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Reply to comment by Stamatakos *et al.* on 'Early Silurian palaeolatitude of the Springdale Group redbeds of central Newfoundland: a palaeomagnetic determination with a remanence anisotropy test for inclination error'

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Stamatakos *et al.* raise several objections to our recent palaeomagnetic study of the Springdale Group redbeds of Newfoundland. We discuss their comments below.

In their summary, Stamatakos *et al.* comment that 'recent palaeomagnetic results from coeval Silurian sedimentary and volcanic rocks of Newfoundland yield contradictory results, with shallow characteristic directions recorded by the redbeds and steeper characteristic directions recorded by the volcanics'. However, the Newfoundland volcanics that give steeper magnetic inclinations lie stratigraphically beneath and, hence, are not coeval with the redbeds (the few volcanic sites within the redbed stratigraphy have shallow inclinations). In the case of the Botwood Group, a portion of the redbeds of the Wigwam Formation are likely to be of Ludlow age according to new fossil evidence (Boyce & Ash 1994) and U-Pb ages of about 423 Ma (Dunning *et al.* 1990) for igneous rocks that are thought to intrude or overlie the Wigwam Formation. On the other hand, the volcanic rocks of the underlying Lawrenceton Formation are older, with Colman-Sadd (1994) proposing a probable Llandovery C3 age for the base of the Formation. Therefore, any difference in magnetic inclination could be due, at least in part, to drift of central Newfoundland to lower palaeolatitudes between the time of emplacement of the volcanic rocks and the deposition of the redbeds.

Stamatakos *et al.* also imply that our 'tectonic reconstruction (is) based solely on the redbed magnetization'. In fact, we utilize results from redbeds and minor intercollated volcanic rocks of Newfoundland and both redbeds and volcanic rocks of Britain (see our Table 3 and Fig. 10).

IRM EXPERIMENTS

We agree with Stamatakos *et al.* that there are limitations to the isothermal remanent magnetization (IRM) test that we propose. However, we argue that these limitations are not as serious as these authors imply and believe that the test can be useful with many redbeds to help determine if inclination shallowing has occurred.

(1) Stamatakos *et al.* state that our maximum applied field of 800 mT is 'too small to magnetize most of the haematite fraction' and seem to imply that more than 8000 mT may be required. We argue that 800 mT may well have magnetized more than half of the haematite fraction because Dunlop (1971, Table 5.1, column 8) only required fields from 229 to 821 mT to attain half of saturation IRM in his fine-grained haematite specimens.

Stamatakos *et al.* claim that 'if the graph in Fig. 8(a) is extrapolated to higher fields in the range near haematite saturation, it appears that the increasing difference between the intensity of the IRM_x compared to the IRM_z would lead to the opposite conclusion, i.e. that significant deflection of the remanence within bedding has occurred'. This is incorrect. It is not the **difference** between IRM_x and IRM_z but their **ratio** that predicts inclination error. The ratio IRM_z/IRM_x shows no significant change with increasing field as clearly shown by the linearity of the plot in our Fig. 8(b).

Stamatakos *et al.* suggest that our IRM experiments may mostly be measuring the anisotropy of the coarsest haematite, whereas the natural remanent magnetization (NRM) may mostly be carried by much finer haematite whose anisotropy and inclination error may be much higher. However, the finest haematite in our specimens is likely that in haematite cement which should postdate much of the compaction and, hence, should show relatively low anisotropy and inclination error. Besides, most of the volume of haematite in our specimens occurs as abundant grains of large size (averaging 0.05 mm judging by microscope examination of polished thin sections of the 10 specimens of our Table 2). If one suspects that most of the NRM in a specimen is carried by much finer detrital grains (which seems more likely in clay-rich sediments that we have avoided), we suggest giving the samples a thermo-remanent magnetization (TRM) at 45° to bedding. Then use the TRM component parallel to bedding (TRM_x) and the TRM component perpendicular to bedding (TRM_z) in place of IRM_x and IRM_z respectively in our eq. (4).

(2) Stamakatos *et al.* want us to determine the whole anisotropy of the IRM tensor. We (and Tauxe *et al.* 1990) found that this was not possible with haematite-bearing rocks because, as we discussed on pp. 647–648, 'the first direction to which the field was applied tended to acquire a stronger remanence (IRM) than subsequent directions'.

Fortunately, measuring only in the plane perpendicular to bedding that contains the NRM direction is adequate if one is testing for inclination error due to deposition or compaction.

(3) Only in experiments on **clay-rich** sediments has it been demonstrated that initial consolidation may cause a significant remanence shallowing that is unaccounted for by the theoretical relation of Jackson *et al.* (1991). However, 'we were careful to avoid clay-rich specimens in our collecting' as we state on p. 649 and as can be seen in the grain diameter estimates in our Table 1.

CONGLOMERATE TEST

Stamatakos *et al.* conclude that the conglomerate test, although it rules out thermal overprinting of the redbeds, does not exclude chemical remagnetization. We agree. Indeed, we said so on p. 645: 'This (conglomerate) test also shows that the haematite in the redbeds was probably not thermally remagnetized. However, prefolding chemical remagnetization in the redbeds is not ruled out by this test.'

IMPLICATIONS FOR APPARENT POLAR WANDER

(1) Since they consider inclination shallowing likely in the case of redbeds of Newfoundland, it is surprising that Stamatakos *et al.* accept the Silurian data from cratonic North America for calculating a reference field. The bulk of the data from the craton is derived from sedimentary rocks (often redbeds) for which no tests for inclination shallowing have been conducted.

(2) In our paper, we mentioned only one controversial aspect of the age of the Dunn Point Formation remanence. There are, however, several reasons to reserve judgement on the age of this remanence. To summarize: (a) the age of the Dunn Point volcanics is poorly constrained radiometrically (Fullagar & Bottino 1968) and could be much older than early Silurian (Hodych & Buchan 1994). Therefore, even if the remanence were known to be primary it would be difficult to use it with confidence for polar wander purposes. (b) The remanence has not been demonstrated primary on the basis of a palaeomagnetic field test. (c) Sampling sites used in the fold tests are all in steeply to vertically dipping flows where 'interlayered sediments suitable for bedding measurements are rarely available' (Johnson & Van der Voo 1990), perhaps explaining the fact that both positive and inconclusive fold tests have been reported for this unit.

(3) We are unable to comment on the discussion of Stamatakos *et al.* concerning their Fig. 1(c) since the data contained in it are not referenced and the paper from which it was adapted is not yet published.

CONCLUSIONS

Stamatakos *et al.* note that our conclusions are 'difficult to reconcile within the frame work of established continental reconstructions.' We submit, however, that the present palaeomagnetic data on which continental reconstructions in the Silurian (and more generally in the Early Palaeozoic) are based are often poorly constrained, especially in age (Buchan & Hodych 1993). Hence, it may be premature to consider continental reconstructions as 'established' until ages of rock units have been accurately determined and their palaeomagnetic directions are clearly established as primary or secondary.

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