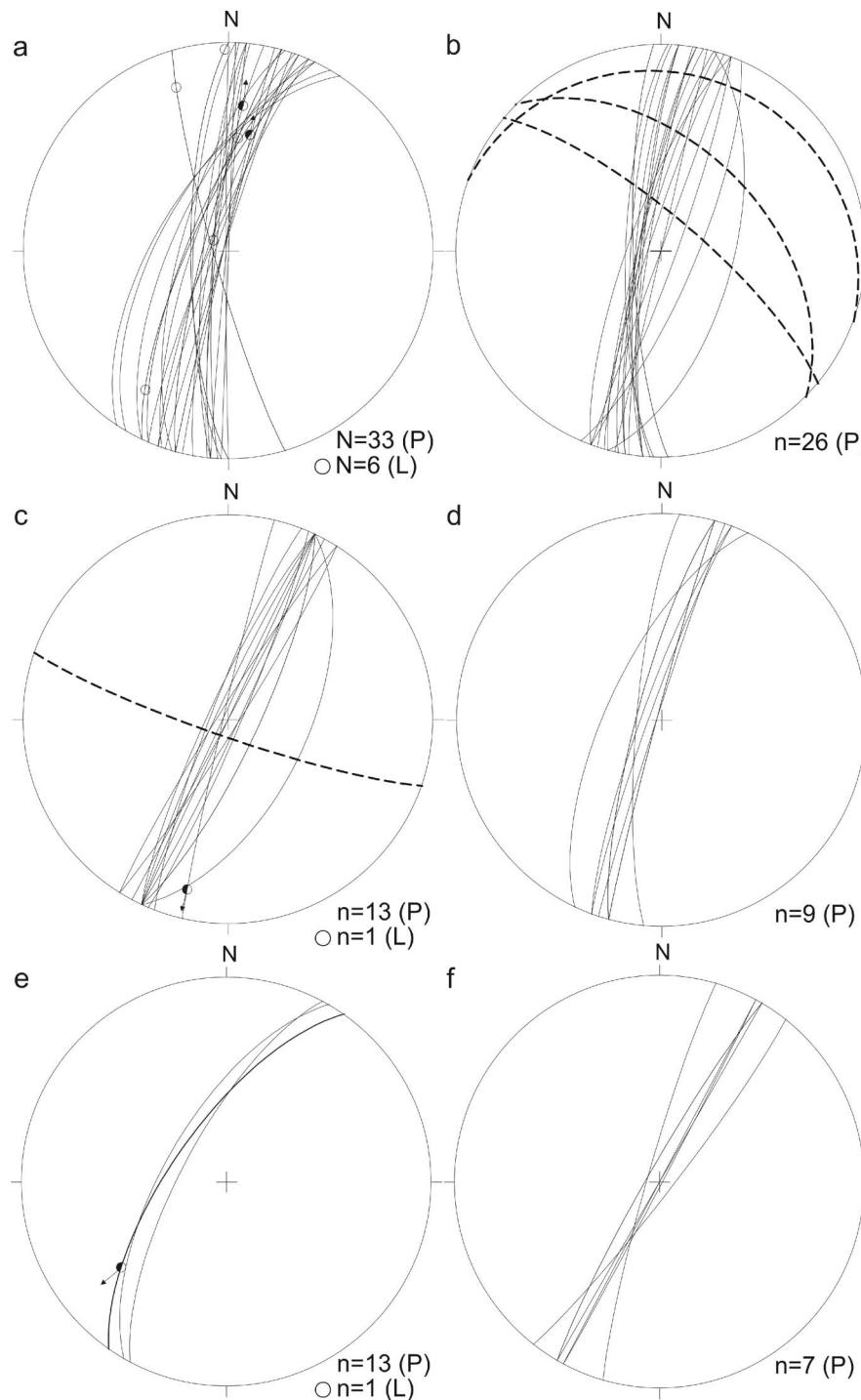


Figure 4 Equal-area plots of faults and lineations measured in various locations. Dashed great circles show orientation of thrust faults measured at the same location. Half-filled circle with arrow denotes the orientation and sense of movement of slickenlines. (a) Luna Park. (b) Heathcote. (c) Bankstown. (d) Cunningham Street. (e) Rhodes. (f) South Era Beach.

resistance furnace, the released gases were subjected to a two-stage purification procedure with a CuO getter for the first step and two Ti getters for the second step. Blanks for the extraction line and mass spectrometer were systematically determined and the mass discrimination factor was determined periodically by airshots. Normally 20 mg of sample material was required for Ar analyses. During the course of the study, standards ($n=10$) and airshot values were measured ($n=24$). The error for Ar analyses was below 1% and the $^{40}\text{Ar}/^{36}\text{Ar}$ value for airshots averaged 293.39 ± 0.29 (2σ , $n=24$). The K-Ar ages were calculated using ^{40}K abundance and decay constants recommended by Steiger & Jäger (1977).

The K-Ar dating results are summarised in Table 1. The age uncertainties take into account the errors during sample weighing, $^{38}\text{Ar}/^{36}\text{Ar}$ and $^{40}\text{Ar}/^{38}\text{Ar}$ measurements and K analysis. K-Ar age errors are within 2σ uncertainty.

Results

Radiogenic ^{40}Ar ranges from 76 to 99% indicating negligible atmospheric Ar contamination and reliable analytical conditions for most samples. However, fractions obtained from sample 630 contain low contents of radiogenic ^{40}Ar (14–52%) indicating contamination

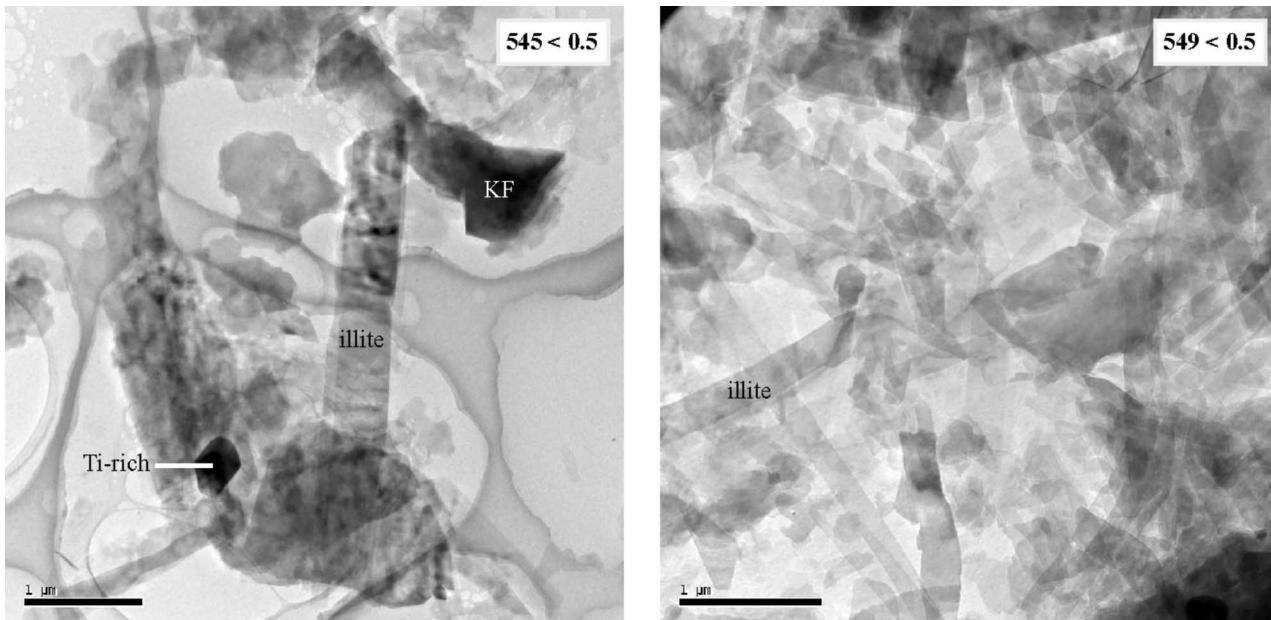


Figure 5 TEM images of $<0.5\text{ }\mu\text{m}$ fractions from 545 and 549. Note distinctive lath-like shape of authigenic illite in both samples as well as contaminant K-feldspar (KF) in 545. Opaque Ti-rich contaminant is probably anatase. Samples stored in the Discipline of Earth Sciences, University of Newcastle.

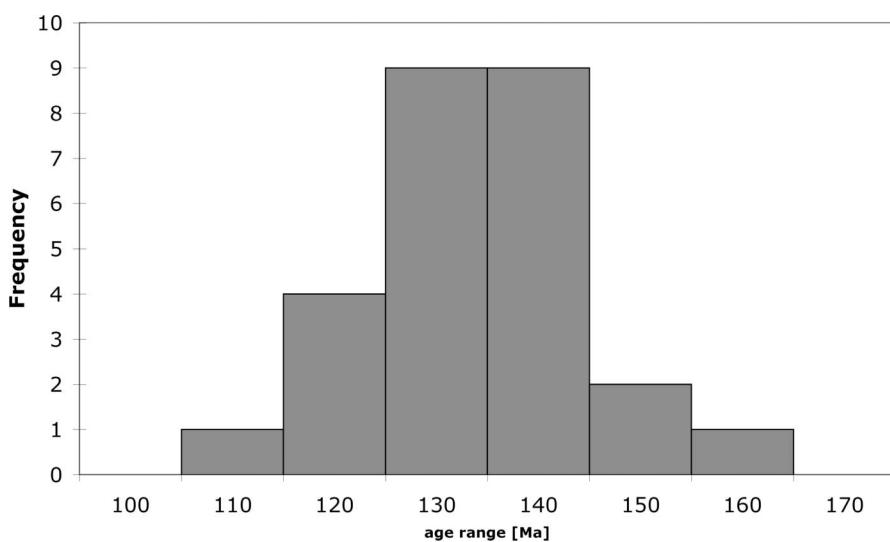


Figure 6 Histogram showing K-Ar ages obtained from all fractions extracted from gouge and host-rocks.

with atmospheric Ar. K content ranges from a low 0.3% for sample 630 $<0.4\text{ }\mu\text{m}$ to 7.0% for sample 545 $<0.5\text{ }\mu\text{m}$ (Table 1). The lower K content in some fractions is due to the presence of kaolinite or halloysite (Offler *et al.* 2009).

K-Ar dating of illite and illite-smectite in fractions extracted from gouges in the major faults at several sites (Figure 1) reveals ages varying between 150 and 100 Ma (Figure 6). In individual fractions, ages of 127.4 ± 2.6 Ma ($2\text{--}10\text{ }\mu\text{m}$), 123.6 ± 2.6 to 134.4 ± 2.7 Ma ($2\text{--}6\text{ }\mu\text{m}$), 121.9 ± 2.4 to 147.8 ± 2.9 Ma ($<2\text{ }\mu\text{m}$), 125.6 ± 2.5 to 133.2 ± 2.7 Ma ($1\text{--}2\text{ }\mu\text{m}$), 115.2 ± 2.3 to 124.1 ± 2.5 Ma ($0.5\text{--}1\text{ }\mu\text{m}$), 106.5 ± 2.1 to 110.4 ± 2.3 Ma ($<0.5\text{ }\mu\text{m}$) and 115.7 ± 2.3 to 138.8 ± 4.4 Ma ($<0.4\text{ }\mu\text{m}$) have been recorded (Table 1); K-Ar dates obtained from the undamaged host-rocks range from 120.0 ± 2.4 to 159.0 ± 3.3

Ma ($<2\text{ }\mu\text{m}$; Figure 7; Table 1). The K-Ar dates recorded by the host-rocks are similar to those obtained by Bai *et al.* (2001) from illite in the Narrabeen Group (90.5 ± 0.9 to $146.2.1 \pm 1.6$ Ma, $<0.2\text{ }\mu\text{m}$; 126.2 ± 1.3 Ma, $0.2\text{--}0.5\text{ }\mu\text{m}$; Figure 8) and at Lucas Heights by Zwingmann (2001: 116.07 ± 2.32 Ma gouge; 107.34 ± 2.12 to 121.39 ± 2.45 Ma, host: $<2\text{ }\mu\text{m}$). In contrast, ages obtained from gouges in north-south-striking faults at Burwood Beach, Newcastle are slightly older (Zwingmann *et al.* 2004: 139.44 ± 2.04 Ma, $<0.1\text{ }\mu\text{m}$; 119.05 ± 2.37 to 121.24 ± 2.42 Ma, $<0.4\text{ }\mu\text{m}$; 122.15 ± 2.04 to 150.91 ± 2.64 Ma, $<2\text{ }\mu\text{m}$; 138.14 ± 2.27 to 164.45 ± 2.92 Ma, $2\text{--}6\text{ }\mu\text{m}$; 142.13 ± 2.83 to 172.34 ± 3.42 Ma, $6\text{--}10\text{ }\mu\text{m}$) and much older from the host-rocks outside the damage zone (237.04 ± 3.9 to 244.89 ± 4.1 Ma, $<2\text{ }\mu\text{m}$; 272.04 ± 4.5 to 281.75 ± 4.7 Ma, $2\text{--}6\text{ }\mu\text{m}$).

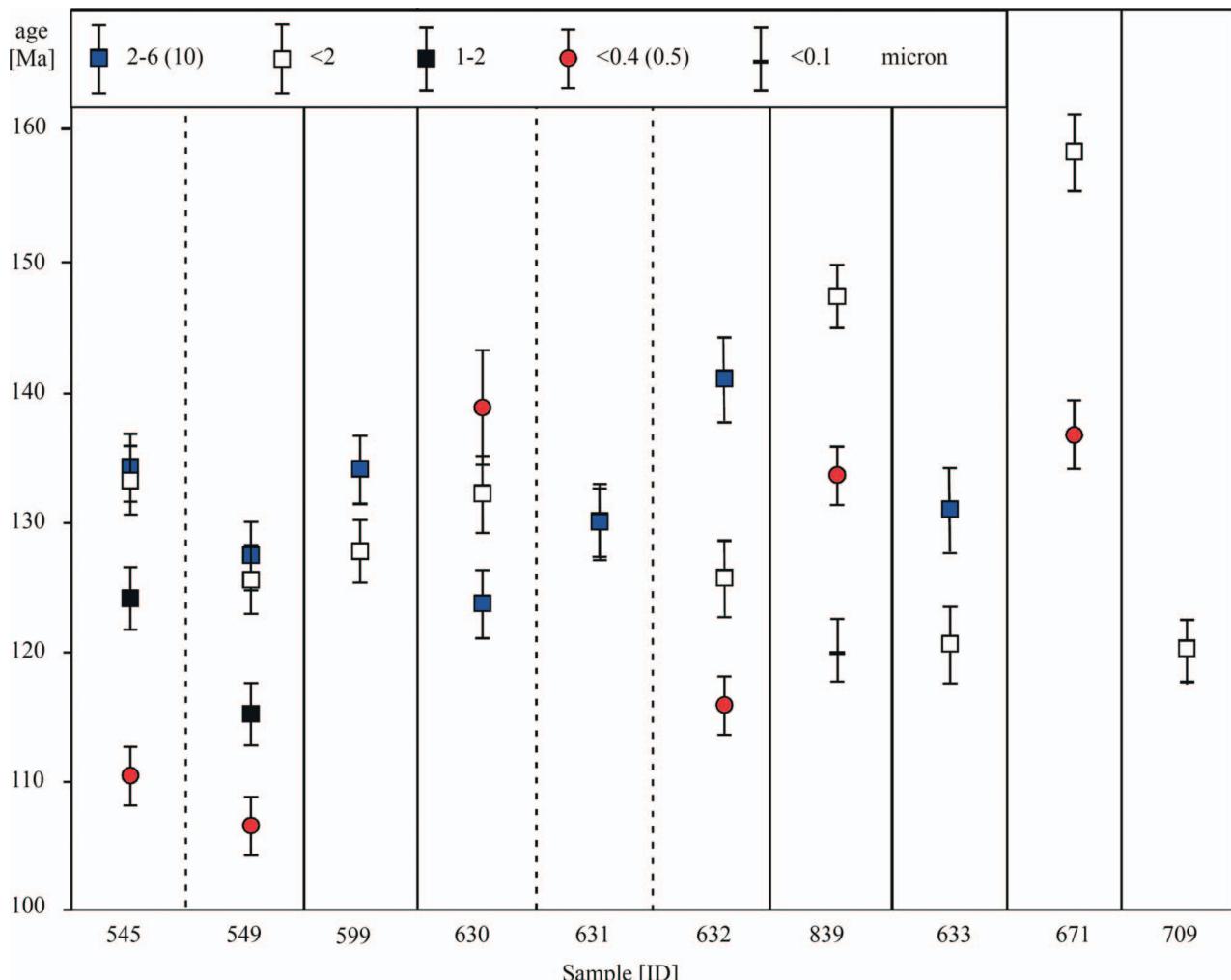


Figure 7 K–Ar dates obtained from various fractions extracted from gouge and host-rocks. Note overall decrease in age from coarse to fine fractions. 545, 549, Luna Park Fault Zone; 599, Woolloomooloo Fault Zone; 630–633, Heathcote Road Fault Zone; 709, host-rock, Cunningham Street, Sydney, located between Luna Park and Woolloomooloo Fault Zones; 671, host-rock adjacent to Luna Park Fault Zone.

DISCUSSION

The correlation of K–Ar ages obtained from illite separates with geologically meaningful events requires careful consideration of the assumptions underlying the method. Meunier & Velde (2004) and Zwingmann & Mancktelow (2004) have stressed that for the dates to be meaningful, no contaminants should be present and the sample should contain no excess or extraneous Ar. Further, the sample should show closed system behaviour.

Examination of Figure 7 shows that the ages progressively become younger from the coarse to fine fractions in most samples, suggesting that the finer fractions are least contaminated by detrital phases, a feature commonly recognised in other studies (Clauer *et al.* 1997 and references therein). The fractions obtained from sample 630 indicate a reverse age trend that is decreasing ages with increasing grainsizes (Figure 7). This inverse age trend could be due to enrichment in the finest fraction of very fine illite particles representing nuclei for subsequent illite

neocrystallisation and growth (Clauer *et al.* 1997; Nadeau 1999). Ostwald ripening can influence continuous overgrowth and grain coarsening (Eberl & Środoń 1988; Eberl *et al.* 1990) and in this process coarser grains would therefore give a younger average age. The trend is similar to that reported by Clauer *et al.* (1997), who observed that the smallest fundamental particles (nanoscale particles: Nadeau 1999) have ages the same as, or older than, larger particles.

The dates obtained from all fractions in the host-rocks are much younger than their stratigraphic age (Middle Triassic, 240–230 Ma: Gradstein *et al.* 2004) supporting the interpretation that contamination by detrital phases is limited. This is confirmed by the XRD analyses that show 24% or less 2M₁ polytype (detrital muscovite) in these samples (Table 2). The ages obtained from the finest fractions (<0.5 μm or less) extracted from the fault gouge range from 107 to 138 Ma with a mean of 121 Ma ($n=6$). The latter is interpreted to represent the maximum possible age for slip on the north-northeast-striking faults since it is unlikely that these fractions were entirely free of radiogenic ^{40}Ar

bearing contaminants. However, close examination of the data reveals that this is a rather simplistic interpretation and that other factors may be playing a role in determining the ages obtained from the various fractions. For example, K-Ar ages obtained from the finer fractions extracted from the gouge accord with those recorded in the host-rocks (Table 1) and at Lucas Heights by Zwingmann (2001: 121–107 Ma, $<2\ \mu\text{m}$) in contradiction to the results determined by Zwingmann *et al.* (2004) in the Newcastle area where the host rocks record diagenetic ages. This observation suggests that the K-Ar system in the clays has been reset by a later event. If this interpretation is correct then the K-Ar data do not indicate the age of the last slip movement on the north-northeast-striking faults. Rather they suggest that there has been a thermal overprint that has reset the K-Ar system. Supporting evidence includes: (i) decrease in K-Ar dates towards the coast where the thermal high prevails (Bai *et al.* 2001) (Figure 8); (ii) iso-reflectance (R_o) and R_o/depth data show an area of higher rank and geothermal gradient in the Sydney–Wollongong area (Diessel 1975; Middleton & Schmidt 1982); (iii) R_o contours from the Upper Coal Measures define northwest- and southwest-trending structures that are discordant with north-south-trending tectonic structures (Brown *et al.* 1996) (Figure 9); similar iso-reflectance patterns are shown by the Lower Illawarra Coal Measures (Mauger *et al.* 1983); (iv) fission-track studies indicate a denudation event related to doming between 110 and 90 Ma (O’Sullivan *et al.* 1996)—these studies indicate that overprinting of earlier older ages and dominance of younger ages in apatite becomes increasingly pronounced closer to the coast; and (v) natural remanent magnetisation studies of pyrrhotite and magnetite in the Milton Monzonite, southeast Australia, record an overprint related to a heating event at *ca* 100 Ma (Dunlop *et al.* 2000) that is believed to be related to doming prior to rifting responsible for the formation of the Tasman Sea.

The existence of such a thermal event has been recognised by others (Maung *et al.* 1997 and references

therein) who suggested that it occurred prior to the formation of the Tasman Sea. The cause of the high heat flux required to produce the unusually high maturation, indicated by the R_o values and resetting of the K-Ar system in the fault gouge, is not known. It is possibly due to underplating of felsic or mafic magmas during the early stages of breakup of Gondwana during the Late Jurassic–Early Cretaceous (Scheibner & Basden 1998). Mafic intrusives of this age are uncommon in the Sydney region (Helby & Morgan 1979; Embleton *et al.* 1985) and there is no gravity evidence for their presence in the subsurface (R. Musgrave pers. comm. 2007). However, felsic rocks of similar age to those recorded in the gouge and host-rocks occur on the New South Wales south coast (Mt Dromedary Igneous Complex; 108 ± 3.9 Ma: Hirata *et al.* 2005). Further, a syenite intrusive ~ 33 m thick occurs in core from DM Cape Banks DDH No. 1 (Menzies & Stuntz 1971) but its age could not be determined due to alteration (Barron 1975). In central Queensland, felsic volcanic activity occurred between 132 and 95 Ma during a rift-related event that Bryan *et al.* (1997) believed was responsible for the dispersal of eastern Gondwana. These occurrences provide strong evidence for felsic magmatism being responsible for the thermal event recorded in the Sydney region.

Although the ages obtained from the fault gouge do not directly date the last slip movement, they nevertheless imply that movement must have occurred prior to *ca* 120 Ma, the time when heating of the sediments and gouge in the Sydney region took place. A further constraint on the timing of slip movement is provided by the observation that the Great Sydney Dyke (163 Ma) is displaced by a north-northeast-striking joint swarm suggesting that these faults must have been active post-Middle Jurassic. An additional constraint is provided by an alkali basaltic dyke that was emplaced during the Early Eocene (51 Ma: Table 1) along a north-northeast-striking fault at South Era Beach. This dyke and others associated with it, have brecciated borders, suggesting that the north-northeast-striking faults have been reactivated post-51 Ma. It follows therefore, that slip movement occurred prior to 120 Ma and subsequently after 51 Ma. In making this interpretation, it is assumed that the thermal event reset the K-Ar system in the clays from the gouge but not that in the plagioclase in the Great Sydney Dyke from which the K-Ar date was obtained. This interpretation is in accordance with commonly accepted closure temperature relationships (McDougall & Harrison 1999).

The influence of the thermal event appears to have been much less in the Newcastle area where older ages in the finer fractions extracted from the host rocks are recorded (Zwingmann *et al.* 2004). Reflectance (R_o) values (0.7: Brown *et al.* 1996) indicate temperatures in this area are lower than those in the Sydney region ($R_o = 1.3$). This suggests they were too low to reset the K-Ar system in the illites present in the host rocks and gouges. This is borne out by the apatite fission-track studies of the Sydney Basin by O’Sullivan *et al.* (1996) who recorded older ages in the Newcastle area than in the Sydney region.

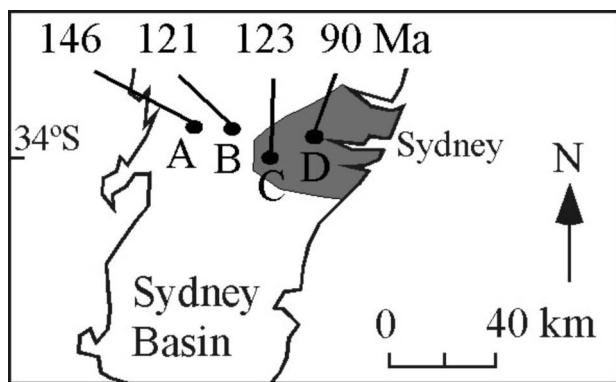


Figure 8 K-Ar ages obtained from $<0.2\ \mu\text{m}$ fractions extracted from Narrabeen Group sandstones by Bai *et al.* (2001). A, Werombi 2; B, Cobbity 3; C, Campbelltown 2; D, Liverpool 1 drillholes from which samples were extracted. Note decrease in ages towards the coast.

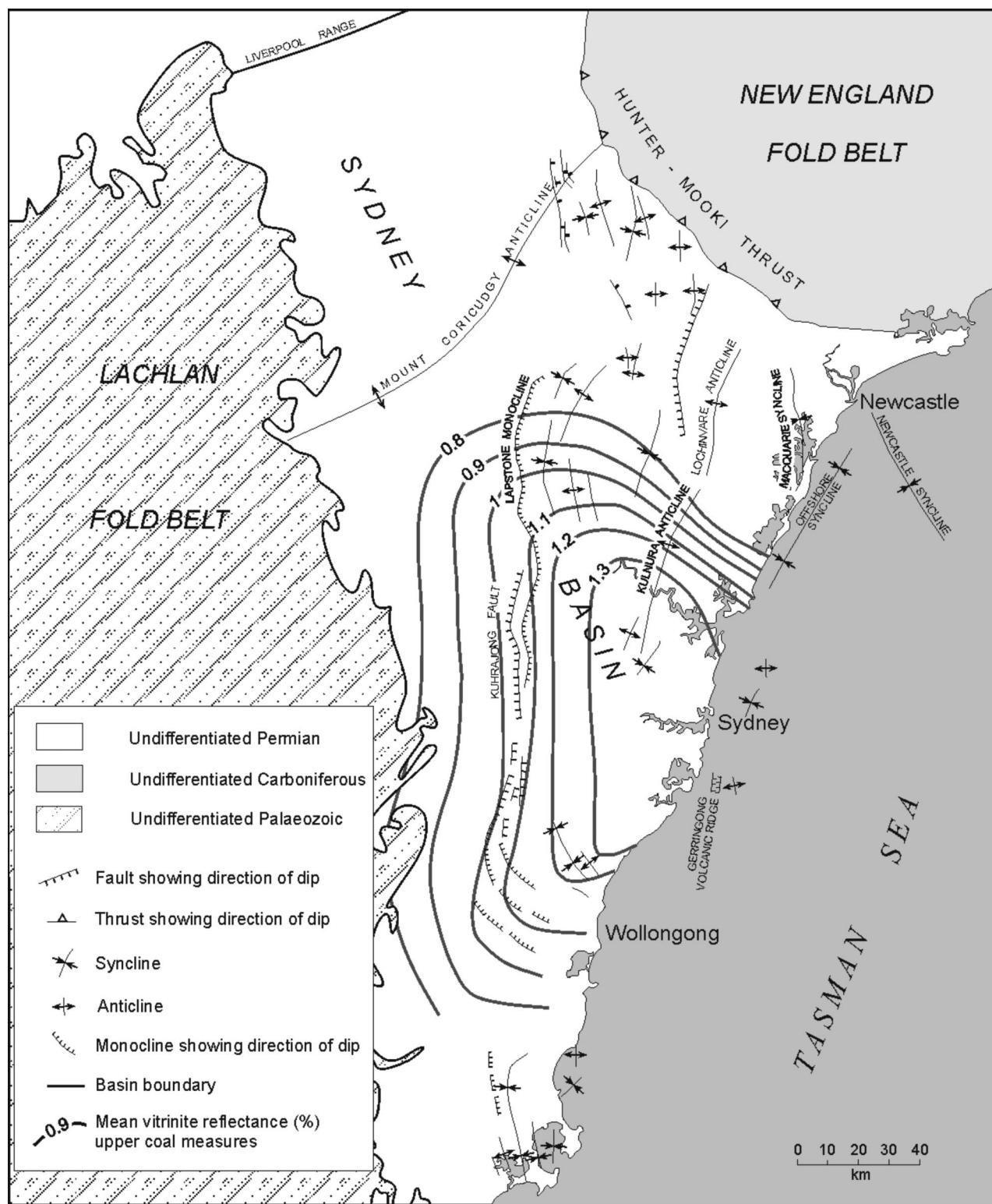


Figure 9 Mean maximum vitrinite reflectance (%), Upper Coal Measures (modified from Brown *et al.* 1996). Note discordance between axial-plane traces of folds and trend of closed structure defined by reflectance contours.

Breakup of eastern Gondwana

On the basis of the data obtained from Newcastle area by other authors (Lohe *et al.* 1992) and in this study, we propose that the following events related to the breakup of Gondwana took place. Initially, north-northeast-striking faults developed at *ca* 136 Ma, the earliest stage

of extension or breakup of Gondwana (Li & Powell 2001). They developed parallel to the margin of the continent with a normal sense of movement during extension. Later, at *ca* 120 Ma, underplating of felsic magma took place as extension continued, resulting in the gouge developed on the north-northeast-striking faults and

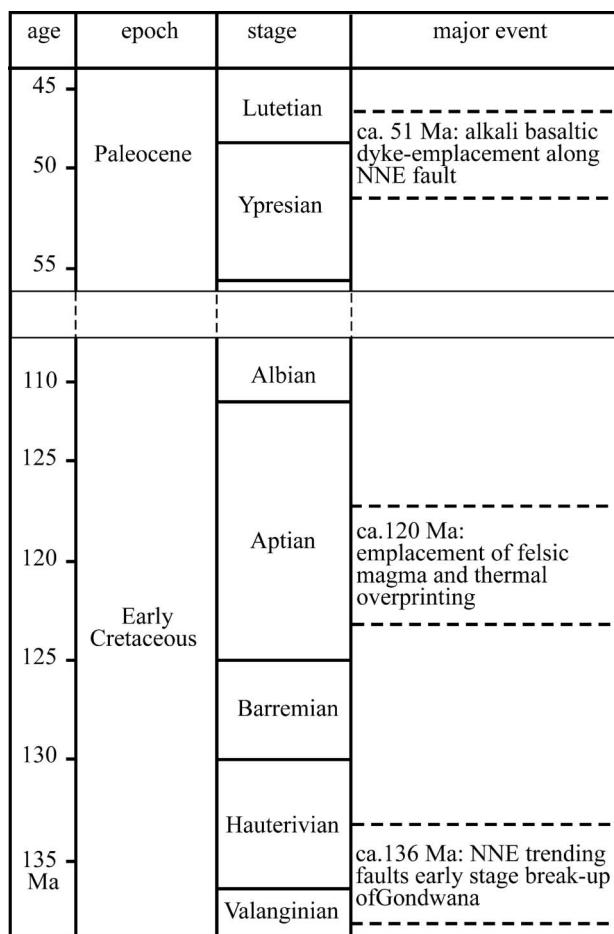


Figure 10 Events recorded in the Sydney region during and after the Early Cretaceous.

rocks hosting them, recording a thermal overprint (Figure 10). Emplacement of basaltic magma along these faults then took place at 51 Ma (age of dyke along north-northeast-striking fault, South Era Beach). Subsequently, these faults were reactivated resulting in brecciated margins. This event may relate to the oblique or strike-slip movement on them noted by Lohe *et al.* (1992) on north-northeast-striking faults elsewhere in the Sydney Basin.

CONCLUSIONS

Mapping of road cuts, excavations and tunnels in the Sydney region has revealed the presence of vertical to near-vertical, north-northeast-striking faults manifested as joint swarms and highly brecciated zones in which gouge of varying thickness is developed. Strike-slip movement accompanied by minor dip-slip, normal movement occurred on these faults. Less well-developed thrust faults are associated with the north-northeast-striking faults.

K-Ar dating of clays in 2–10 to <0.1 µm fractions extracted from the gouge and host rocks, range from 106.6 ± 2.1 to 159.5 ± 3.2 Ma ($n=26$) with finest fractions recording a mean age of 121 Ma, similar to ages obtained

from host-rocks in the Sydney region. We interpret that the cataclastic failure that produced gouge zones along these north-northeast-striking faults occurred prior to a thermal event associated with the underplating of felsic magmas during the early stages of the rifting of East Gondwana at ca 120 Ma and subsequent to the emplacement of alkali basaltic dykes along these faults in the Early Eocene (51 Ma).

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