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Paleomagnetic and K-Ar dating studies of Late Cretaceous basaltic dykes intruding Late Permian sediments of Newcastle Coal Measures, Newcastle, Australia—Relationship to the opening of the Tasman Sea

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Abstract: Paleomagnetic studies of Late Cretaceous basaltic dykes (K-Ar age of *ca*. 80 Ma) and associated sediments reveal the presence of both normal and reverse polarity magnetizations. Correlation with the geomagnetic polarity time scale shows that the normal polarity magnetization could have been acquired in the geomagnetic polarity chron (C33n) and the reversed polarity magnetization may have been acquired in the C33r or C32r polarity chron, respectively. This indicates that pulses of magmatism occurred in the region over a substantial period.

The normal and reverse magnetic directions show a clockwise deflection from the north-south direction of 40–50°, which may be related to block rotation associated with deformation events that have occurred subsequent to dyke emplacement or to the opening of the Tasman Sea.

key words: Paleomagnetism, Late Cretaceous, Newcastle, Tasman Sea opening, VGP

1. Introduction

During the Cretaceous, there was a period when normal polarity prevailed for 35 million years between 118 and 83 Ma (Cande and Kent, 1995) in the so called Cretaceous geomagnetic quiet zone (CQZ). This is a unique period, because the periods before and after the CQZ record many geomagnetic polarity reversal events. Recently, it has been suggested that the reversal events before the end of the CQZ may be related to a change in the activity of the the Earth's core. In eastern Australia, basaltic dykes of Cretaceous age intrude Permian sediments of the Sydney Basin. Further, around this period, the breakup of Australia and Antarctica occurred and the formation of the Tasman Sea commenced. Thus a study of dykes formed during this period will be important in determining the history of Gondwana. In this study, we investigate the rocks of eastern Australia.

Before and after the CQZ, basaltic dykes intruded Permian sediments of the Sydney Basin, Australia. Between Sydney and Newcastle, they occur sporadically in wave cut

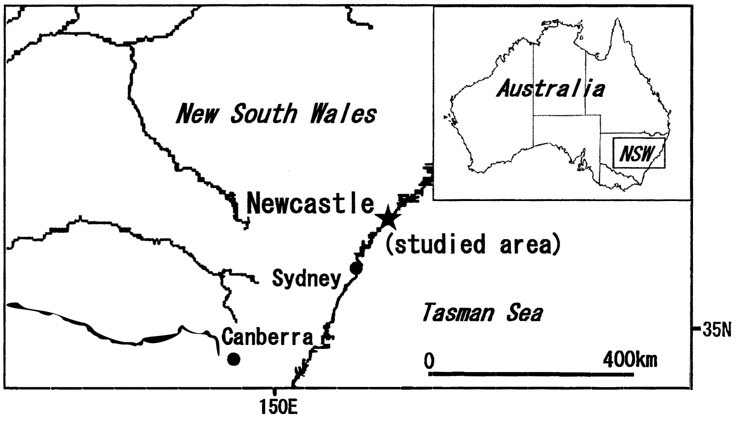

Fig. 1. Locations of dykes examined in this study. Inset: location of study area in New South Wales, Australia.

platforms, road and railway cuts, boreholes and underground in collieries (Rickwood, 1985). They vary in age from 111 to 90 Ma (Embleton *et al.*, 1985) and are considered to be related to crustal stretching and the subsequent rifting responsible for the opening of the Tasman Sea (Maxwell, 1990). Although geochemical (Maxwell, 1990), structural (Rickwood, 1985; Smith, 1988) and radiometric dating (Embleton *et al.*, 1985) studies have been carried out on these dykes, there have been few paleomagnetic studies. In order to gain a better understanding of the geomagnetic polarity at the time these dykes were emplaced, we carried out a preliminary paleomagnetic study of alkali basaltic dykes intruding sandstones and siltstones of the Late Permian, Lambton Formation, Newcastle Coal Measures, exposed on wave cut platforms, Newcastle, NSW, Australia (Fig. 1). We also carried out a whole-rock K-Ar analysis on one of the dykes and of plagioclase extracted from it to ascertain whether it was similar in age to the dykes dated elsewhere in this region.

The data obtained from this study have provided further insights into the paleomagnetic history of the eastern margin of Australia during and after the Cretaceous.

2. Methods and techniques

Samples for the paleomagnetic studies were taken from 3 dykes (site NC1, 3, 4) and from a siltstone (site NC2) adjacent to one of the dykes (Table 2). These four sites are in close proximity. The K-Ar analyses were carried out on a dyke of site NC1.

2.1. K-Ar analytical procedures

Analytical procedures for K-Ar dating were carried out at the Center of Isotope Studies, CSIRO, North Ryde, NSW, and the University of Newcastle, Australia. Sample 114 (of site NC1), which is an alkali basalt, and plagioclase extracted from this sample were analyzed. Plagioclase was chosen for analysis because it showed less alteration than the basalt and would therefore give an age closer to the time of emplacement. The basalt contains zoned titan-augite, zoned plagioclase, kaersutite, biotite, magnetite and accessory apatite. Minor alteration of titan-augite to chlorite-smectite is apparent in some parts of the rock.

Whole rock

Sample NC1-114 was split by a hammer into chips with maximum dimension <10 mm and crushed with a shatter box (Siebtechnik ring grinder with chrome steel barrel). Two size fractions were obtained: For Ar analyses a <750–500 micron fraction, and for K analyses a split of the <750–500 micron fraction, which was treated for an additional few seconds in the shatterbox to obtain a <500 micron fraction.

Plagioclase separation

Sample NC1-114 was crushed in a Tema Mill for one minute and sieved, and grains the size of plagioclase (0.35 to 0.65 mm) collected. This fraction was washed in distilled water to remove the clay sized particles and dried. The plagioclase was then separated magnetically using a Franz Isodynamic Separator. The purity of the extract was checked repeatedly during the separation until a pure concentrate of plagioclase was obtained.

K-Ar Analysis

Potassium contents of NC1-114 and plagioclase extracted from it were determined by atomic absorption spectrophotometer (Varian AA 20) using Cs at 1000 ppm concentration for ion suppression. 100–200 mg sample aliquots were dissolved with HF and HNO_3. The samples once in solution were diluted to 0.3 to 1.5 ppm K for the atomic absorption analysis. The pooled error of duplicate K determination on all samples and standards is better than 2%. 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. Argon was extracted from the whole rock and plagioclase by fusing samples within a vacuum line serviced by an on-line spike pipette.

The isotopic composition of the spiked Ar was measured with a high sensitivity on-line VG3600 mass spectrometer. The spike was calibrated against a standard biotite GA1550 (McDougall and Roksandic, 1974). After fusion of the sample in a low blank Heine 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 air shots. Normally 15 mg of sample material was required for argon analyses. During the course of the study, one measurement each of 2 international standards (1 LP-6, 1 HD-B1) and two air shot values were measured. The results are summarized in Table 1. The error for argon analyses is below 1%, and the $^{40}Ar/^{36}Ar$ ratio for air shots averaged 293.94 ± 0.09.

Analysis of the radiogenic content of the analyzed sample splits yielded values of 69 and 73%, respectively, indicating reliable analytical conditions, *i.e.* minor atmospheric ^{40}Ar contamination. The K-Ar ages were calculated using the K decay constants ($^{40}K/K = 0.01167\%$) recommended by Steiger and Jaeger (1977). K-Ar age errors are within 2 sigma uncertainty.

Table 1. K-Ar data for sample 114 of site NC1 (whole rock, plagioclase) and standard samples.

Sample ID	K [wt%]	rad.^{40}Ar [mol/g]	rad.^{40}Ar [%]	Age [Ma]	Error [Ma]	Error [%]
<sample 114 of site NC1>						
FS	1.16	1.64×10^{-10}	72.63	79.6	1.8	
WR	0.96	1.33×10^{-10}	68.72	78.0	2.2	
LP6-39 standard-measured	8.37	1.91×10^{-9}	97.12	126.9	1.8	−0.8
LP6 reference	8.33	1.92×10^{-9}	N/A	127.7	1.4	
HD-Bl-26 standard-measured	7.96	3.44×10^{-10}	94.60	24.8	0.4	2.5
HD-Bl reference	7.96	3.36×10^{-10}	N/A	24.2	0.3	

FS: feldspar(plagioclase), WR: whole rock.
LP6 standard reference: Odin and 35 collaborators, 1982.
HD-B1: Hess and Lippolt, 1994.

2.2. *Paleomagnetic analytical procedures*

At each site of 3 dykes (sites NC1, 3 and 4) and a siltstone (site NC2) listed in Table 2, five 1-inch diameter cores were collected and cut into 1-inch lengths in the laboratory. The remanent magnetization was studied using a cryogenic magnetometer (2G Enterprise 760R). To obtain reliable paleomagnetic directions from the core specimens, thermal demagnetization studies were conducted. Heating was done progressively up to 600°C with 50°C temperature steps in an Ar atmosphere. Figure 2 shows the examples of thermal demagnetization results expressed in a Zijderveld diagram (Zijderveld, 1967). Besides NC2-6, each sample shows the stable remanent magnetization with the high blocking temperature range. Sample NC2-6 is a siltstone which may have acquired secondary thermal remanent magnetization during the intrusion of an adjacent dyke, so that the deviated plot in the Zijderveld diagram suggests the maximum temperature of heating at the dyke intrusion.

After obtaining a reliable magnetization vector for each specimen, the site average direction of magnetization was calculated and the associated error angle determined. In Table 2, the average direction of magnetization, α_{95} (Fisher's semi-angle of 95%

Table 2. The average of magnetization, α_{95} (Fisher's semi-angle of 95% confidence), k (Fisher's precision parameter) for the studied sites. In the lower column, the average magnetization from four sites and the estimated VGP position are shown.

Site	Sample no.	Rock-type	Dec. (°)	Inc. (°)	α_{95} (°)	*k*
NC1	5	Basaltic dyke	49.6	−67.4	19.4	16.5
NC2	5	Siltstone	57.5	−62.6	16.3	22.9
NC3	5	Basaltic dyke	217.7	73.0	5.2	17.9
NC4	5	Basaltic dyke	226.7	63.8	32.6	30.8

Average magnetization; dec.: 48.9°, inc.: −66.8°, α_{95}: 6.4°.
Estimted VGP position; latitude: 51.2°N, longitude: 280.6°E.

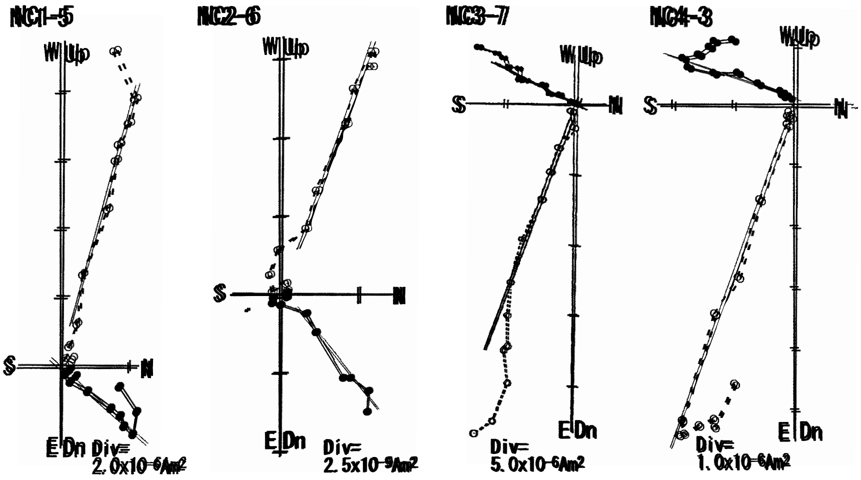

Fig. 2. *Examples of thermal demagnetization experiments shown in the Zijderveld diagram. The straight line crossing the plot circles in each diagram shows the characteristic direction for each specimen.*

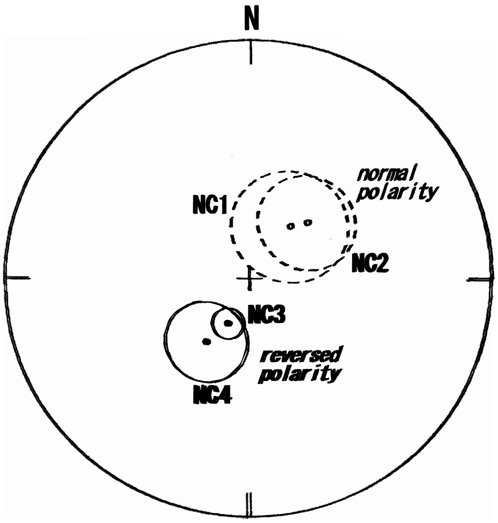

Fig. 3. *The directions of remanent magnetization from the four sites (NC1, 2, 3, 4).*

confidence) and k value (Fisher's precision parameter) are shown (Fisher, 1953). The present declination was corrected by using an angle of 12 degrees east. The average directions and the α_{95} circle for the four sites are shown in Fig. 3.

3. K-Ar and paleomagnetic results and discussion

3.1. *K-Ar*

A K-Ar age of 79.6±1.8 Ma was obtained from the plagioclase and the age 78.0±2.2 Ma from the whole rock sample (Table 1). Close agreement in age was reached between the plagioclase and whole rock, suggesting a late Cretaceous age (*ca.* 80 Ma) for the dyke exposed in the wave cut platform at Fort Scratchley. The obtained K-Ar ages are identical within error indicating no major alteration.

3.2. *Paleomagnetic direction*

The results of the paleomagnetic studies are shown in Figs. 2 and 3. One dyke (NC1) shows a normal magnetization (negative inclination), while the other two dykes (NC3, NC4) show reverse magnetization (positive inclinations). Site NC2 has a normal magnetization direction similar to that of NC1. Field and petrological studies indicate that this sedimentary rock has been heated by the intrusion of the dyke (NC1).

Table 3. Geomagnetic polarity time scale between 73.3 Ma and 118.0 Ma (Cande and Kent, 1995).

Polarity interval (Ma)	Polarity chron
73.374 – 73.291	C32n (normal)
73.619 – 73.374	C32r (reverse)
79.075 – 73.619	C33n (normal)
83.000 – 79.075	C33r (reverse)
(118.0) – 83.000	C34n (normal)

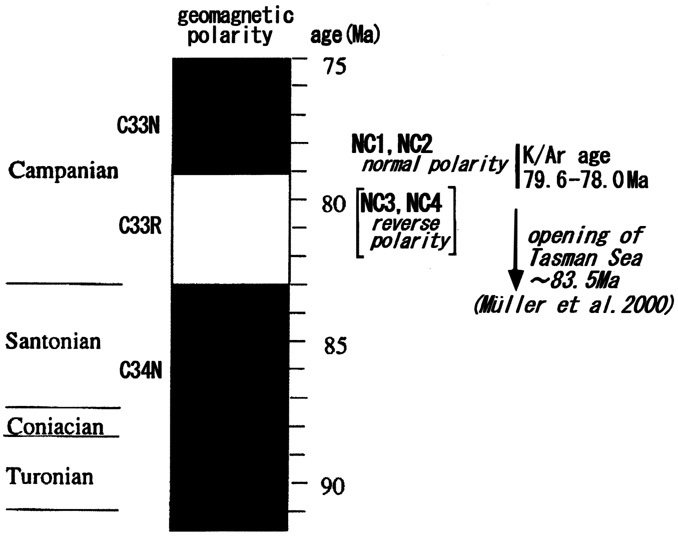

Fig. 4. Geomagnetic polarity time scale between 92 Ma and 75 Ma (after Cande and Kent, 1995).

Thus it may have been remagnetized during the contact metamorphism and acquired magnetization together with NC1 during the period of normal polarity chron. The remagnetization of the host rock by the basaltic dyke noted in this study is similar to that observed by Sakai and Funaki (1988) in the Beacon Super Group in Antarctica, which was affected by the Fellar Dolerite during the Jurassic.

Using the K-Ar dates as a guide, correlation with the geomagnetic polarity time scale (Cande and Kent, 1995) shows that the normal magnetization may have been acquired in the normal polarity chron (C33n). In Table 3, the geomagnetic polarity time scale (Cande and Kent, 1995) between 73.3 Ma and 118 Ma covering the age range of interest in this study is shown, and the time scale between 92 Ma and 75 Ma is shown in Fig. 4. For the two dykes (NC3, NC4) of reversed polarity magnetization, we consider that the magnetization may have been acquired in the C33r or C32r polarity chron. The reason is that the studied four sites are in close proximity and it is geologically plausible that the volcanic activity in the area proceeded in a sequence over not such a long period.

The normal and reverse magnetizations recorded in the basaltic dykes suggest that pulses of magma were injected into the sediments over a substantial period. Dating of the dykes at NC3 and 4 is necessary to confirm this interpretation.

3.3. *Tectonics*

The data obtained in this study reveal that the normal and reversed magnetic directions are deflected clockwise 40–50° from the north-south direction. Further, when the virtual geomagnetic pole (VGP) calculated from the data is compared with the apparent geomagnetic polar wandering path (APWP) of Australia (McElhinny and McFadden, 2000), it is displaced a few tens of degrees clockwise from the interpolated pole position of 75–80 Ma (Fig. 5). Lohe *et al.* (1992) have found evidence for a series of compressional deformation events occurring after normal faulting which are believed

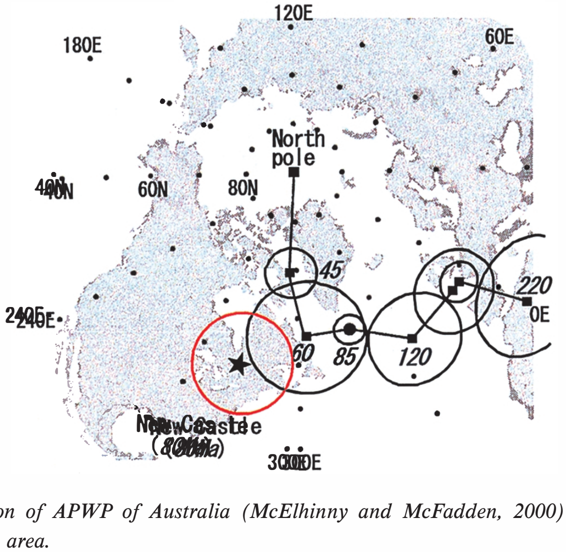

Fig. 5. Comparison of APWP of Australia (McElhinny and McFadden, 2000) and VGP for the Newcastle area.

to be associated with the opening of the Tasman Sea. Thus the displacement of the VGP may be due to block rotation subsequent to dyke emplacement as a result of these later events. Alternatively, the clockwise rotation may be related to the progressive opening of the Tasman Sea basin from 83.5 to 55.9 Ma, at which point the direction of spreading changed to NNE (Müller *et al*., 2000).

4. Conclusions

K-Ar dating of one of the basaltic dykes examined in this study, which intruded into sediments of the Late Permian Newcastle Coal Measures, indicates an age of *ca.* 80 Ma. Paleomagnetic studies of these dykes and an associated contact metamorphosed sediment reveal that both normal and reverse magnetizations are recorded. Correlation with the geomagnetic polarity time scale shows that the normal magnetization may have been acquired in the normal polarity chron (C33n) and the reversed polarity magnetization may have been acquired in the C33r or C32r polarity chron, respectively.

The normal and reverse magnetic directions show a clockwise deflection from the north-south direction of 40–50°, which is thought to be related to the localized block rotation associated with deformation events that have occurred subsequent to dyke emplacement or to the opening of the Tasman Sea.

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References

Bonhomme, M.G., Thuizat, R., Pinault, Y., Clauer, N., Wendling, R. and Winkler, R. (1975): Methode de datation potassium-argon. Appareillage et Technique, Strasbourg, 53 p.

Cande, S.C. and Kent, D.V. (1995): Revised calibration of the geomagnetic polarity timescale for the Late Cretaceous and Cenozoic. J. Geophys. Res., **100**, 6093–6095.

Embleton, B.J.J., Schmidt, P.W., Hamilton, L.H. and Riley, G.H. (1985): Dating Volcanism in the Sydney Basin: Evidence from K-Ar ages and palaeomagnetism. Volcanism in Eastern Australia with Case Histories from New South Wales, ed. by F.L. Sutherland *et al.* 59–72 (Geological Society of Australia, New South Wales Division, Publication No. 1).

Fisher, R.A. (1953): Dispersion on a sphere. Proc. R. Soc. London, **A217**, 295–305.

Hess, J.C. and Lippolt, H.J. (1994): Compilation of K-Ar measurements on HD-B1 standard biotite, 1994 status report. Bull. Lias. Inform., **12**, 19–23.

Lohe, E.M., McLennan, T.P.T., Sullivan, T.D., Soole, K.P. and Mallett, C.W. (1992): Sydney Basin—Geological structure and mining conditions assessment for mine planning. NERDDC Project No. 1239. Final Report. CSIRO Division of Geomechanics, Institute of Minerals, Energy and Construction.

McElhinny, W.M. and McFadden, P.L. (2000): Paleomagnetism. Academic Press, 386 p.

McDougall, I. and Roksandic, Z. (1974): Total fusion ages using HIFAR reactor. J. Geol. Soc. Austr., **21**, 81–89.

Maxwell, S. (1990): Geochemical characterization of dykes intruding the northeast Sydney Basin, Australia. Mafic Dykes and Emplacement Mechanisms, ed. by A.J. Parker *et al.* Rotterdam, Balkema Press, 415–419.

Müller, R.D., Gaina, C. and Clark, S. (2000): Seafloor spreading around Australia. Billion-year Earth History of Australia and Neighbors in Gondwanaland, ed. by J.J. Veevers. Sydney, Germoc Press, 18–28.

Odin, G.S. and 35 collaborators (1982): Interlaboratory standards for dating purposes. Numerical Dating in Stratigraphy, Part 1, ed. by G.S. Odin. Chichester, J. Wiley, 123–148.

Rickwood, P.C. (1985): Igneous intrusions in the Greater Sydney Region. Engineering Geology of the Sydney Basin, ed. by P.J.N. Pells. Rotterdam, Balkema Press, 215–307.

Sakai, H. and Funaki, M. (1988): Paleomagnetic study of the Beacon super group in Antarctica: remagnetization in the Jurassic time. Proc. NIPR Symp. Antarct. Geosci., **2**, 46–54.

Smith, J.V. (1988): Structure and engineering implications of offset dykes of the Sydney Basin. Proceedings of the 22nd Newcastle Symposium. “Advances in the Study of the Sydney Basin”, The University of Newcastle.

Steiger R.H. and Jaeger, E. (1977): Subcommission on geochronology: Convention on the use of decay constants in geo- and cosmochronology. Earth Planet. Sci. Lett., **36**, 359–362.

Zijderveld, J.D.A. (1967): A.C. Demagnetization of rocks: analysis of result. Method in Palaeomagnetism, ed. by W. Collinson *et al.* Amsterdam, Elsevier, 254–286.