<u>Response to Consideration by Geoscience Australia of ANSTO Submission to ARPANSA on Site Geological Investigations of Lucas Heights</u>

1. Introduction

A number of comments and questions were raised by Geosciences, Australia in considering the ANSTO submission and during a site visit on 26th September. Supplementary information was requested on the paleomagnetic sampling. This report provides supplementary information on the substantive issues raised by Geosciences, Australia. It is based on additional information provided by Dr Pillans, by IGNS and by Professor Gleadow.

2. Interpretation of palaeomagnetic results.

Geoscience Australia acknowledged the work of Dr Pillans and his conclusions on the age of the last movement. However they requested additional information on the ferruginous layer and on the sample taking process.

The critical paleomagnetic samples are those of Group 2, taken from an iron-oxide cemented layer in the south wall of the reactor pit. The position of the layer, which can be traced right around the reactor excavation (north, east, south and west walls), is controlled by bedding in the basement rock. Such lithological control of secondary iron oxides is common in deep weathering profiles, and reflects the influence of rock permeability on water movement with the profiles. Faults and joints also strongly control water movement and the resultant distribution and nature of secondary iron-oxides.

Field observations by Dr Pillans of the curved section of the ferruginous layer at the reverse fault plane leave him in no doubt that the layer is "draped across the fault", subsequent to fault movement, and that its position is structurally and lithologically controlled. The paleomagnetic results are consistent with this field assessment. Hence Dr Pillans is confident that the fault has not moved for more than 780,000 years, and indeed, from the polar wander path results, has not moved for more than 5 million years.

For constraining the timing of movement on the western fault strand the most important paleomagnetic samples from Group 2 are PM 12 and PM 13. These samples were collected from a 10x10x10 cm block, part of which included the ferruginous cemented layer, centred 15 cm west of the fault strand on its downthrown side. The samples were further sub-sampled and from these portions of the original block 11 sets of paleomagnetic declination and inclination measurements were collected. Careful relocation of the sample site for PM 12 and PM 13 by Mr Idnurm, with assistance from Dr Pillans, confirmed that the sample was taken from a portion of the layer which was folded (see Figure 1). Inspection of the beds at the sample locality indicated that bed dips within the sample ranged from 0 to 50°. It is estimated that approximately 50% of the ferruginous layer within the sampled block had bed dips of 10° or more and that about 40% was characterised by dips of approximately 30-50°.

Data from PM 12 and PM 13 show that the paleomagnetic remanence directions are strongly clustered (Figure 2). Given that the samples included beds of variable dip this clustering provides good evidence that ferruginous oxidation post-dates fault movement. If the iron oxidation were older than the folding (and fault movement) then the folding would tend to scatter the remanence directions, a scatter that would be removed by 'unfolding' the remanence directions. The stereographic plot in Figure 2 shows the spread of remanence directions that would be expected if magnetisation, similar in orientation to that observed in the ferruginous layer today, predated folding that produced bed dips of up to 50°. This plot shows that the scatter produced by such folding would be likely to extend well beyond the limits of the current data and bed rotations of as little as 5-10° would move most of the data beyond the spatial limits of the current data. As bed dips of 10° or more account for about 50% of the sampled ferruginous layer we would expect perhaps half (e.g., 5-6) of the 11 remanence directions from samples PM 12 and PM 13 to fall outside the present distribution of orientations. Four of these 5-6 samples would be expected to plot well to the east of the observed data.

To determine whether the paleomagnetic samples taken from the folded beds close to the fault showed any signs of rotation due to the folding the individual field orientations from the Group 2 samples were projected onto a plane perpendicular to the fault strike using the declination and inclination measurements. In this projection, any rotation should be evident in the key PM12 and PM13 samples, either as a mean orientation different from the other Group 2 samples or as a wider spread in orientations if only a proportion of either the PM12 or PM13 samples were rotated. The results are shown in Table 1.

The standard deviation data show that the key PM12 and PM13 samples appear to have a smaller spread than the rest of the Group 2 samples. This is true even after Bessel's correction is applied to take account of small sample sizes. Application of Snedecor's F test shows that the spread in samples PM12 and PM13 does not differ significantly from that in the other Group 2 samples combined.

Student's t test, applied using the method for small samples, has been used to confirm that the mean orientations of samples PM12 and PM13 do not differ significantly from that of the other Group 2 samples combined.

It is concluded that the paleomagnetic data show no significant sign of any rotation that would have been apparent had any fault-induced folding occurred after oxidation.

Table 1 Distribution of paleomagnetic samples perpendicular to fault strike

Group	Sample	Mean orientation From vertical (°)	Standard deviation (°)	Number in sample
2	PM1,18,20,21	3.6	3.5	13
2	PM13	5.7	1.6	6
2	PM12	0.1	3.2	5

2.1. Relations between the fault and the iron oxidation

The ferruginous layer occupies a finely bedded (range 0.2-3 cm) fine to medium sandstone unit which is 5 to 15 cm thick. Close inspection of the western fault strand close to the ferruginous layer shows that the fault does not pass through it, but is evident again above the layer (Figure 1b). Within the ferruginous layer the thin beds are intensely fractured. The fracturing breaks the beds up into angular pieces, which are commonly about 0.5-1.5 cm in diameter. The zone of fracturing extends for about 10 cm along the beds, however, individual beds cannot be traced through this zone. The areas between angular pieces of rock appear infilled with iron oxidation. The location and high density (spacings < 1-2 cm) of fractures suggests that they were produced by fault movements. The apparent infilling of the fracture fabric is consistent with the view that oxidation is post faulting.

Within the ferruginous layer the intensity of oxidation varies both vertically and laterally along the beds. The zone of most intense oxidation occurs within 30 cm of the fault and is particularly well developed on its downthrown side. The thickest and most intensely oxidised unit, which occurs towards the top of the layer, reaches up to 4 cm in thickness on the downthrown side of the fault but is less than 1 cm thick on the upthrown side of the fault. Such changes in the pattern of iron oxidation across the fault together with the close proximity of the iron oxidation to the fault itself suggest that the presence of the fault influenced the spatial distribution of oxidation. This would require that iron oxidation post-dated fault movement and is consistent with suggestions that the fault provided a conduit for the flow of fluid from which the iron oxide was precipitated.

2.2. Group 1 and 3 samples

The main purpose in collecting the Group 1 and 3 samples was to establish whether the pervasive oxidation in the bedrock at the site was of one or more ages, and not to establish a link to the faulting. Dr Pillans conclusion was that at least two episodes of ferruginisation had occurred: one "young" episode (< 3 Ma; Group 1 samples) and one "old" episode (14±8 Ma; Group 3), the latter being statistically indistinguishable from the age of Group 2 samples. It is, thus, concluded that multiple episodes of iron mobilisation are likely, a conclusion also supported by the previous paleomagnetic results of Bishop et al (1982) at Lapstone. However, the existence of multiple episodes of iron mobilisation does not negate the conclusions concerning the age of Group 2 paleomagnetic specimens from the unfaulted ferruginous layer.

Figure 3 shows orthogonal plots of three representative paleomag specimens: A = Group 2, B = Group 1, and C = Group 3.

3. Interpretation of the regolith

Geoscience Australia note that the evidence provided in the submission is sufficient to justify the conclusion that deposition of the sediments overlying the saprolite in Trench 4 post-dates faulting. A minimum OSL age estimate of >104ka for the last fault movement is therefore supported.

However, they asked for further clarification on the relation between the saprolite and the faulting seen on the bedrock and on the dip of the faults in Trench 4.

3.1. Saprolite determination

The relationship between the bedrock, weathered bedrock (saprolite) and Quaternary cover deposits in Trench 4 is as follows. Saprolite is *in situ* weathered bedrock. It forms in place, generally over a long time interval. Bedrock refers to unweathered Hawkesbury Sandstone rock. Quaternary cover deposits, e.g. Units 1-3 in Trench 4 (Langridge et al, 2002a), are transported sediments and surficial soils. The contact between the weathered bedrock (saprolite) and the younger Quaternary cover is described as the "critical contact" in Trench 4, with respect to faulting.

The mapped position of the bedrock-saprolite contact is not, as was suggested by Geosciences, Australia, arbitrarily assigned to the top of the bench. Bench 2 was excavated at its level for the very reason that a distinct change in competency existed that made it harder for the excavator to dig deeper than this level, i.e. it is a real geologic contact and the bench approximates its location. This is not surprising as the saprolite is soft and the underlying bedrock is hard. To help locate the bedrock-saprolite contact and faults as accurately as possible excavation also occurred by hand within the bench. Therefore, in Trench 4 the saprolite is a 20-40 cm thick unit of weathered bedrock material (see Langridge et al, 2002a). Displacements across this contact were not visible, but may not be visible if they were there, due to the wavy and diffuse nature of the contact across the whole trench. The initiation of the saprolitic weathering must have been before the deposition of Unit 3. Indeed, prior to, or in association with, deposition of Unit 3 the saprolite may have undergone some stripping (erosion) of its upper surface. Therefore, the development of the saprolite is older than 104 ka as defined by the age of Unit 3 using OSL (Smith, 2002).

The critical contact for the age control of faulting in Trench 4 is still the contact between the weathered bedrock (saprolite) and overlying Unit 3 contact. This contact is both defined by a series of cemented and rotated clasts that occur along the contact and age control from Unit 3 above it using the OSL technique. The clasts of cemented sandstone at this contact have an undefined age, but have been physically rotated into different orientations, which is interpreted to mean that they were transported to their position by a sedimentary process. This provides the best evidence that this is a contact between *in situ* bedrock (including saprolite) and cover deposits. The contact can be located to within ~5-15 cm. The immediately overlying layers (e.g., Unit 3 to Unit 2 contact) are however, relatively sharp and would record displacements of as small as ~1-2 cm if present. Therefore, if the western strand with its apparent reverse displacement was present with displacements of greater than 2-4 centimetres we believe that it would be detectable within the Quaternary cover beds.

The saprolite to Unit 3 contact still provides the best constraint on the age of faulting in Trench 4. The saprolite is older than Unit 3 but has no further age constraint. However, it is re-iterated that there is strong evidence that the contact between the saprolite and Unit 3 is unfaulted and that in concert with the OSL dating results (Unit 3; >104 ka) that no faulting has occurred at this location (trench) since at least c. 104 ka.

Geoscience Australia suggested that the faults in trench 4 dip to the west in the opposite direction to the eastern and western strands. This statement is only partially correct as fault E in trench 4 dips to the east. It is the view of GNS that the faults in trench 4 are part of the structure that passes through the Reactor Hall. By trenching bedrock it was possible to trace both the eastern and western strands into trench 5 which is 50 m south of trench 4. Projecting the fault in the north- northeast direction gave the expected location for excavation of Trench

4. The fault was found directly in the centre of this trench. This conclusion on the single fault system is supported because; a) the faults share a common strike and predominately dip steeply (80-83° west in trench 4 and 70-85° east in trench 5), and b) the faults in trench 4 are immediately along strike from, and in close proximity to, the western and eastern strands. Even if the fault strands within the RRR site could not be correlated directly to faults within trench 4, displacement considerations suggest that they are likely to be kinematically related. Across the RRR site, including trench 5, apparent normal displacement on the eastern strand is commonly approximately 1-1.3 m. To terminate the eastern strand northwards between trenches 4 & 5 would require high displacement gradients for this size of fault. The most efficient way to achieve these high gradients would be to transfer displacement from the eastern strand to an adjacent fault strand. The ~0.5 m cumulative apparent normal displacement in trench 4 would be consistent with a component of the displacement from the eastern strand being transferred onto the faults in trench 4.

4. Statement on page 6 of the summary

The reviewers questioned the statement on page 6, that '*Palaeomagnetic results of ferruginous material laid down across the fault and post dating any movement on the fault…yield a minimum age of 9 million years and not younger than 5 million years*'. We agree that the statement would be better described as '*Palaeomagnetic results of ferruginous material precipitated out along bedding in the bedrock across the fault and post dating any movement on the fault* …".

5. Relevance of the fission track data.

An important general point to make quite explicit at this stage is that for fault movements of such small magnitude as those found at the site, no geochronological method exists that will directly date the time of fault movement. Rather the approach taken with all of the methods employed is to establish a consistent time framework within which the observed stratigraphic and structural relationships can be used to constrain the possible time of fault movement. It is important to take cognisance of this basic point, which is well founded in geology.

The reports on geochronology have argued that fault movements predate the deep weathering episode, and, consequently, it is important to understand the landscape evolution that culminated in this episode. The antiquity of the onset of the deep weathering episode has the potential to support a considerably greater minimum age for the time of fault movements that that achieved by the luminescence or palaeomagnetic evidence. The key argument in this, as pointed out previously, is not to do with the geochronology, however, but about the fundamental observation that faulting predates the deep weathering. It is recognised that this represents a broad interval of time of at least millions, and probably tens of millions of years.
It is correct that the thermochronology data apply to the district, rather than the local scale, and this is clearly to be understood from the reports provided as support to the main submission (ANSTO, 2002). However it is not reasonable to suggest that regional-scale phenomena are not an important part of the local sequence of events and can therefore be ignored in building up a picture of the overall chronology of events for the site. Geosciences, Australia concurred that the data support the proposition that normal faulting most likely

occurred in relation to the extensional events that accompanied opening of the Tasman Sea. We agree with this assessment and reiterate that the objective has been to establish an overall chronology for the site within which the probable timing of fault movement can be constrained.

It remains the contention of Professor Gleadow, therefore, that it is important to understand the sequence of events bracketing the time of fault movements. The only direct method which had some potential to provide direct information closely approximating the time of fault movements is K-Ar dating, as discussed below. Unfortunately, in this case the K-Ar results, while strongly indicative of an old age, are not unambiguous.

Geoscience Australia remarked that a link needs to be established between the discolouration and cementation associated with the fault planes and the deep weathering profile examined by fission track dating. It is emphasised that the interpretation of the geochronological data does depends on the geological field observations, and this applies equally to all of the dating techniques. In this context, the fundamental arguments are about the field-based structural and stratigraphic relationships and their relationship to datable events. The point of the discussion in the ANSTO submission is that the patterns of bleaching and ferruginous cementation are typical of those found in deep lateritic weathering. Although they may have occurred in several cycles (Pillans mentions at least two such cycles) over long periods, these were a long time in the past. Their lack of later disruption implies that fault movements have not occurred subsequently. GNS also concluded, during trench logging, that there was no evidence of movement since bleaching. Further analysis was undertaken for the key ferruginous layer, where it has been conclusively shown that no movement has taken place since oxidation. This is the basis for arguing that fault movements predate the time of deep weathering so that establishing the time relationship of this episode is important. The constraint can be stated more clearly that there is no evidence of any fault movements postdating at least the last stages of the prolonged deep weathering episode.

The minimum age of ~10Ma suggested for the deep weathering episode was based on the arguments of Herbert (1980). This was mentioned not as a firm constraint, but simply because it is consistent with observations, and with the palaeomagnetic data of Dr Pillans. Herbert's argument, concerning the age of deep lateritic weathering profiles found at various localities around the Sydney Basin, is basically that such deep weathering profiles form in a climatic regime quite different to that prevailing in the area today. This is a generally-held view about such profiles, which maintains that they are formed in warm to moist, heavily forested environments. Herbert summarises the palaeobotanical evidence from early Miocene sediments nearer the coast that such conditions did prevail across this area at that time. Herbert argues that deforestation and consequent induration and fossilization of the lateritic profiles, was most probably related to the late Miocene drop in sea-level that would be consistent with an age of ~10 Ma. This was not intended to be a precise time constraint, but rather one that is broadly consistent with the palaeomagnetic data.

6. The relevance of dykes used as support for interpretation 1.

The dykes in question are some 56 m west of the western strand, in a trench dug in an east-west direction from the excavation and not 400 m away as Geosciences, Australia suggested. The mapping of faults on the site and the views of consultants provide evidence that the faulting on the site is part of a consistent zone of faulting, related to the two main fault strands on the site. The interpretation is that the dykes must necessarily intrude along pre-existing fractures. The fact that these dykes have a consistent orientation with the other faults at the site supports this interpretation. In other words the faults must have existed prior to the time of dyke intrusion. Again the fundamental argument is not chronological, but structural, i.e. about whether all of the faults belong to a single related set of faults. The orientation of the structures is strongly suggestive of their belonging to a single coherent set.

The weathering, therefore, post-dates the major fault development processes on the site. The fact that the dyke material is undeformed supports the contention that no major reactivation has occurred since that time.

7. Opportunity for directly dating fault materials.

The normal fault (eastern strand) contains minor fault gouge that was considered for K-Ar dating. The work was undertaken by Dr H Zwingmann and its purpose was to see if it were possible to identify the faulting in the excavation with the normal faulting that occurred in the distant past.

Four samples were selected for K-Ar work, three from the main reactor excavation and one from a 0.45 m wide, completely weathered dyke (0222-3) from the shallow excavation 56m west of the western strand. Samples from the main excavation included a fault gouge (0222-5) about 2-3 cm thick from the largest normal fault on the south face of the pit. This is the only fault which showed an apparent gouge zone and the sample was collected at the only site where sufficient gouge material could be obtained. Two samples of cross-bedded sandstone (0222-6 and -7) were also collected approximately 2 m and 5 m from the cluster of faults to reveal the background age away from the fault. Samples were processed at the CSIRO facility in Perth and sufficient illite (a K-bearing clay) was recovered from all four samples, although the weathered dyke material contained very little. Kaolinite was also present in all samples, although this is not K-bearing and therefore does not contribute to the age. The kaolinite probably formed largely during the deep weathering, but is possibly also diagenetic in part. All of the samples lie within the deeply weathered zone which encompasses all the excavations at the site.

Table 2: K-Ar Results on Illite clays (2 µm fraction)

Unimelb	*CSIRO*	*K*	*Rad. 40Ar*	*Rad. 40Ar*	*Age*	*Error*	*Remark*
ID	*ID*	*[%]*	*[mol/g]*	*[%]*	*[Ma]*	*[Ma]*	
O222-3	377 <2 CT	1.75	2.7703E-10	79.87	89.03	1.98	Weathered dyke
O222-5	378 <2 CT	3.21	6.6746E-10	87.38	116.07	2.32	Clay Gouge in 'normal
O222-6	379 <2 CT	2.19	4.7698E-10	43.04	121.39	2.45	Weathered Sandstone
O222-7	380 <2 CT	5.69	1.0915E-09	86.74	107.34	2.12	Weathered Sandstone

The results in Table 2 show that the illites are of early–mid Cretaceous age and the range from 121 – 89 Ma is very similar to that reported by Bai et al. (2001) from boreholes across this region of the Sydney Basin (146-90 Ma). The results reported by Bai et al. are for authigenic illites that were formed during diagenesis of sandstones during what is interpreted to be the period of maximum basin burial and heating in the early Cretaceous, probably in the range 100°-150°C. The same explanation is the simplest interpretation of the new results quoted here for the two sandstone samples.

The lack of contrast in the K-Ar age for the clay gouge relative to the host rock ages can be interpreted in two ways. First, the fault movement may have been older than the K-Ar age, and then been reset during subsequent diagenesis, so that similar ages are now found in both the gouge and adjacent unfaulted material. Zwingmann (pers. comm.) has found comparable >100Ma ages for narrow fault gouges in the northern Sydney Basin, which have been interpreted as dating the time of fault movement. In these northern examples, however, there was an observed age difference between the gouge age and that of the surrounding host rocks.

A second possible explanation is that the time of faulting occurred later than illite formation and that the gouge simply represents sediment that has been smeared out along the fault plane with little alteration, and no change in the K-Ar age. However the similarity of the observed ages with those found for clay gouges elsewhere in the Sydney Basin strongly suggests that the first explanation is the most likely, and that the fault movements are probably related to early Cretaceous extension during continental rifting prior to Tasman Sea opening.

The age of 89 Ma for illite from the weathered dyke material sets a reasonable minimum age for the time of dyke emplacement, which, in turn provides a minimum age for the small fault into which it intrudes. The only possible alternative is that there has been some infiltration of illite from adjacent sediments during the later stages of diagenesis. This is regarded as much less likely, however, as the dyke material appears to have been compact and lacking in any visible internal veins or fractures. The low potassium value for the clay sample from the dyke is a reflection of the low illite content, probably in turn reflecting the low-potassium nature of the original basaltic rock. This diagenetic alteration age of 89 Ma is also consistent with rapid cooling after ~80 Ma indicated by the thermochronology.

In conclusion, the weight of evidence from the K-Ar dating favours an early Cretaceous age for fault movements on at least those faults which could be examined by this method. Alternative explanations cannot be categorically ruled out, but there is nothing in the K-Ar evidence, or indeed any of the other geochronological evidence that points to a young age for any of the fault movements.

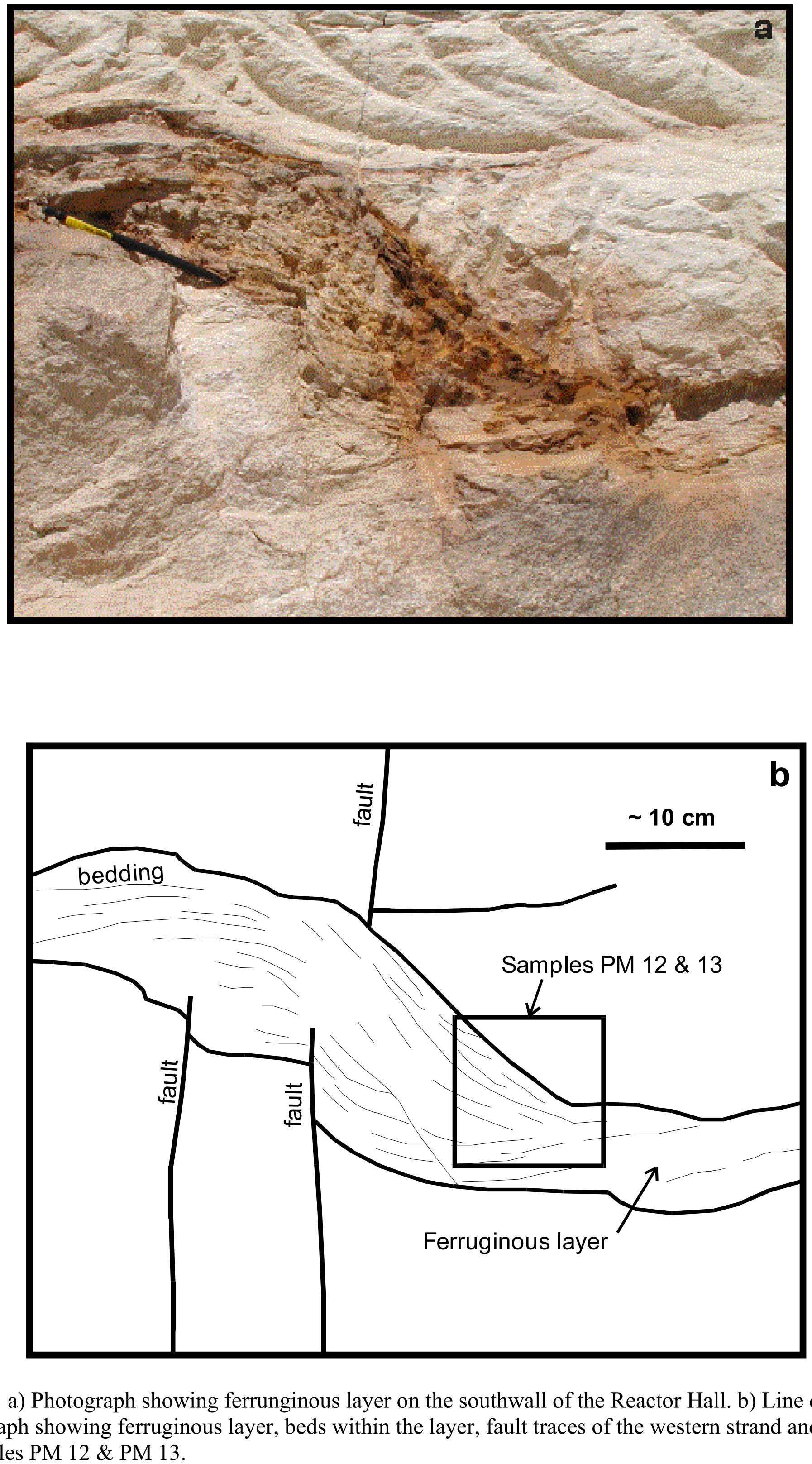

Figure 1 a) Photograph showing ferrunginous layer on the southwall of the Reactor Hall. b) Line drawing of photograph showing ferruginous layer, beds within the layer, fault traces of the western strand and the location of samples PM 12 & PM 13.

Paleomagnetic Remanence Directions - Group 2 samples

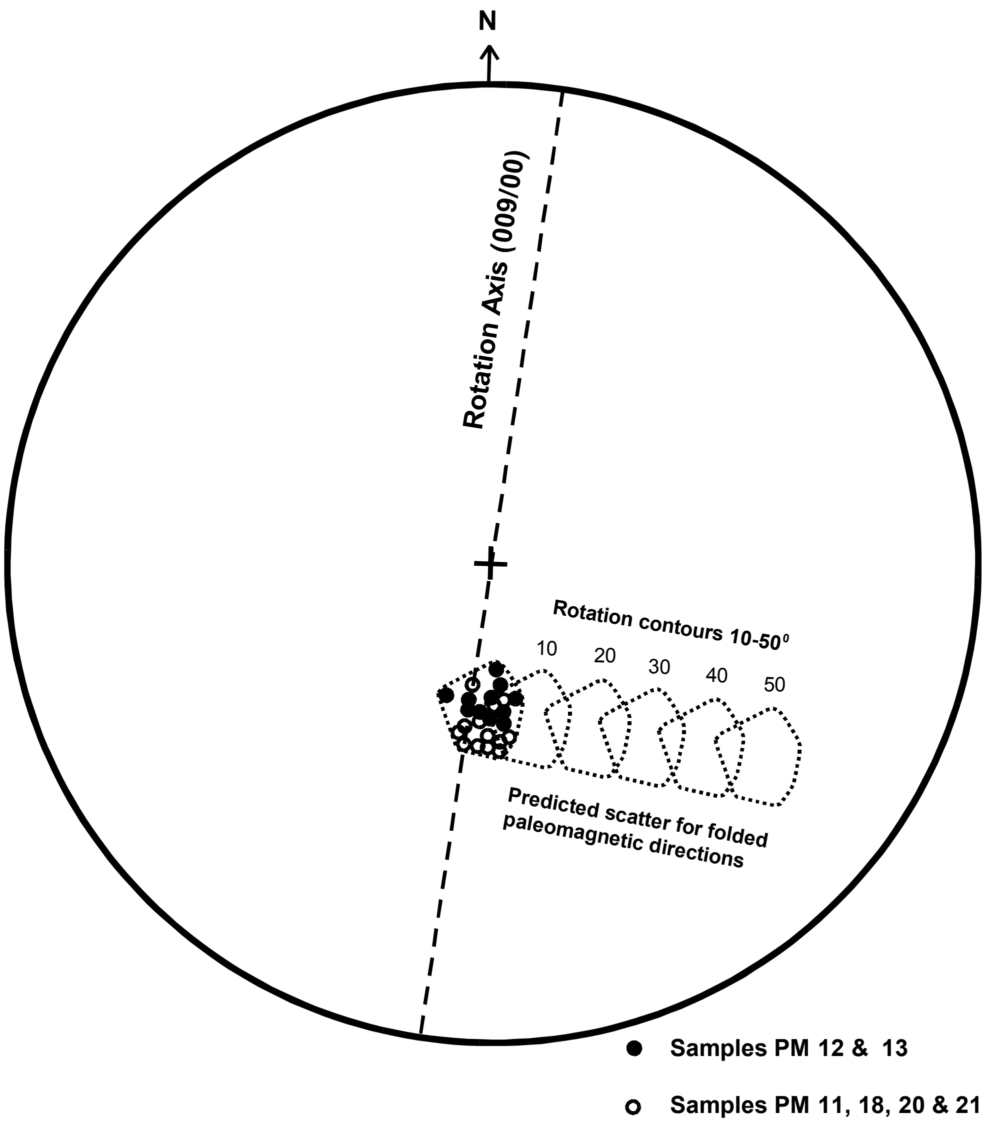

Figure 2 Stereographic plot of paleomagnetic remanence orientations of Group 2 samples. Filled circles indicate data from folded beds and open circles data from unfolded sub-horizontal beds. Contours show scatter of plaeomagnetic directions predicted for bed rotations of 10-50°. Contours derived by rotating the present orientations of paleomagnetic remanence orientations about a horizontal axis parallel to the fault. These rotations are in accord with the amount of dip and the dip direction of beds within the fold adjacent to the western fault strand.

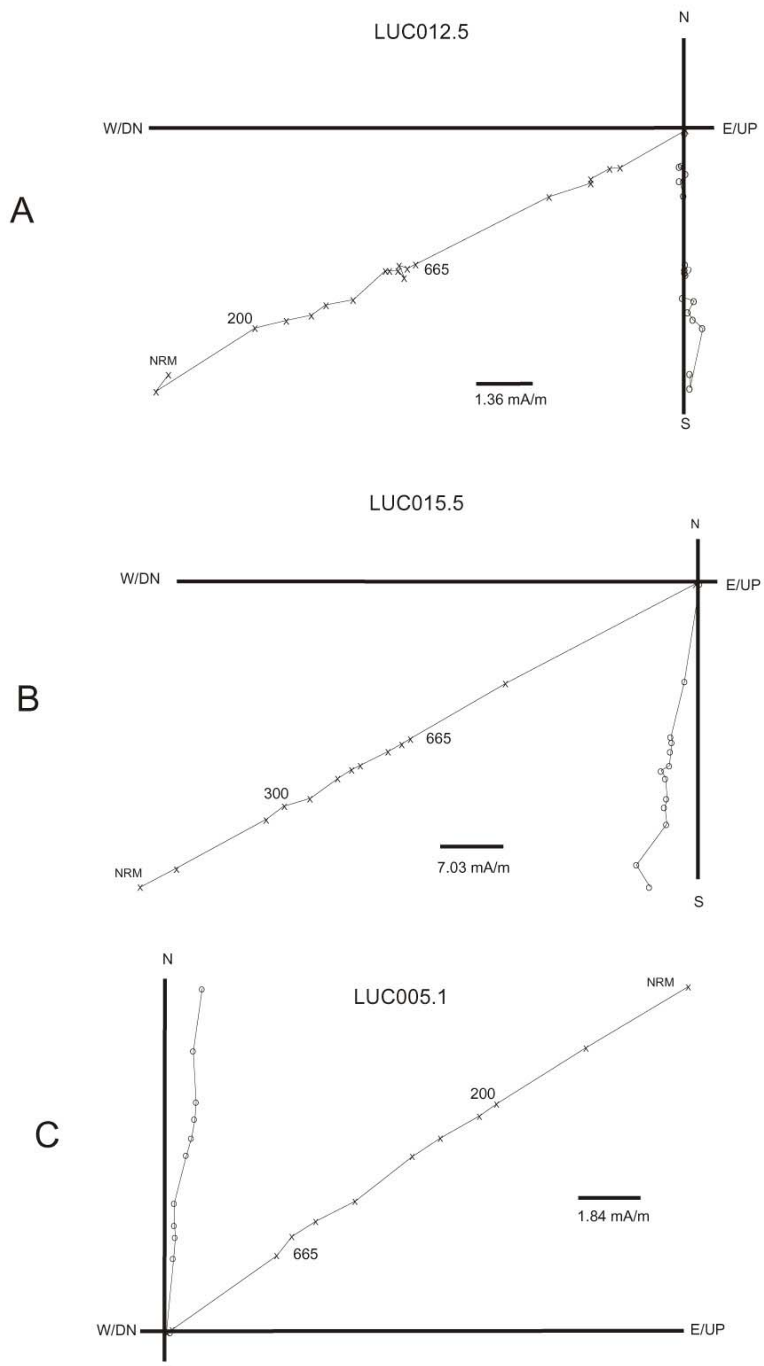

Figure 3 shows orthogonal plots of three representative paleomag specimens: A = Group 2, B = Group 1, and C = Group 3.