DATING FERRUGINOUS REGOLITH TO DETERMINE FAULT CAPABILITY AT LUCAS HEIGHTS, SYDNEY

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BACKGROUND

Following several major reviews of Australia's nuclear science and technology needs, the Federal Government made the decision in 1997 to fund replacement of the obsolete research nuclear reactor, HIFAR (High Flux Australian Reactor), which has operated since 1958 at the ANSTO (Australian Nuclear Science and Technology Organisation) facility at Lucas Heights in Sydney. Full details of the siting and design of the replacement research reactor (RRR), including geotechnical studies by Coffey Partners International and regional seismic hazard analysis by the New Zealand Institute of Geological & Nuclear Sciences (GNS), were assessed by the newly constituted ARPANSA (Australian Radiation Protection and Nuclear Safety Agency), and in April 2002 a licence for construction of the RRR was issued. Total cost was estimated to be $286.4 million, with commissioning of the reactor expected in 2005.

Prior to issuing the construction licence, ARPANSA had required ANSTO to undertake geological studies to determine the seismic risk associated with any faults with the potential for surface displacements at or near the site. None were found by a GNS investigation team. ARPANSA also requested that ANSTO commission further studies to examine any faulting in the excavation itself. These studies, undertaken for ANSTO by GNS and Coffey Geosciences (formerly Coffey Partners) between April and June 2002, showed that there were two faults on the reactor site (Figure 1).

FAULT CAPABILITY

The two faults in the RRR excavation offset sandstone and mudstone beds in the Triassic Hawkesbury Sandstone. They are steeply dipping (65-80°), generally strike NNE (000-020°), and can be traced 120-140 m across the site. The eastern fault strand is an apparent normal fault, with a dip separation of 1-1.3m, while the western fault strand is an apparent reverse fault with a dip separation of 0.25-0.30 m (Figure 1). The two fault strands converge in the northern part of the site to from a single fault zone (ANSTO 2002).

The key issue for assessment of seismic hazard is whether a fault is "capable", i.e. whether it has significant potential for displacement at or near the ground surface. Both the IAEA (International Atomic Energy Agency) and the USNRC (United States Nuclear Regulatory Commission) have criteria for determining if a fault shall be considered capable. The criteria relate to such things as historical evidence of seismicity associated with the fault, the timing of last movement of the fault, and whether the fault has a structural relationship with a known capable fault. In the case of the faults at the RRR site, there is no evidence of historical seismicity. Neither can they be structurally related to a known capable fault. The key criterion is therefore the timing of last movement.

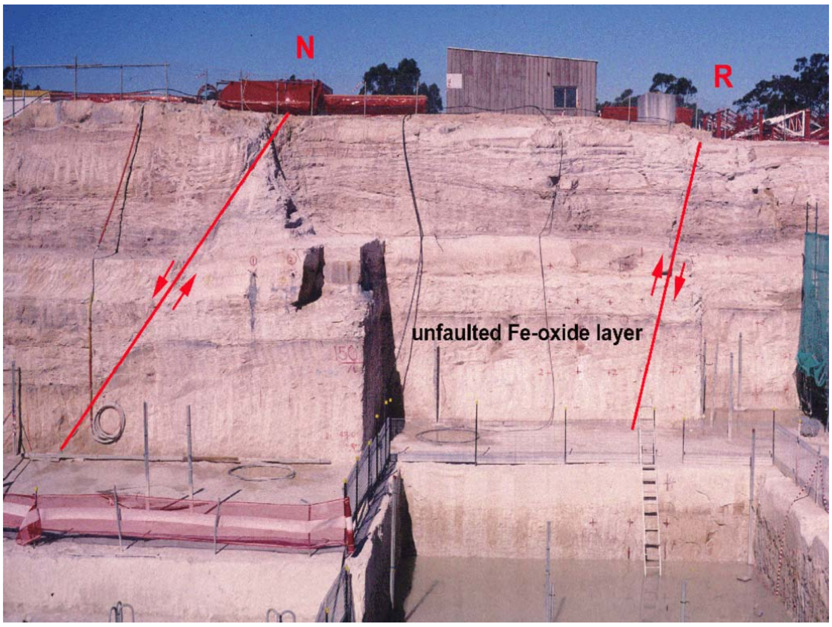

Figure 1: South wall of the excavation for the replacement nuclear reactor at Lucas Heights, showing reverse and normal faults displacing Triassic Hawkesbury Sandstone.

The USNC (quoted in ANSTO 2002) prescribes that a fault is considered capable if there is evidence of repeated surface or near surface deformation of landforms or geological deposits in the last 500,000

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years, or at least once in the last 50,000 years. The IAEA definition is conceptually similar, though somewhat less precise in its prescription of the timing of last movement. According to the IAEA definition (IEAE 1991), a fault shall be considered capable if: "*It shows evidence of past movement or movements of a recurring nature within such a time period that it is reasonable to infer that surface movement at or near the surface can occur. (In highly active areas, where both earthquake and geological data consistently reveal short earthquake recurrence intervals, periods of the order of tens of thousands of years may be appropriate for assessment of capable faults. In less active areas, it is likely that much longer time periods may be required).*"

In July 2002 I was asked to assist in determining the timing of last movement on the faults at the RRR site, with a view to determining their capability.

PALEOMAGNETIC DATING

The Hawkesbury Sandstone at the RRR site is characterised by pervasive oxidative deep weathering, with zones of reddish ferruginization evident to depths of several metres. Thin sections show that the secondary iron oxides occur as a dark-coloured cement or matrix between sand-sized quartz grains (Figure 2). The ferruginous zones have generally smooth, sharp boundaries to surrounding pallid zones. Structural and bedding control of the colour patterns is evident from the way in which the pallid zones tend to follow faults and joints. This suggests that iron mobilisation post-dates the faults and joints, which acted as pathways for water movement and controlled oxidation-reduction processes. On the south wall of the RRR excavation, one prominent iron oxide layer is draped across, but not displaced by either the reverse or the normal fault strands (Figures 1 and 3). If an age for the unfaulted iron oxide layer could be determined, this would establish a minimum age for last fault activity.

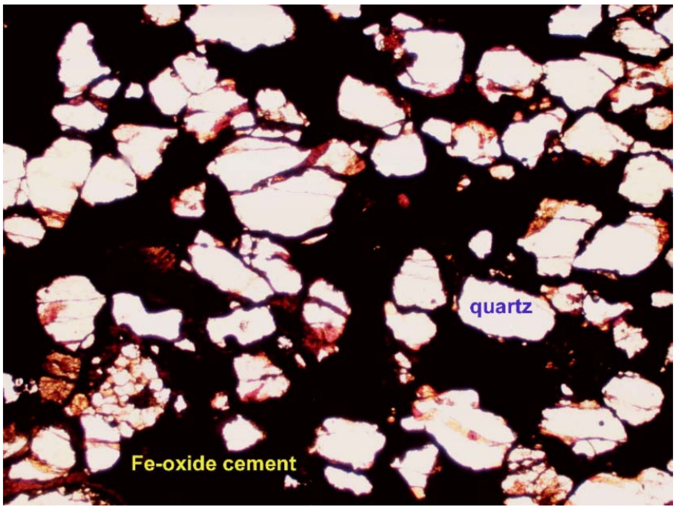

Figure 2: Thin section view (cross-polarized light) of a sample from the unfaulted iron-oxide layer, south wall, RRR excavation, Lucas Heights. Field of view ~2 mm wide.

Oriented paleomagnetic samples were collected from the ferruginous zones at two sites adjacent to the faults (Sites 1 and 3), and from the unfaulted iron-oxide layer in the south wall of the RRR excavation (site 2). Samples were stepwise thermally demagnetised at the ANU Black Mountain paleomagnetic facility, and magnetic remanence directions determined on an ScT 2-axis cryogenic magnetometer. Characteristic Remanent Magnetisations (ChRM's) were identified by Principal Component Analysis (PCA) (Kirschvink 1980). NRM intensities are moderately strong, in the range 1 to 100 mA/m. Susceptibilities are in the range 1 to 50 SI units. Magnetic remanences in all specimens have unblocking temperatures above 660°C, indicating that hematite is the likely remanence carrier. This remanence would have been acquired as a Chemical Remanent Magnetisation (CRM), aligned to the earth's magnetic field, at the time the hematite was formed by weathering processes.

Figure 3: Close-up view of the unfaulted iron oxide layer, draped across reverse fault, south wall, RRR excavation, Lucas Heights. Crosses are 1 m apart.

Site 1. All specimens yielded single component reversed polarity ChRM's. PCA of demagnetisation data defined a high temperature ChRM (unblocking temperature >660°C) in 24 specimens that was used to calculate a paleomagnetic pole (Table 1).

Site 2. Approximately 50% of specimens yielded single component reversed polarity ChRM's. Remaining specimens were variably affected by a strong normal overprint. PCA defined a high temperature reversed polarity ChRM in 25 specimens that was used to calculate a paleomagnetic pole.

Site 3. Specimens were variably affected by a strong normal overprint (PM 1 to 6), which was successfully removed in some specimens to reveal a reversed polarity ChRM. In some specimens a single component normal polarity ChRM was present. PCA defined a high temperature ChRM in 14 specimens that was used to calculate a paleomagnetic pole.

The presence of reverse polarity ChRM's in the majority of specimens from the oxidised zones, and the ferruginous layer, clearly indicates remanence acquisition prior to the Matuyama/Brunhes polarity transition at 780,000 years (Pillans & Bourman 1996). Since the formation of the iron oxide layer at Site 2 post-dates fault movement, the fault has not been active for at least 780,000 years. Short intervals of reversed polarity of up to a few thousand years have been reported in the Brunhes Normal Chron (e.g. Jacobs 1994). However, the ChRM's were acquired during weathering over long enough intervals that such short-term field changes would not be recorded.

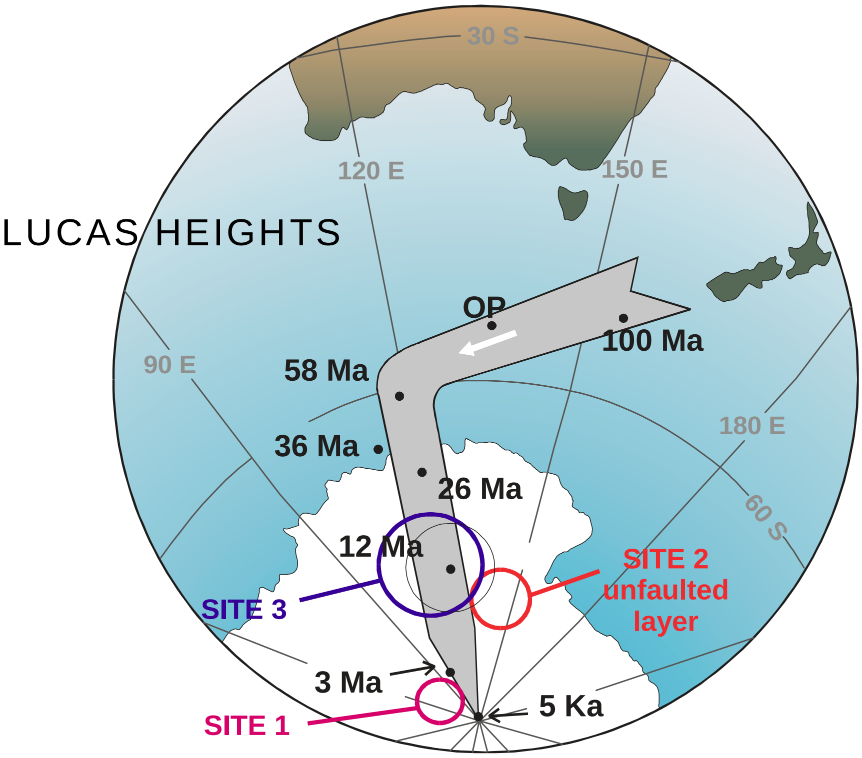

Figure 4: Paleomagnetic poles determined for three groups of ferruginous regolith samples from Lucas Heights (circles are 95% confidence limits for each pole), compared with the Late Cretaceous-Cainozoic apparent polar wander path for Australia (after Idnurm 1985, 1994). Ages of reference poles are in millions of years (Ma). OP = late Cretaceous thermal overprint pole from Sydney Basin. Interpolated paleomagnetic ages are 2±1 Ma (Site 1), 9±4 Ma (Site 2 = unfaulted iron oxide layer) and 14±8 Ma (Site 3).

Since the unfaulted iron oxide layer at Site 2 is of reversed polarity, and therefore older than 780,000 years, then according to the UNSC criterion the fault is not capable. However, a review panel from the IAEA concluded that such a minimum age was not "adequately conservative" because one fault strand had a reverse component of movement, consistent with the present regional stress field that has prevailed for the last 20 million years (IAEA 2002).

Specimens from all three sites yielded well-defined paleomagnetic poles that can be dated using the Cainozoic Australian apparent polar wander path (Figure 4). Site statistics and resultant ages are summarised for each site in Table 1. The paleomagnetic ages of iron mobilisation at Lucas Heights are similar to other weathering ages determined by paleomagnetism in the Sydney Basin (e.g. at Lapstone - Bishop et al. 1982), and consistent with evidence for widespread Late Tertiary to early Pleistocene climate-driven, deep oxidation of regolith in southern Australia (e.g. Schmidt & Embleton 1976).

The critical group of specimens (Site 2) from the unfaulted iron oxide layer yielded an age estimate of 9±4 million years, which the IAEA review panel accepted as sufficiently long to establish the fault as "non-capable". In other words, the risk of future fault movement was considered to be negligible, and approval was given to proceed with construction at the reactor site.

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Table 1: Summary of paleomagnetic results from Lucas Heights, and comparison with other studies.

SITE	N(+)[1]	REMANENCE DIRECTIONS[2]				SOUTH POLE[2]				AGE[3]
		Decl.	Incl.	K	α_{95}	Long.	Lat.	K	A_{95}	(Ma)
	Lucas Heights (this work)									
LUC1	24(24)	185.1	53.5	250	1.87	066.9E	85.8S	220	2.00	>0.78
LUC2	25(25)	181.5	63.4	232	1.90	145.3E	79.0S	118	2.68	9±4
LUC3	14(7)	191.1	63.2	127	3.54	117.1E	75.9S	71.7	4.73	14±8
	Perth Basin (Schmidt & Embleton 1976)									
PB	128					109.9E	82.7S		2.4	6
	Lapstone Monocline, Sydney Basin (Bishop *et al.* 1982)[4]									
HS46	7	008.4	-59.0		3.4	106.4E	81.0S		4.6	8
HS27	6	002.2	-53.7		5.2	083.0E	87.9S		5.1	<3

Notes:
[1] N = number of specimens; (+) = number of specimens with positive inclination, if known
[2] k and K are Fisher precision parameters; α_{95} and A_{95} are semi-angles of 95% confidence.
[3] Ages interpolated from Australian Apparent Polar Wander Path (Idnurm 1985, 1994)
[4] Oldest (HS46) and youngest sites (HS27) of Bishop *et al*. 1982.

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