Geological Magazine

www.cambridge.org/geo

Original Article

Cite this article: Piper JDA, Kokelaar BP, and Roberts AP. Palaeomagnetic study of the Lorne Plateau Lavas, Scottish Caledonides: two emplacement episodes of normal polarity during the Pridoli-Lochkovian and a precisely dated Siluro-Devonian pole position. *Geological Magazine* **162**(e6): 1–14. https://doi.org/10.1017/S0016756824000463

Received: 17 January 2024
Revised: 26 June 2024
Accepted: 8 November 2024

Keywords:
British Caledonides; Siluro-Devonian; Lorne Plateau Lavas; Palaeomagnetism

Corresponding author:
J.D.A. Piper;
Email: johnallenpiper1@gmail.com

CAMBRIDGE UNIVERSITY PRESS

Palaeomagnetic study of the Lorne Plateau Lavas, Scottish Caledonides: two emplacement episodes of normal polarity during the Pridoli-Lochkovian and a precisely dated Siluro-Devonian pole position

J.D.A. Piper, B.P. Kokelaar and A.P. Roberts

Department of Earth and Ocean Sciences, University of Liverpool, Liverpool, AE, UK

Abstract

The Lorne Plateau lava succession of the north-west Grampian Highlands of Scotland is an early component of post-collisional Late Silurian to Early Devonian magmatism in the Orthotectonic Caledonides emplaced in two phases between the Late Silurian (425.0±0.7 Ma U-Pb zircon) and the Siluro-Devonian boundary at ~419 Ma. Palaeomagnetic study comprising thermal demagnetization and component analysis embracing the time frame of the preserved succession yields a coherent mean direction of magnetization from 58 sites (D/I = 43.7/−47.4°, $\alpha_{95} = 4.0°$). A palaeomagnetic fold test is significantly positive with sills intruding unlithified sediment on the island of Kerrera confirming primary remanence. The ~600 m thick succession has uniform normal polarity throughout permitting correlation with the beginning of a normal polarity chron extending from ~426 to 403 Ma. The pole position at 2.7°N, 317.3°E ($dp/dm = 3.8/5.8°$) predicts a palaeolatitude of 26°S and corresponds precisely with remanence in contemporaneous rocks from the Midland Valley of Scotland. Regional palaeofield directions are evaluated in the context of transpressional moulding of the Acadian Orogeny on the Great Glen Fault system (~416−380 Ma).

1. Introduction

Following closure of the British sector of the Iapetus Ocean during late Ordovician times, the Caledonian orogenic belt was characterized by intense and protracted calc-alkaline igneous activity extending from the Shetland Islands in the north to Donegal in the southwest. This is illustrated in Fig. 1 covering the sector between the Northern Highlands of Scotland and Western Ireland. The extended duration of magmatic activity (mid Silurian to mid Devonian) presents an interpretive challenge because subduction had by then effectively ceased following the collision between Laurentia and Avalonia accompanying closure of the Iapetus Ocean. The interval embraced by magmatism following collision included a tectonic regime of left-lateral strike-slip initiating the Great Glen and subsidiary faults with an associated thermal anomaly responsible for major uplift and voluminous calc-alkaline magmatism. The latter persisted for at least 25 Ma (Thirlwall, 1988; Kokelaar & Moore, 2006; Neilson *et al.* 2009). Neilson and co-workers emphasize the close petrogenetic association of the vast volumes of andesite and dacite lavas with the granitic (*sensu lato*) plutons; they identify repeated erosional removal of uplifted volcanic rocks and attribute protracted post-collision magmatism to slab breakoff (see also Atherton & Ghani, 2002).

Geological investigations (Moore & Kokelaar, 1997, 1998; British Geological Survey, 2005; Kokelaar & Moore, 2006; Neilson *et al.* 2009) resolve a detailed sequence of volcanic and intrusive events within the Lorne-Rannoch sector of the igneous province (Fig. 2) comprising lava piles, caldera volcanoes, subvolcanic plutons and NE-SW trending dyke swarms. Complementary radiometric studies (Rogers & Dunning, 1991; Fraser *et al.* 2004; Neilson, 2008; Neilson *et al.* 2009) yield a range of high precision age determinations dating intrusive events extending between ~430 and ~405 Ma. Complementary palaeomagnetic investigations have aimed to monitor movements of this sector of the Caledonides and place magnetic polarities within a magnetostratigraphic time frame. Previous palaeomagnetic studies of the Siluro-Devonian rocks of Scotland incorporating 'Old Red Sandstone' sedimentary successions together with plutons within the Orthotectonic Caledonides (this latter term used here to embrace the medium-high grade metamorphic Caledonides together with their igneous component) identify magnetizations mostly acquired in a magnetic field including polarity reversals. The collective results have contributed towards a wider understanding of Siluro-Devonian Apparent Polar Wander (APW) and a range of regional tectonic

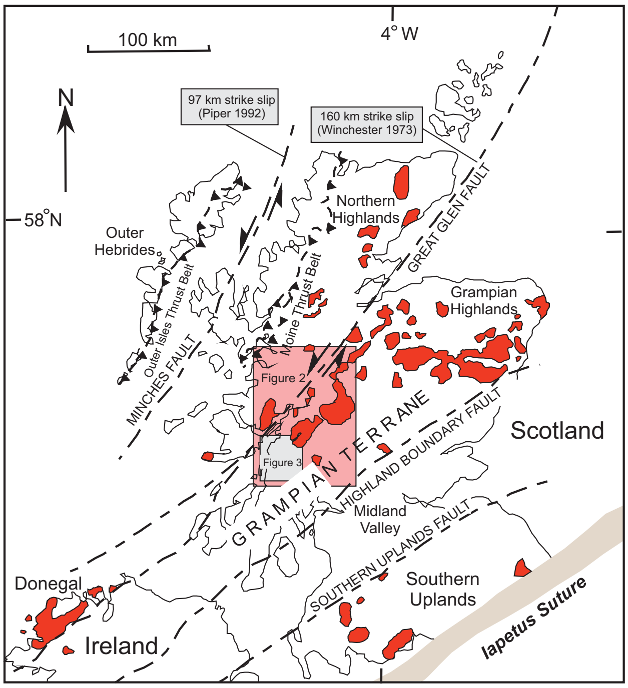

Figure 1. Outline of the Caledonides of northern Britain showing the distribution of major faults and thrusts and the distribution of the "Newer Granites" (red). Locations of Figs. 2 and 3 are indicated.

interpretations (see, for example, Trench & Haughton, 1990; Torsvik *et al.* 1992; Piper, 1991, 1997*a*, 1997*b*, 2006).

In this paper, we report a detailed palaeomagnetic study of the Lorne Lava pile, the major extrusive component of this volcanic province which comprises a large outcrop at the SW extremity of the Lorne-Rannoch volcanic district (Fig. 2).

2. Geological framework

The igneous outcrop extending from Rannoch Moor in the NE to the region of Loch Awe and the borders of the Firth of Lorne in the SW is the degraded remnant of several major volcanoes with extrusive constituents preserved mostly in the Lorne Plateau and Glencoe Caldera Volcano (Fig. 2). The subvolcanic components comprise plutons including Rannoch (>422.5±0.5 Ma), Clach Leathad – Glencoe (417.9±0.9 Ma), Etive – Cruachan (414.9 ±0.7 Ma) and Etive – Starav (408.0±0.5 Ma). Regional outcrops are shown in Fig. 2 with age assignments from Neilson *et al.* (2009). The plutons are cut by dykes of the 'Etive Swarm' predominantly of andesitic and dacitic composition. This swarm was evidently emplaced over an interval of at least 7 Myr because early members are cut by the 415 Ma Cruachan intrusion whilst young members cut the outer ~408 Ma Starav intrusion. Lorne–Rannoch magmatism was therefore contemporaneous with initiation of NE-SW faulting which incorporates both strike slip and normal motions. This last major phase of tectonism is part of a wider system dissecting the entire orogen in fault trends ranging from NNE on the foreland in the northwest to ENE in the Paratectonic Caledonides (this term here used for low-grade metamorphic terranes and incorporated igneous rocks) farther south (e.g. Hutton, 1987 and Fig. 1). The largest displacement identified to date of ~160 km derives from offset of metamorphic zonation (Winchester, 1973) on the Great Glen Fault (GGF) immediately to the northwest of the Lorne-Rannoch igneous complex; a further left-lateral strike-slip of 97 km is recognized from offset of magnetic properties of the Lewisian basement in the Minches Basin beyond the orogenic foreland to the northwest (Piper, 1992, Fig. 1). Smaller but unquantified motions are present on a family of sub-parallel faults within the Grampian Highlands to the south-east (Fig. 1, e.g. Soper *et al.* 1992; Dewey & Strachan, 2003). The focussing of the NW Grampian magmatic activity in the vicinity of the largest scale faulting along the Great Glen System is interpreted by Neilson *et al.* (2009) to stresses applied during thermal erosion with weakening of the lithosphere that accompanied slab-breakoff and subjacent rise of asthenosphere.

The Lorne lava succession is the largest preserved remnant of late-orogenic calc-alkaline extrusive volcanism within the Orthotectonic Caledonides and covers an area of ~300 km^2 cropping out to the north, east and south of the town of Oban (Kynaston & Hill, 1908). It is a typical mildly deformed 'Lower Old Red Sandstone' succession and overlies, locally with a basal conglomerate and sandstones, an uneven eroded basement of Dalradian metamorphic rocks. The lava succession comprises up to 600 metres of predominantly andesitic and dacitic compositions (Thirlwall, 1979; Neilson *et al.* 2009); subordinate sediments are present in the lower part of the succession and intercalated tuffs occur higher up. The lava pile was originally dated from fish and arthropod remains in basal sediments assigned to the 'Old Red Sandstone' by Kynaston and Hill (1908). Palynological studies together with further fish-bed research have indicated a Pridoli (end Silurian, 423–419 Ma) to earliest Lochkovian (basal Devonian) age (Marshall, 1991; Wellman & Richardson; 1996; Trewin *et al.* 2012). Lava samples were dated 394±9 Ma by the K-Ar method by Evans *et al.* (1971); a slightly older age was inferred by Latham and Briden (1975), whilst Clayburn *et al.* (1983) obtained a Rb/Sr isochron age of 400 ± 5 Ma. Significantly older ages in the range 415–424 Ma were derived from the Rb-Sr whole-rock dating by Thirlwall (1988) with subsequent precise U-Pb zircon dating of a lava close to the topographically highest remnant interior part of the pile yielding an emplacement age of 425.0 ± 0.7 Ma (Neilson *et al.* 2009); the equivalent (Late Wenlock, Homerian Stage) is marginally older than the Pridoli age indicated by the palynology. However, in the context of this tight collective control of 2–3 Ma for the age of the major part of the Lorne succession, the pre-1988 age dates will reflect an overprint signature of Late Silurian-Early Devonian tectonism and low-grade metamorphism.

Emplacement of the Lorne lavas overlapped progressively onto an eroded surface of Dalradian metamorphic rocks facing downward to the west. The main thickness of the lava pile, preserved on the mainland east of the town of Oban (Fig. 2), is altered by pervasive high pumpellyte-prehnite to low greenschist hydrothermal metamorphism including disseminated mineralization. However, south and west of Oban andesite and dacite sheets overlie, and are intercalated within, sediments close to present sea level; the suite here is less altered than the major pile to the east and yields uppermost Silurian to basal Devonian (Pridoli-Lochkovian) fossils defining an age of ~419 Ma (Gradstein *et al.* 2012; Trewin *et al.* 2012) for this part of the succession. The contrasts in age, topographic elevation and scale of the low-grade metamorphism are interpreted in terms of the initiation of a palaeo-valley, at least 600 m deep, along the GGF and bordering strands. 'Basal' conglomerates and sandstones along the fault zone, on the island of Kerrera and mainland opposite, record contemporary normal- and strike-slip fault activity and show local transport of boulders rich in

https://doi.org/10.1017/S0016756824000463 Published online by Cambridge University Press

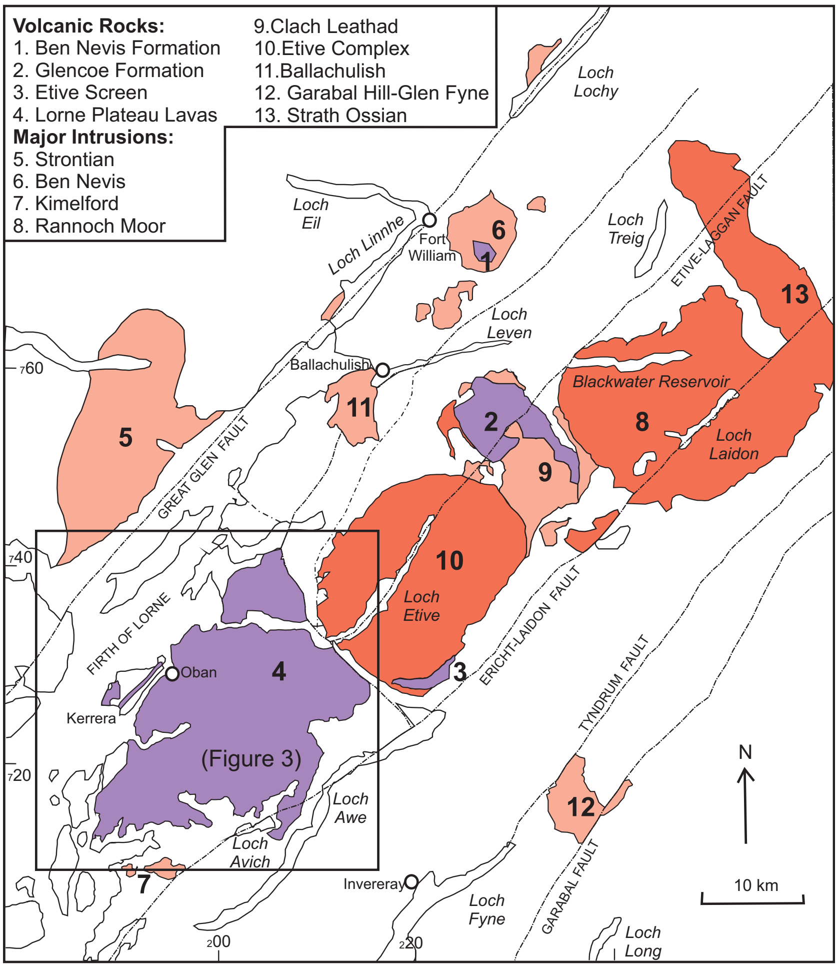

Figure 2. Siluro-Devonian post-collision plutons and volcanoes in the SW Grampians of Scotland; the Ben Nevis and Etive Dyke Swarms are not shown.

andesite and dacite compositions (Neilson, 2008). It appears that the main lava pile was emplaced at ~425–423 Ma contemporaneous with emplacement of the Rannoch and Clach Leathad-Glencoe plutons, with the less altered lava suite to the west, stratigraphically higher but now topographically lower, emplaced during a subordinate episode ~5 Myr later. Ensuing magmatism over an interval of ~10 Myr built the Etive Volcanic complex and fed the Etive Dyke Swarm (Kokelaar & Moore, 2006; Neilson *et al.* 2009). Metamorphism of both the main Lorne Lava pile and the aureole of the Etive Pluton (Moazzen & Droop, 2005) require a former cover of ~1.5 – 2 km thickness most of which has since been removed by uplift and erosion with only the Kerrera succession constituting a preserved remnant. The trace of the intra-successional side to the palaeovalley, and hence an unconformable contact on the mainland, is currently unclear. Samples of Kerrera andesitic lavas, an intrusion sample and a boulder unfortunately failed to yield sufficient non-inherited zircon for radiometric dating. Nevertheless, the ~419 Ma age estimate for this part of the succession can be closely assigned by the boundary fossil evidence together with the field relationships noted above.

Low tectonic tilts rarely exceeding 20° are attributed to block rotations during the regional tectono-magmatic episode and are applied here as tilt adjustments to site palaeomagnetic directions. The bounding faults to these block rotations become more abundant towards the centre and west of the lava pile and have predominantly NE-SW trends.

3. Background to the present study

Following a small study by Embleton (1968), the Lorne Plateau lava succession was investigated palaeomagnetically by Latham and Briden (1975) using a distributed sample mostly derived from the Oban district in the west of the outcrop. Samples were treated to alternating field (a.f.) demagnetization with 33 sites yielding significant groupings and 29 sites identifying uniform negative (upward) inclination directions of magnetization consistent with a normal polarity Siluro-Devonian palaeofield, Britain, then being located in the southern hemisphere. Since Late Silurian to Early Devonian rocks are known from the wider global record to include reversals, this uniform polarity suggested rapid emplacement during a single polarity chron. However, a.f. demagnetization also found variable, sometimes high, magnetic coercivities, and the end-point analysis employed was unable to properly resolve component structures. Furthermore, these collections came predominantly from lavas near the base of the preserved succession and were unable to assess polarity throughout the preserved sequence.

Accordingly, the present study has aimed to unravel magnetic component structures of the natural remanent magnetizations by incorporating progressive thermal demagnetization and principal component analysis (PCA) to establish characteristic remanent magnetizations (ChRMs). These are linked to a quasi-primary thermal remanent origin using appropriate palaeomagnetic field

https://doi.org/10.1017/S0016756824000463 Published online by Cambridge University Press

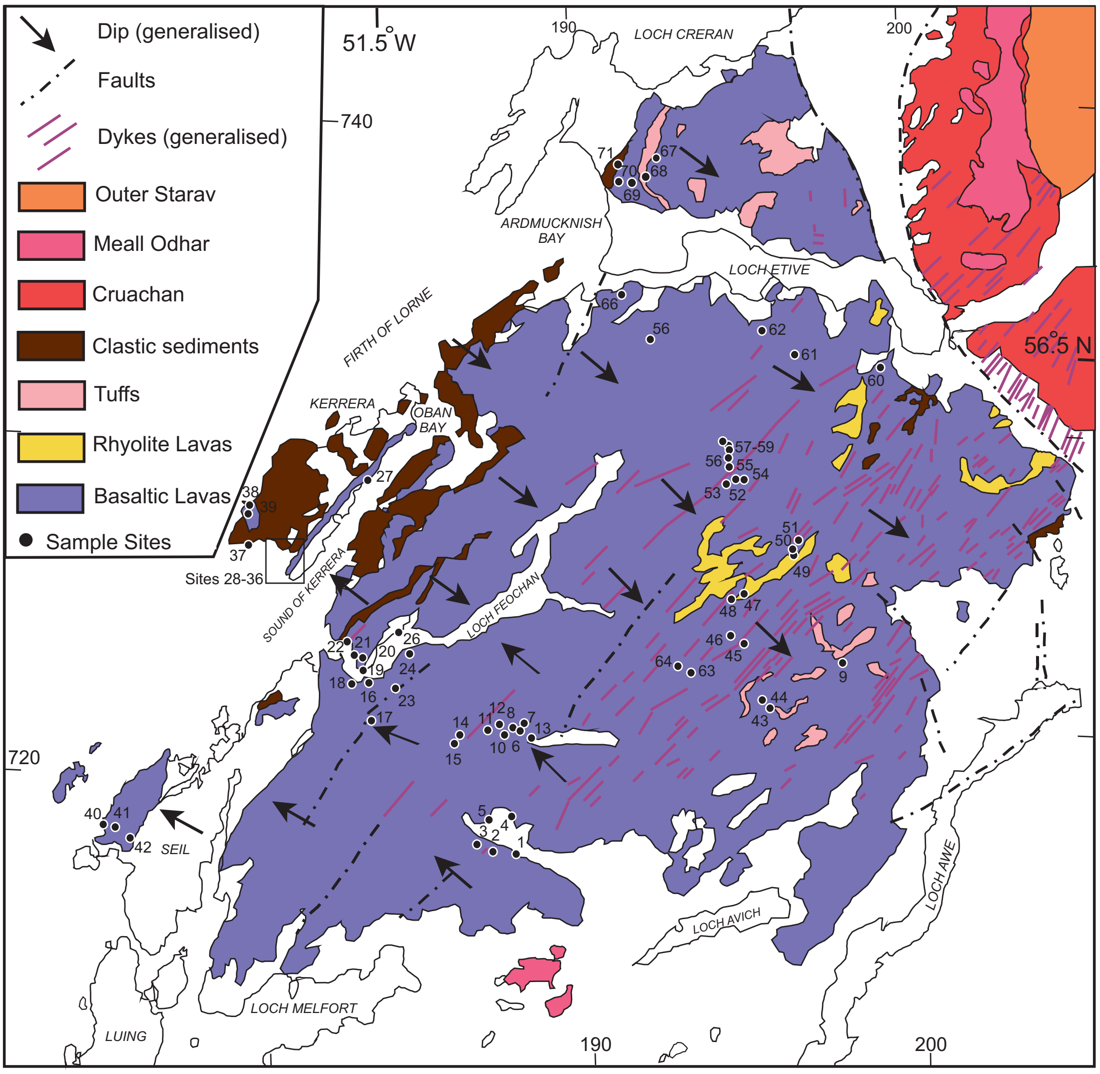

Figure 3. Geological Map of the Lorne Plateau with the distribution of the palaeomagnetic sampling sites of this study.

tests. By using a sample distributed through the succession, and specifically including late eruptive events, we have aimed to resolve the significance of the uniform normal polarity. We also place the study in its paleogeographic context and include a revised comparison of palaeomagnetic results from Caledonian igneous suites from the sectors of the metamorphic Caledonides on either side of the GGF.

4. Palaeomagnetic study

4.a. Field sample and laboratory procedures

Samples for palaeomagnetic study were derived from field drilling and orientation of in situ cores by sights on the Sun and magnetic bearings, and from laboratory drilling of oriented block samples. Site locations are shown on the geological map of Fig. 3 with site grid references listed in Supplementary Data File Table 1. The lavas were emplaced onto an irregular Dalradian basement, which, together with incomplete exposure and effects of faulting, preclude recognition of a completely ordered stratigraphic sequence. Nevertheless, the prominent lava step topography in the main outcrop between Loch Awe and the Firth of Lorne, coupled with field studies of Joanne Neilsen (personal communication) and one of us (BPK), permits successions to be evaluated locally, although it is not always clear that each sampled unit is a lava flow. We designate the older, strongly altered sequence as the ‘main’ succession and the younger, less altered rocks as the ‘Kerrera’ succession. Excellent coastal exposures show that some sheets were intruded into sedimentary layers as sills, with the formation of peperite indicating that the host was wet and unlithified at the time of emplacement (Kokelaar, 1982). It is possible that some of the sampled units are sills, and sites are therefore given the general designation lava/sheet. Our field sites 43–44 and 49–51 (Fig. 3) are sited near to the top of the main preserved succession. In addition, a narrow NE-SW tending down-faulted feature running along the axis of the Island of Kerrera cuts basement metamorphic rocks; it exhibits a range of volcanic features recording emplacement into unlithified sediments sampled at sites 28–36. These sites, together with 27 and 37–39, comprise the ‘Kerrera’ succession. The northern part of the outcrop bordering Loch Etive lying just above the Dalradian unconformity in proximity to the Cruachan pluton although not included in this study was thoroughly sampled by

https://doi.org/10.1017/S0016756824000463 Published online by Cambridge University Press

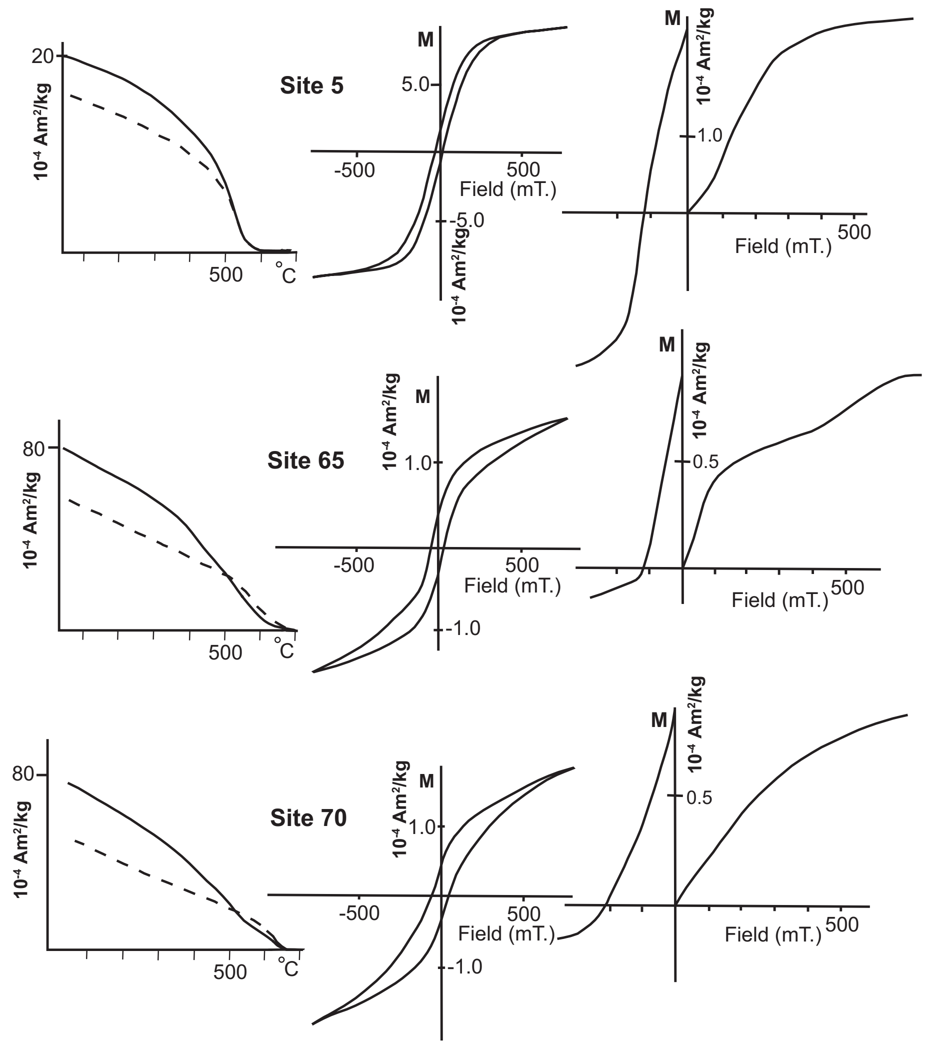

Figure 4. Examples of magnetic properties in representative Lorne Plateau sites. The hysteresis loops show a single magnetic phase saturating in low applied fields. The thermomagnetic determinations identify Curie points of low-Ti titanomagnetite as the dominant ferromagnet; dashed lines are cooling curves and intensities of magnetization are x10^{-5} Am^2/kg. The IRM forward and backfield curves identify the presence of a low coercivity ferromagnet, presumably titanomagnetite.

Latham and Briden (1975). The outlier of the succession in the Benderloch region north of Loch Etive was sampled through lower to higher levels via sites 67 to 71.

In the laboratory magnetic susceptibilities of 2.4 cm diameter samples were measured by Bartington Bridge followed by determination of anisotropy of magnetic susceptibility (AMS) at selected sites using 'Minisep' or Kappabridge delineators. Rock magnetic properties were evaluated at a range of sites using a variable field translation balance (VFTB). Most cores were then treated to progressive thermal demagnetization in steps of 50°C to 500°C and subsequently in steps of 20°C to Curie points of the magnetic carriers using MM2D demagnetizers with magnetizations measured at each stage by 'Molspin' magnetometers. Magnetic vectors were resolved into orthogonal projections and components comprising the ChRMs evaluated by eye; equivalent directions were calculated by PCA and site and group mean populations assessed using standard Fisherian statistics.

4.b. Rock magnetism

Hysteresis properties are a function of ferromagnet mineralogy, grain size and domain state: titanomagnetites and titanomaghemites saturate in fields of 300 milliTesla (mT) or less, whilst titanohematites require much larger fields to achieve saturation. Parameters used to express these properties (Supplementary Data File Table 2) are saturation magnetization (M_s) saturation remanence, residual remanence with applied field reduced to zero (M_{rs}), coercive force (H_c) and backfield required to subtract this field (B_{cr}). Parameters M_s and M_{rs} are dependent on the concentration and type of magnetic minerals present: M_s is independent of grain size, but M_{rs} is smaller for multidomain (MD) than for single domain (SD) grain properties. Hence, the ratio of M_{rs}/M_s is a useful indicator of domain states: if M_{rs}/M_s is <0.1, the sample is dominated by MD grains; if M_{rs}/M_s >0.1 small but significant fractions of SD grains are present within a dominant MD assemblage. If mixed domain sizes are present within magnetite only (as indicated by M_{rs}/M_s values of 0.2–0.5), the equation $X_{MD} = (0.5 - (M_{rs}/M_s))/0.48$ yields a semi-quantitative estimate of the fraction of MD grains present.

MD contents in the Lorne lavas/sheets are mostly in the range of 70–90% with the residual fractions of SD/pseudo-single domain grains likely to account for moderate to high palaeomagnetic stabilities observed at most sites. Curie points show typical low-Ti titanomagnetite values of 550–580°C although Site 70 (Fig. 4) is an example with the thermomagnetic spectrum dominated by hematite and the magnetite Curie point suppressed. The hysteresis of this rock shows clear constriction ('wasp-waisting') identifying a mixed ferromagnet content. At other sites such as 65 (Fig. 4), there

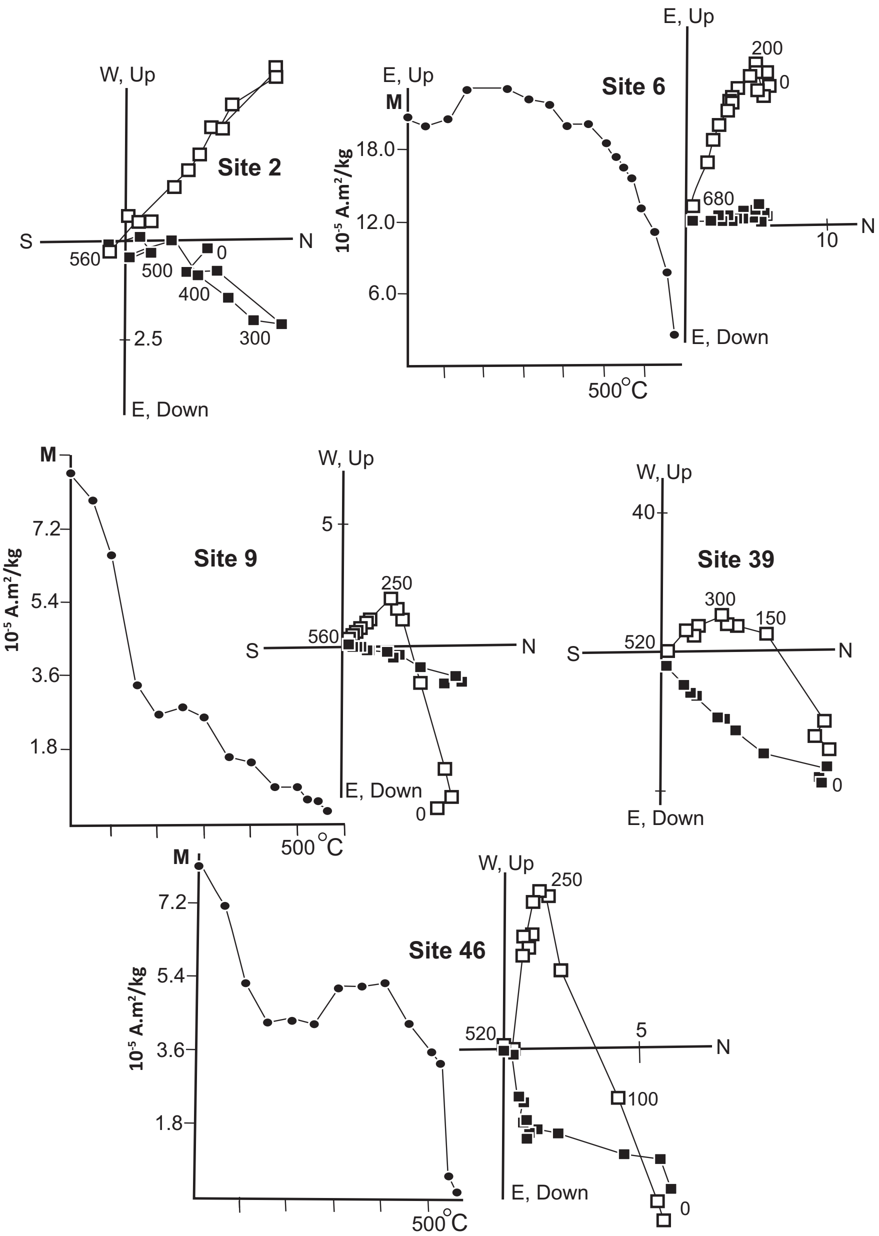

Figure 5. Examples of progressive thermal demagnetization behaviours for samples from the Lorne Plateau Lavas. The orthogonal projections show magnetization vectors projected as closed squares onto the horizontal plane and as open squares onto the vertical plane; figures are demagnetization temperatures in degrees centigrade. The intensity spectra show decline of the magnetization, M, with progressive treatment; the units of intensity of magnetization are x10^{-5} A.m^2/kg.

is evidence for slight constriction, which, although the thermomagnetic spectrum is dominated by magnetite, shows that some hematite is present; since this effect is incipient rather than ubiquitous through the lava pile it is likely to be the result of deuteric oxidation during primary cooling of the lava pile. Site 5 (Fig. 4) is an example of a site dominated by low-Ti titanomagnetite and low coercivity hysteresis with simple ('pot-bellied') form (Tauxe *et al.* 1996).

IRM acquisition shows saturation largely achieved by 300 mT in dominant titanomagnetite-bearing sites such as 5, whereas mixed assemblages highlight a rapid increase in the low coercivity spectrum followed by a further climb into the higher coercivities characteristic of hematite; in these high coercivity samples, IRMs continue to rise to the limits of the applied field (Site 70, Fig. 4). The illustrated examples of demagnetization behaviours in Figs. 5 and 6 illustrate contrasting behaviours confined to the magnetite spectrum (sites 9, 26, 46 and 66) and examples with significant hematite fractions (2, 47).

4.c. Palaeomagnetic results

The majority of samples are characterized by moderate to high magnetic stabilities to progressive thermal demagnetization treatment with the highest stabilities generally characterizing samples with higher distributed unblocking temperatures. Some component structures, such as site 47 in Fig. 6, are predominantly single, but more commonly progressive thermal treatment isolates two or three (site 39, Fig. 5) components. The lower unblocking temperature components do not categorize simply; some yield directions analogous to the later Palaeozoic field, but the commonest feature is a N+/S- component fraction attributable either to a regional thermal imprint of the Tertiary Igneous

https://doi.org/10.1017/S0016756824000463 Published online by Cambridge University Press

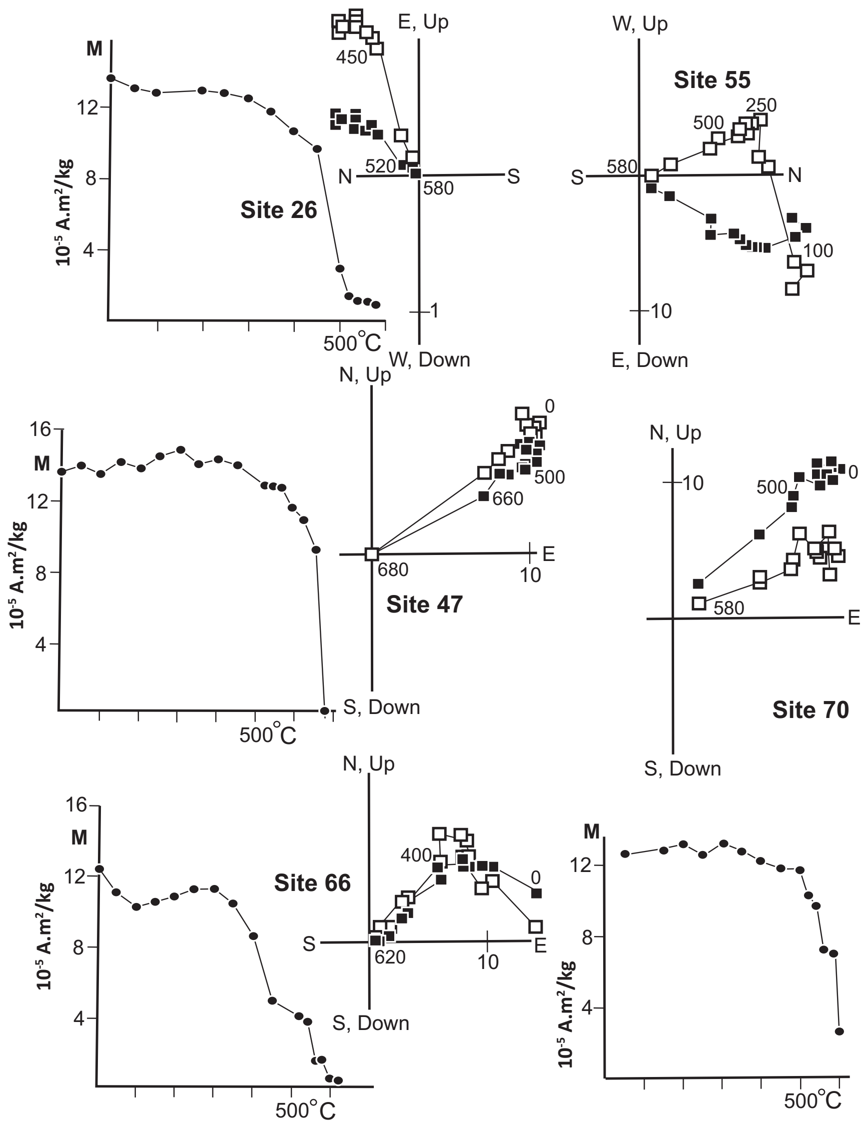

Figure 6. Examples of thermal demagnetization behaviours for samples from the Lorne Plateau. Symbols etc. are as for Fig. 5.

Province or to the present-day field direction (in the normal magnetizations). However, the highest unblocking temperature convergent segments of the orthogonal projections comprising the ChRMs are removed at temperatures between ~530 and 680°C (Figs. 5 and 6). They reside in both magnetite and hematite carriers compatible with the rock magnetic results, and the majority have N- to NE-directed negative inclinations. Where the unblocking temperature spectra extend into the hematite range (>580°C), the hematite component has a direction close to, or indistinguishable from, the titanomagnetite component indicating that the hematite in these lavas is of quasi-primary deuteric origin.

Site group mean directions of the convergent ChRM magnetizations yield statistics summarized in Table 1 and directions plotted in Fig. 7. The latter are concentrated in the NE-negative quadrant, a field direction equivalent to normal geomagnetic field polarity when Britain was sited in mid-southerly latitudes during Siluro-Devonian times. The exceptions are sites 49–51 in the east of the outcrop sharing a contrasting positive inclination but have unacceptably high dispersions. A partial record of a field transition or excursion is the likely explanation of aberrant field directions recorded at the other two excluded sites (59 and 60, the former based on just two samples); however, no clear reversed direction (SW declination/intermediate positive inclination) is observed. Sites 40 and 41 in an outlier at the western limit of the outcrop yield high-quality data with declinations at the limits of the distribution in Fig. 7. In the context of their location bordering the Sound of Kerrera, these could record local block rotation. There appears to be no case for excluding any other sites (excepting site 4), and the coherent group of 58 sites (including 6 coherent site directions from the younger succession on the Island of Kerrera, see below) yields an overall mean of D/I = 43.7/−47.4° (α_{95} = 4.0°, Table 1 and Fig. 7). Our field observations indicate that lava/sheet tilts are low and ~20° or less over the mainland outcrop; adjustments to palaeomagnetic directions on the assumption that primary emplacements were quasi-horizontal significantly influence the distribution of site mean directions: the overall mean direction is marginally changed with the overall distribution, becoming tighter and more circular (Fig. 7). For the unfolded distribution, the statistic ξ_1 (see McFadden, 1990) is 0.333 (ξ_{95} = 0.782) giving no reason for rejecting the hypothesis that remanence was acquired before folding. The minimum value of ξ (0.072) is attained at 98% unfolding indicating that the ChRMs resolved by thermal cleaning predate the influence of later (Acadian) phases of Caledonian deformation. The Palaeogene

https://doi.org/10.1017/S0016756824000463 Published online by Cambridge University Press

Table 1. Summary of Palaeomagnetic Results from the Lorne Plateau Lavas

Mean result, in situ:				
58 Sites	D/I = 42.3/−49.4°	R = 54.21	α_{95} = 4.7°	k = 16.7
Palaeomagnetic Pole: 319.0°E, 3.8°N, (dp/dm = 4.4/6.7°)				
Mean result, tilt adjusted:				
58 Sites	D/I = 43.7/−47.4°	R = 55.49	α_{95} = 4.0°	k = 22.7
Palaeomagnetic Pole: 317.3°E, 2.4°N, (dp/dm = 3.8/5.8°)				

Note: D and I are the mean declination and inclination derived from N sampling sites yielding a resultant vector of magnitude R, where $R = (N-1)/(N-R)$; k is the Fisher precision parameter and alpha95 is the radius of the cone of 95% confidence about the mean direction. Dp and dm are the radii of the oval of confidence about the derived pole position calculated according to the Geocentric Axial Dipole assumption in the colatitude direction and at right angle to it, respectively.

British Tertiary Igneous Province (~55 Ma), and specifically the Mull central volcano and related dyke swarms sited immediately to the west of Lorne, comprises the obvious post-Caledonian thermal influence in this region; Early Tertiary normal and reversed field directions, however, are widely removed from magnetizations in the Lorne lavas and with the possible exception of sites 49–50, no magnetic influence of a Tertiary field direction surviving to higher temperatures has been recognized in the Lorne succession.

In the absence of polarity reversals within the Lorne lava pile, the primary record of a Siluro-Devonian dipolar axis cannot be identified. However, the influence of early overprinting of this age can potentially be tested locally from features contemporaneous with emplacement. Sample sites 28–36 are located within a ~250 m wide NE-SW trending down-faulted block running down the eastern side of Kerrera Island (Fig. 8). Coarse clastic sedimentation influenced by contemporaneous faulting was occurring here as andesite magma was being emplaced into unconsolidated sediment to produce peperite, a hybrid rock formed *in situ* from disintegration of magma during intrusion and mingling with a saturated slurry. The host sediment is found as raft, vein and sill-like features within the peperite as it grades into 'massive' andesite. The latter forms blob-like small intrusions that comprise the palaeomagnetic sites used here to provide a test for the influence of later regional overprinting.

Sample distributions and examples of palaeomagnetic behaviours from sites within this rifted block are summarized in Fig. 8. AMS fabrics, with three examples shown in this figure, tend to be internally well grouped, but show no consistency between sites; there is no indication here for tectonic influence of the faulting and the AMS would therefore appear to be a primary signature of site-level magma flow. ChRM directions of magnetization at these sites have mostly intermediate negative inclinations but with three anomalous declinations when compared with the lava succession elsewhere. Tilts are difficult to assess reliably at the point of drilling due to complex syn-emplacement deformation of the host sediment, but when corrected for estimates of mean dip in proximity to these locations (and excluding the three sites with aberrant declinations), the site directions at 28, 31 and 33 to 36 converge (precision $k = 11.5$ to $k = 21.2$). The improvement in grouping is insufficient to reject a post-folding origin positively ($\xi_1 = 1.725$, $\xi_2 = 1.198$, $\xi_{95} = 2.862$), but optimum grouping is achieved at 100% unfolding as the mean direction moves marginally closer to the mean direction from the lavas elsewhere (D/I = 39/−57° to D/I = 47/−54°). Since deformation was occurring in the soft sediment as it was incorporating the lava, this

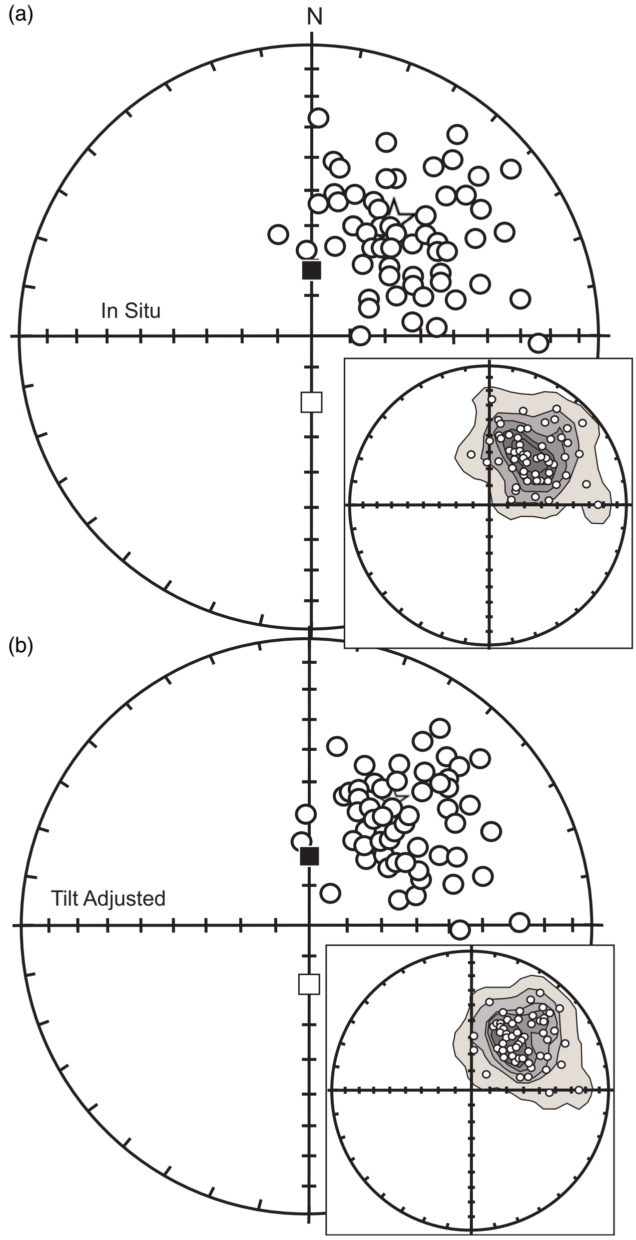

Figure 7. Site mean directions of magnetization from Lorne samples belonging to the selected set of 58 NE directed negative inclination ChRM components (a) before and (b) after tilt adjustment; equal area projections. The inset projections show contoured versions of the data. The squares are the present mean normal and reversed dipole geomagnetic directions in the study area and the stars are population mean directions.

indicates that ChRMs in the Lorne lavas in the western sector of the outcrop are not only pre-folding but also date from primary cooling.

The palaeopole position derived from 58 thermally cleaned and tilt-adjusted sites from the Lorne Plateau lies at 2.7°N, 317.3°E ($dp/dm = 3.8/5.8°$) indicating that the Grampian region lay at a palaeolatitude of 25.5°S during emplacement of this succession in Late Silurian-Early Devonian times. The Lorne result satisfies reliability criteria of Van der Voo (1993) except number 6 (presence of reversals) and therefore has a quality factor of $Q = 6$.

The mean direction and pole position derived from the Lorne succession is a composite result embracing a majority of sites from the main lava pile dated ~425 Ma and exhibiting variable degrees of

https://doi.org/10.1017/S0016756824000463 Published online by Cambridge University Press

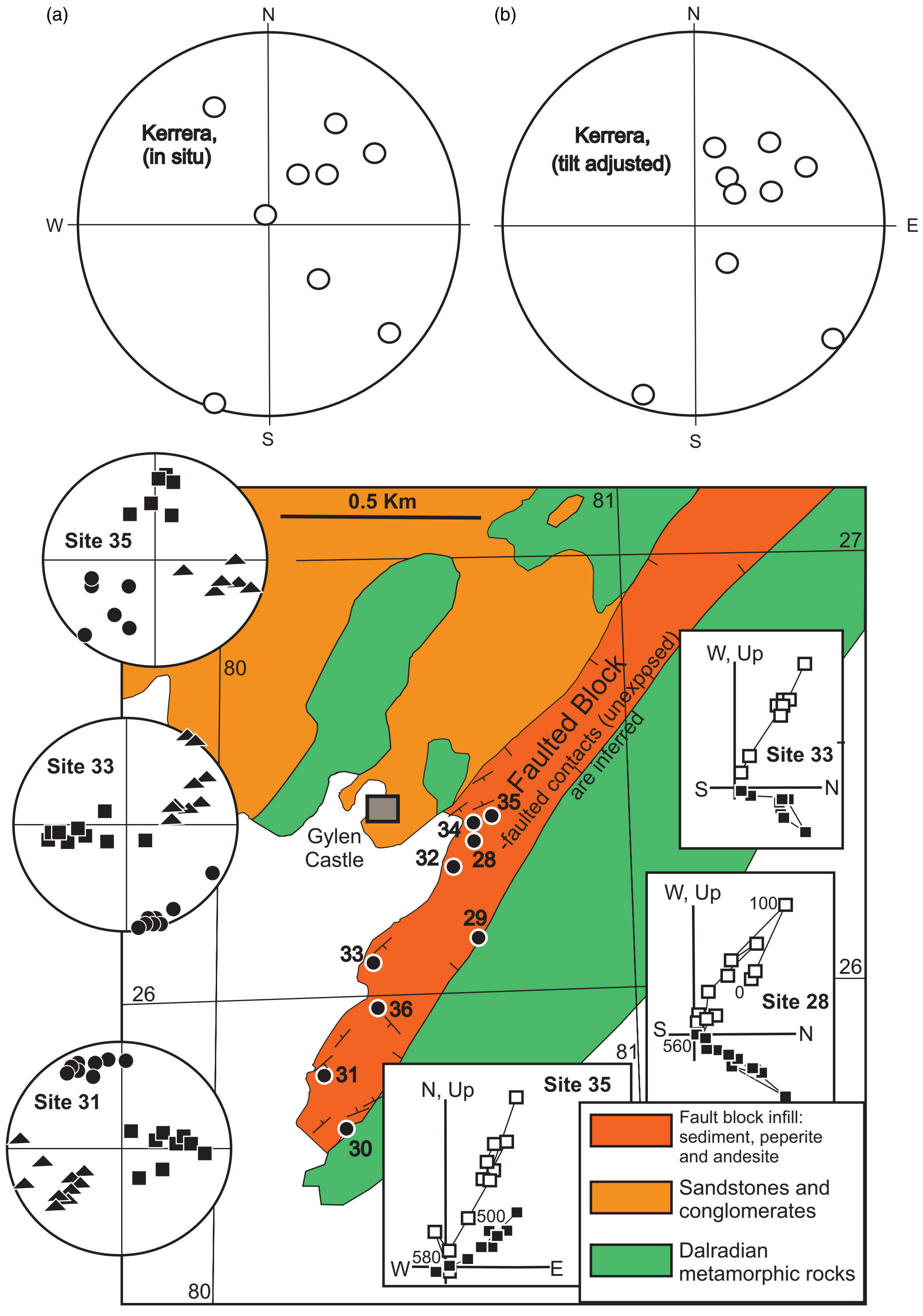

Figure 8. Site mean directions of magnetization from magmatic pods emplaced into wet sediment in the NE-SW rift on the Island of Kerrera (a) before and (b) after tilt adjustment. The lower diagram shows the location of the sites on a simplified geological map with representative orthogonal projections of demagnetization data (symbols etc. as for Figs. 5 and 6). Equal area projections on the left show three examples of directions of AMS fabrics; the squares are k_1 axes, triangles are k_2 axes and circles are k_3 axes.

low-grade alteration, and a minority of younger sites from Kerrera in the down-faulted palaeo-valley assigned to the Siluro-Devonian boundary at ~419 Ma. The six sites from Kerrera with NE-directions yield a tilt-adjusted mean of D/I = 53.3/−53.5° ($k = 20.2$, $\alpha95 = 11.7°$) rotated marginally clockwise from the mean result from the older outcrop to the east (D/I = 42.4/−46.9°, $k = 19.1$, $\alpha95 = 4.5°$, $N = 54$ sites). This suggests, but is unable to prove, block motion of the Grampians during the ~425–419 Ma interval. Excluding results at sites 16–26 from the Loch Feochan margin of the main outcrop bordering the palaeo-rift (Fig. 3) does not affect this conclusion (D/I = 41.1/−46.2, $N = 43$ sites).

The 1973 study of Latham and Briden was based on a.f. demagnetization, mostly to fields of 25–30 mT. Although only employing end point analysis, the a.f. cleaned mean NRM directions at 27 of 30 sites are comparable to the cleaned group means and broadly consistent with the integrity of the component

https://doi.org/10.1017/S0016756824000463 Published online by Cambridge University Press

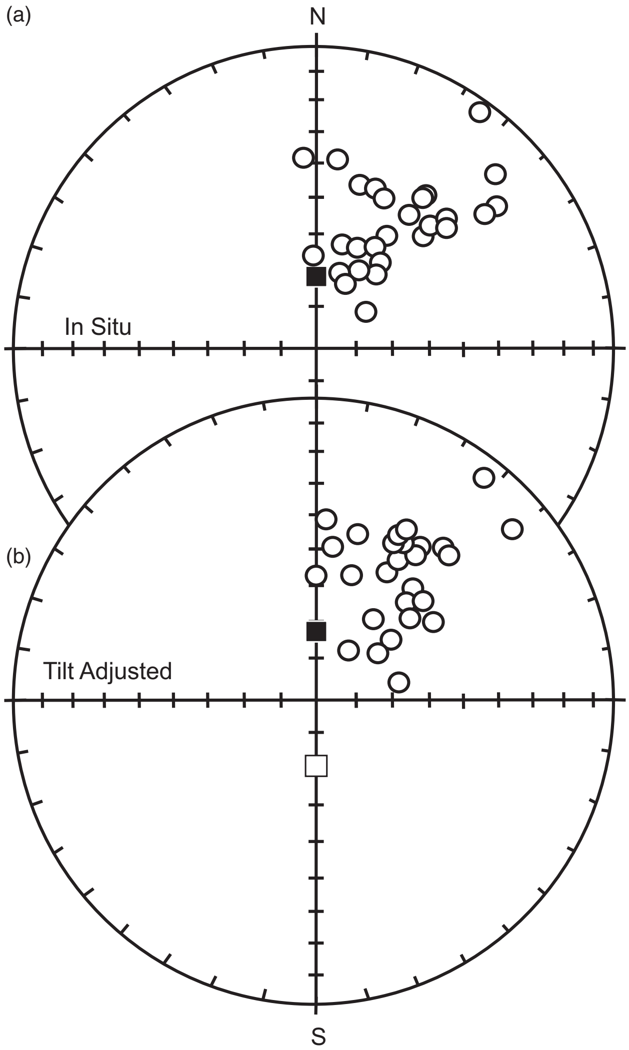

Figure 9. Site mean directions of magnetization from the a.f. demagnetized study of Latham and Briden (1973) (a) before and (b) after revised tilt adjustments. The squares are present mean normal and reversed dipole directions in the sample area and the stars are population mean directions.

structures resolved by thermal demagnetization in this study. Twenty nine of 30 sites, all within the older (~425 Ma) main outcrop, yielded significant within-site directional groupings with uniform normal polarity and the extended distribution supporting the finding of the present study that this single polarity is present throughout the Lorne volcanic field. Although only 15 of the sites were linked to structural information in the 1973 study, our wider knowledge of lava tilts within the pile now allows more sites to be integrated into the overall mean (Fig. 9); the exception remains a few sites at the eastern extremity of the outcrop (23–26) where tilt adjustments are unclear. Revised tilt adjustments and overall mean calculations for the a.f. cleaned collection are summarized in Supplementary Data File Table 3. Twenty-one sites yield a group mean of D/I = 36.1/−46.6° ($\alpha95 = 7.6°$) closer to the result from the mainland outcrop of this study and distinct from the mean from Kerrera. Marginal but non-significant improvement in overall grouping is achieved following tilt adjustment (α_{95} is reduced from 8.2 to 7.6°). The net effect of the thermal demagnetization and component analysis of the present study has been to increase the declination and marginally increase the negative inclination of the tilt-adjusted mean with both effects indicating that a small residual influence of the present field remained in the a.f. demagnetized result. The pole position of the inclusive a.f. demagnetized result is at 323.2 °E, 0.5°S ($dp/dm = 6.3/9.7°$).

The individual sites represent rapidly chilled volcanic units expected to record short-term components of the palaeosecular variation of the geomagnetic field rather than longer term integrated effects of palaeomagnetic significance; a population of site directions is therefore always required to yield a time-averaged mean for tectonic analysis, a criterion which should be adequately met by the large number of sites included in this study. The dispersion of virtual geomagnetic poles (VGPs) can be used to assess whether secular variation has been effectively averaged and therefore whether the overall means can yield time-averaged palaeomagnetic poles. The circular standard deviation ($S \approx \delta_{63}$) for the distribution of Lorne lava/sheet VGPs is 18.6° with 95% upper and lower bounds of $S_u = 21.3°$ and $S_l = 16.5°$ for the sample population ($N = 58$ sites; Cox, 1969). These values compare favourably with a value of $S_\lambda = 19°$ and lower and upper values of 17.7° and 20.5° in the palaeolatitude band 20–30° during Late Tertiary times and $S_\lambda = 17.3°$ with upper and lower bounds of 15.0° and 20.4° during Early to mid-Tertiary times for palaeosecular variation model G of McFadden *et al.* (1991). Although reversals of polarity are not present, the VGP dispersion thus indicates that the recovered group mean result is a representative time average of secular variation near the Siluro-Devonian boundary.

4.d. Anisotropy of magnetic susceptibility (AMS)

Anisotropy of magnetic susceptibility (AMS) has been delineated at 16 sites from site locations at Loch Tralaig, Loch Scammadale and Deadh Choimhead near the central axis of the Lorne outcrop, employing a Kappabridge KLY-3. Since the samples are part of the palaeomagnetic collection and not systematically located within flows as would be strictly required to resolve lava flow regimes (e.g. Canon-Tapia *et al.* 1997), the results are general rather than specific.

AMS is approximated by a triaxial ellipsoid defined by orthogonal maximum (k_1 or k_{max}), intermediate (k_2 or k_{int}) and minimum (k_3 or k_{min}) axes. Of the 16 lava sites investigated, three showed no significant directional groupings and in two others k_1 lay within a girdle embracing one of the remaining axes. However, 11 sites (1–4, 8, 9, 13, 53–56) showed significant within-site groupings with an example of internal coherence illustrated by Site 56 in Fig. 10. Collectively, the tilt corrected k_1 directions have low inclinations close to the lava/sheet planes with declinations broadly east-west (Fig. 10(a)); the complementary k_3 axes mostly have shallow northerly and southerly directions although partially girdled along a NE-SW plane.

Whilst mechanical models have suggested that k_{max} is typically aligned perpendicular to flow (Khan, 1962), experimental models and field studies tend to find that k_1 is more commonly aligned with the direction of flow (Wing-Fatt & Stacey, 1966; MacDonald *et al.* 1992); most recent work has emphasized the complexity of ellipsoid orientation within lavas and its dependency on flow regime (Canon-Tapia, 2004). Thus, the results summarized in Fig. 10 are provisionally compatible with lava movement from a W-NW direction lapping onto a westward-dipping erosion surface of Dalradian metamorphic basement, although a wider sample systematically collected through individual lava units would be required to test this proposition further.

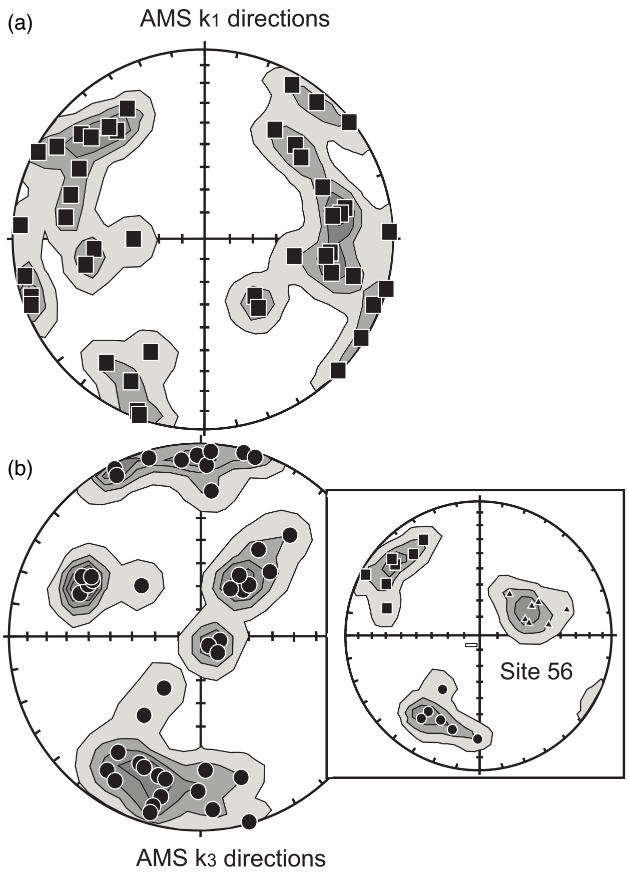

Figure 10. Distributions of maximum (k_1) and minimum (k_3) AMS directions from 11 lava/sheet sites showing coherent fabric groupings.

5. Discussion

5.a. Duration of the Lorne Volcanic activity

Although this study is unable to confirm that all phases of the Lorne volcanism belong to a single polarity subchron, the normal polarity observed throughout the preserved ~600 m thickness of the lava pile on the mainland is likely to record a significant interval of normal polarity. The wider Global Palaeomagnetic Database (GPDB) identifies reversed polarity beginning at 430 Ma early in the Wenlockian Epoch (433.4-427.4 Ma) and continuing through the subsequent Ludlow Epoch (427.4-423.0 Ma). Beginning at 423 Ma in the last Pridoli Epoch (423-419 Ma) of Silurian times, an interval of normal polarity extending into the Devonian Period is then recognized lasting to ~391 in Eifelian times although interrupted by a brief period of reversed polarity at ~404 Ma. Since the polarity boundary assignments are inherently less precise than the 425.0±0.7 Ma U-Pb zircon radiometric date for the Lorne lavas, this would favour moving the end of this reversed polarity subchron back to ~426 Ma. In the Southern hemisphere, the Ainslie (426-423 Ma) and Laidlow (428-419 Ma) volcanic rocks of SE Australia (Luck, 1973) spanning the time of Lorne volcanism somewhat less precisely dated, also exhibit uniform normal polarity. The Lower Old Red Sandstone deposits of the Midland Valley of Scotland have traditionally been regarded as Lower Devonian in age from a range of radiometric dates. However, new evidence from fossil biotas shows that the lowest part of this succession is of late Wenlockian age (i.e. older than 427.4 Ma, Wellman *et al.* 2024) implying that the succeeding succession including the Strathmore Volcanics is close to the Lorne activity in age; since these volcanics include both polarities, they either span the R/N transition and are therefore inferred to be marginally older than Lorne or alternatively there are currently undefined short polarity inversions within this normal subchron. The palaeomagnetic remanence in the Strathmore succession (D/I = 45/−46°, Torsvik, 1985*a*) is statistically indistinguishable from the new Lorne result. An early palaeomagnetic result from lavas sited in the Glencoe Caldera (417.9±0.9 Ma) also yielded a normal polarity direction slightly removed from the Lorne/Strathmore direction and likely ~7 Ma younger (D/I = 36/−54°, McMurry, 1970). The interval of normal polarity spanning the Siluro-Devonian boundary includes the Lochkovian, (**419.2 ± 3.2–410.8 ± 2.8 Ma)** the first of three faunal stages in the Early Devonian, a period that might just include the Kerrera succession where the inclination is comparable but rotated clockwise (D/I = 53/−53°) although in this case based on only 6 sites.

The palaeolatitude of the Grampian Block is part of a wider paleogeographic history following "soft" closure of Avalonia with the Laurentian Block and northward motion to cross the equator in Permo-Triassic times. This motion accompanied closure of a residual Rheic Ocean as it merged with the Gondwana Block beginning in the Early Devonian, a suturing completed during the Mississippian. Monitoring this motion within the Grampian Block is limited to a result from the Comrie intrusion (408±5 Ma, Rb-Sr, Turnell, 1985) yielding a mean direction of D/I = 70/−30° implying movement into a lower palaeolatitude of ~16°S and clockwise rotation between End Silurian and end Lower Devonian times; the large rotation implicated here may be influenced by proximity to the Highland Boundary Fault.

5.b. Tectonic rotation within the Scottish Orthotectonic Caledonides

The time interval incorporated by this study embraced 'soft' closure of the Iapetus Suture and moulding of the orogeny during the end of Acadian orogeny and are likely to have included complex regional block rotations. These are already recognized from palaeomagnetic studies in the Paratectonic Caledonides of Britain (Piper, 1997*a*, 1997*b*) and Ireland (Smethurst & Briden, 1988; Smethurst *et al.* 1994; Piper, 1991; Mac Niocall, 2000). The left lateral strike slip fault system established across the British Isles during culminating phases of Acadian tectonism has trends ranging from NNE in the orogenic foreland in the northwest to ENE in the Menai Fault Zone of North Wales. Although there would be no obvious expectation of rotation as a consequence of the strike slip if fault planes were straight throughout, such linearity is unlikely to be sustained for long distances. The GGF bordering the northwestern margin of the Lorne outcrop is perceptibly straight in its NE landward extension towards Inverness although inferred to curve northwards through a North Sea extension (Fig. 1) and cut the Shetland Islands in the Walls Boundary Fault (Flinn, 1961). The major movement history on this fault zone commenced close to the time of Lorne magmatism lasting for ~30 Myr and moved on a ductile foundation now uplifted by 10–16 km (Stewart *et al.* 1999), a history likely representative of the complex block-bounding faults defining the tectonic divisions framing the British Caledonides (Fig. 1).

Tectonic interpretation of the Lorne palaeomagnetic result within this tectonic framework compares it to palaeomagnetic

https://doi.org/10.1017/S0016756824000463 Published online by Cambridge University Press

Table 2. Palaeomagnetic results assigned to the interval 430–400 Ma from the Orthotectonic Caledonides and NW Foreland of Scotland

Rock Unit	Age	D/I	Pole Position °E	Pole Position °N	*Q*	Reference/Code
A. Orthotectonic Caledonides: NW Foreland						
1. Ross of Mull Amphibolites A	400–430	40/−54	322	7	.xx.xx.	Piper (1998)
2. Canisp Porphyry	~430	23/−36	333	−10	.xxxx.	Darabi and Piper (2004)
3. Ross of Mull Amphibolites A/B	400–440	10/−36	345	−14	.xx.xx.	Piper (1998)
B. Orthotectonic Caledonides: Northern Highlands						
1. Moine Metasediments	410–500	47/−35	310	−5	.xx.xx.	Watts (1982), 704
2. Unst Ophilite B, Shetland	430–420	35/−7	322	−20	.xx.x.	Taylor (1988)
3. Loch Ailsh Complex	416–449	33/−22	321	−16	.xx.x.	Turnell and Briden (1983), 110
4. Alkaline Dykes	~430	30/−23	325	−16	x . . . x.	Turnell and Briden (1983), 111
5. Borrolan Syenite (interior)	430±4	27/−19	327	−18	xxx.xx.	Turnell and Briden (1983), 108
6. Achmelivech Dyke	~430	24/−24	331	−17	.x.x.	Turnell and Briden (1983)
7. Appenite Suite	400–430	9/−29	346	−17	.xx.xx.	Esang and Piper (1984), 1473
8. N. Highlands, minor intrusions	400–430	8/−32	348	−15	.xx.xx.	Esang and Piper (1984), 1474
9. Helmsdale Granite	400±15	1/−2	355	−31	.x.xx.	Torsvik *et al.* (1983), 1460
10. Ben Loyal Complex	410–440	357-/46	358	−4	.x.xx.	Turnell and Briden (1983), 109
11. Borrolan Leucitite	430±4	357/−16	358	−24	x.x.xx.	Turnell and Briden (1983), 107
12. Borrolan Ledmorite (margin)	430±4	344/−37	10	−10	xxx.xx.	Turnell and Briden (1983), 106
C. Orthotectonic Caledonides: Grampian Block						
1. Comrie Intrusion	408±5	75/−30	287	6	xxx.x.	Turnell (1985), 136
2. Lorne Plateau Lavas	425.7	44/−47	317	2	xxxxx.x	This study
3. Glen Coe Lavas	417±4	36/−54	329	6	xx.x.	McMurry (1970)
4. Arrochar Complex	410–440	33/−37	324	−8	.x.xx.	Briden (1970), 3043
5. Garabal-Glen Fyne Complex	406±4	32/−43	326	5	xx.x.	Briden (1970), 3042
6. Foyers Complex	400–453	14/−6	340	−29	xx.xxx.	Kneen (1973), 2515
7. Strontian Granite	400–435	10/−23	344	−21	.xx.xx.	Torsvik (1984), 853
8. Ratagain Complex	419±8	8/−32	347	−15	x.x.xx.	Turnell (1985), 135
9. Foyers Granite	400–453	8/−9	347	−27	.xx.xx.	Torsvik (1984), 852
10. Peterhead Granite	400–430	0/−22	358	−21	.xx.x.	Torsvik (1985*b*), 864

Q values refer to quality factors ('x' meaning acceptance) according to the classification of Van der Voo (1993).

directions from the Orthotectonic Caledonides embraced by assigned ages within the time interval 430–400 Ma (Table 2). Except for a few studies, age estimates are unfortunately rather broad and comparative conclusions necessarily general. Magnetic declinations from both the Northern and Grampian Highlands range from SW to S are listed in order of decreasing declination in Table 2. Declinations on both sides of the fault have a range of ~50° embracing block rotations during this time interval. Nevertheless, the average difference in declination between the two sides of the GGF (excluding the result from the Comrie Diorite) is just 4° and therefore identifies no significance Silurian to Early Devonian differential rotation between the two sides of the fault.

6. Conclusions

The lava pile preserved as the Lorne Plateau in the western Grampians bordering the GGF was emplaced in two stages, the earlier dated 425.0±0.7 Ma (U-Pb) and the later ~419 Ma. It preserves a stable remanence record with field tests showing that the characteristic remanence dates from the time of emplacement. Normal polarity is resolved throughout the ~600 m thickness of the successions, with the earlier lavas emplaced onto an eroded surface of Dalradian metamorphic basement sloping to the west during a single normal polarity chron of Ludlovian age. Slightly younger volcanic and sedimentary rocks on the Island of Kerrera to the west, emplaced around the Siluro-Devonian boundary at ~419 Ma, also record normal polarity with a primary remanence demonstrated from peperites recording intrusion of magma into wet sediment. The normal polarity of the Lorne Plateau is consistent with the wider contemporaneous global record. The collective NE-directed ChRMs yield a palaeomagnetic pole at 2.7°N, 317.3°E ($dp/dm = 3.8/5.8°$) with a quality factor of $Q = 6$. The Grampian and North Highland tectonic blocks comprising the Orthotectonic Caledonides of Scotland were subject to 40–50° rotation during the

https://doi.org/10.1017/S0016756824000463 Published online by Cambridge University Press

Late Silurian and Early Devonian interval, but no significant differential rotation is detected between the two blocks.

Supplementary material. The supplementary material for this article can be found at https://doi.org/10.1017/S0016756824000463

Acknowledgements. Much of the sampling program was based on the thesis fieldwork of Joanne Neilson to whom we extend our thanks. We are grateful to former Liverpool undergraduate students Juliana Bayley, Megan Coopey, Caroline Gilder, Shoena Masterson, Euan Mitchell and Jennifer Winstanley for contributing to aspects of the fieldwork, measurement and demagnetization of the Lorne rocks as part of their Honours projects, and we are grateful to the University of Liverpool for field support.

References

Atherton MP and Ghani AA (2002) Slab break-off: A model for Caledonian, Late granite syn-collisional magmatism in the orthotectonic (metamorphic) zone of Scotland and Donegal, Ireland. *Lithos* **62**, 65–85.

Briden JC (1970) Palaeomagnetic results from the Arrochar and Garabal Hill-Glen Fyne igneous complex, Scotland. *Geophysical Journal of the Royal astronomical Society* **21**, 457–70.

British Geological Survey (2005) *Glencoe. Bedrock. 1:25 000 Geology Series.* Nottingham: British Geological Survey, Keyworth.

Canon-Tapia E (2004) Anisotropy of magnetic susceptibility of lava flows and dykes: a historical account. In *Magnetic Fabric: Methods and Applications* (eds F Martin-Hernandez, CM Luneburg, C Aubourg and M Jackson), **238**, pp. 205–25. Geological Society of London Special Publication.

Canon-Tapia E, Walker GPL and Herrero-Bervera F (1997) The internal structure of lava flows-insights from AMS measurement II: Hawaii pahoehoe, toothpaste lava and aa'aa. *Journal Geothermal Research* **76**, 19–46.

Clayburn JAP, Harmon RS, Pankhurst RJ and Brown JF (1983) Sr, O and Pb isotope evidence for the origin and evolution of the Etive Igneous Complex, Scotland. *Nature, London* **303**, 492–7.

Cox A (1969) Confidence limits for the precision parameter, k. *Geophysical Journal of the Royal astronomical Society* **17**, 545–50.

Darabi MH and Piper JDA (2004) Palaeomagnetic study of the Canisp Porphyry, NW Scotland: an Early Silurian palaeomagnetic pole from the Laurentian Foreland. *Scottish Journal Geology* **40**, 83–92.

Dewey JF and Strachan RA (2003) Changing Silurian-Devonian relative plate motion in the Caledonides: sinistral transpression to sinistral transtension. *Journal of the Geological Society of London* **160**, 219–29.

Embleton BJJ (1968) Laboratory stability test applied to Devonian lavas from Scotland. *Geophysical Journal of the Royal astronomical Society* **16**, 239–51.

Esang CB and Piper JDA (1984) Palaeomagnetism of Caledonian intrusive suites in the northern highlands of Scotland: constraints to tectonic movements within the Caledonian orogenic belt. *Tectonophysics* **104**, 1–34.

Evans AL, Mitchell JG, Embleton BJJ and Creer KM (1971) Radiometric age of the Devonian polar shift relative to Europe. *Nature* **229**, 50–51.

Flinn D (1961) Continuation of the Great Glen Fault beyond the Moray Firth. *Nature* **191**, 589–91.

Fraser GL, Pattison DRM and Heaman LM (2004) Age of the Ballachulish and Glencoe Igneous Complexes (Scottish Highlands), and paragenesis of zircon, monazite and baddeleyite in the Ballachulish Aureole, *Journal of the Geological Society* **161**, 447–62.

Gradstein FM, Ogg JG, Smitz M and Ogg G (2012) *The Geologic Time Scale, 2012.* Amsterdam: Elsevier, 1144 pp.

Hutton DHW (1987) Strike-slip terranes and a model for the evolution of the British and Irish Caledonides. *Geological Magazine* **124**, 405–25.

Khan MA (1962) The anisotropy of magnetic susceptibility of some igneous and metamorphic rocks. *Journal of Geophysical Research* **67**, 2873–85.

Kneen SJ (1973) The palaeomagnetism of the Foyers Plutonic Complex, Invernesshire. *Geophysical Journal of the Royal astronomical Society* **32**, 53–63.

Kokelaar BP (1982) Fluidization of wet sediments during the emplacement and cooling of various igneous bodies. *Journal of the Geological Society* **139**, 21–33.

Kokelaar BP and Moore ID (2006) *Classical Areas of British Geology: Glencoe Caldera Volcano, Scotland.* Nottingham: British Geological Survey, Keyworth.

Kynaston H and Hill JB (1908) *Geology of Oban and Dalmally*. Memoir of the Geological Survey of Scotland (Sheet 45), Geological Society of Great Britain.

Latham AG and Briden JC (1975) Palaeomagnetic field directions in Siluro-Devonian lavas of the Lorne Plateau, Scotland, and their regional significance. *Geophysical Journal of the Royal astronomical Society* **43**, 243–52.

Luck GR (1973) Palaeomagnetic results from Palaeozoic volcanic rocks of SE Australia. *Geophysical Journal of the Royal astronomical Society* **32**, 35–52.

Mac Niocall C (2000) A new Silurian palaeolatitude for eastern Avalonia and evidence for crustal rotations in the Avalonian margin of SW Ireland. *Geophysical Journal International* **141**, 551–671.

MacDonald WD, Palmer HC and Hayatsu A (1992) Egan Range Volcanic Complex, Nevada: geochronolgy, palaeomagnetism and magnetic fabrics. *Physics of the Earth and Planetary Interiors* **74**, 109–26.

Marshall JEA (1991) Palynology of the Stonehaven Group Scotland: evidence for a Mid-Silurian age and its geological implications, *Geological Magazine*, **128**, 283–6.

McFadden PL (1990) A new fold test for palaeomagnetic studies. *Geophysical Journal International* **103**, 163–9.

McFadden PL, Merrill RT, McElhinny MW and Lee S (1991) Reversals of the Earth's magnetic field and temporal variations of the Dynamo Families. *Journal of Geophysical Research* **96**, 3023–933.

McMurry EW (1970) Palaeomagnetic results from Scottish lavas of Lower Devonian age. In *Palaeogeophysics* (ed SK Runcorn), pp. 243–62. London: Academic Press.

Moazzen M and Droop GTR (2005) Application of mineral thermometers and barometers to granitoid igneous rocks: the Etive Complex, W Scotland. *Mineralogy and Petrology* **83**, 27–53.

Moore I and Kokelaar P (1997) Tectonic influences in piecemeal caldera collapse at Glencoe Volcano, Scotland. *Journal of the Geological Society of London* **154**, 765–8.

Moore I and Kokelaar P (1998) Tectonically controlled piecemeal caldera collapse: a case study of Glencoe volcano, Scotland. *Geological Society of America Bulletin* **110**, 1448–66.

Neilson J (2008) *From Slab Breakoff to Triggered Eruptions: Tectonic Controls of Caledonian Post-Orogenic Magmatism*. PhD thesis, University of Liverpool.

Neilson JC, Kokelaar BP and Crowley QG (2009) Timing, relations and cause of plutonic and volcanic activity of the Siluro-Devonian post-collision magmatic episode in the Grampian Terrane, Scotland. *Journal of the Geological Society of London*, **166**, 545–61.

Piper JDA (1991) Siluro-Devonian palaeomagnetism, terrane emplacement and rotation in the Caledonides of western Ireland. *Geophysical Journal International* **106**, 559–80.

Piper JDA (1992) Post-Laxfordian magnetic imprint in the Lewisian metamorphic complex and strike–slip motion in the Minches, NW Scotland. *Journal of the Geological Society of London* **149**, 127–37.

Piper JDA (1997a) Tectonic rotation within the British Caledonides and Lower Palaeozoic location of the Orogen. *Journal of the Geological Society of London* **154**, 9–13.

Piper JDA (1997b) Palaeomagnetism of igneous rocks of the Lake District (Caledonian) Terrane, Northern England: Palaeozoic motions and deformation at a leading edge of Avalonia. *Geological Journal* **32**, 212–46.

Piper JDA (1998) Palaeomagnetism of the Ross of Mull granite complex, western Scotland: lower Palaeozoic apparent polar wander of the Orthotectonic Caledonides. *Geophysical Journal International* **132**, 133–48.

Piper JDA (2006) A ~90° Late Silurian-Early Devonian apparent polar wander loop: the latest inertial interchange of planet Earth? *Earth and Planetary Science Letters* **250**, 345–57.

Rogers G and Dunning GR (1991) Geochronology of appinite and related granitic magmatism in the W. Highlands of Scotland: constraints on the timing of transcurrent Fault movement. *Journal of the Geological Society of London* **148**, 17–27.

Smethurst MA and Briden JC (1988) Palaeomagnetism of Silurian sediments in W Ireland: evidence for block rotation in the Caledonides. *Geophysical Journal International* **95**, 327–46.

Smethurst MA, Mac Niocall C and Ryan PD (1994) Oroclinal bending in the Caledonides of western Ireland. *Journal of the Geological Society of London* **151**, 315–28.

Soper NJ, Strachen RA, Holdsworth RE, Gayer RA and Greiling RO (1992) Sinistral Transpression and the Silurian closure of Iapetus. *Journal of the Geological Society of London* **149**, 871–80.

Stewart M, Strachan RA and Holdsworth RE (1999) Structure and early kinematic history of the Great Glen Fault Zone, Scotland. *Tectonics* **18**, 326–42.

Tauxe L, Mullender TAT and Pick T (1996) Potbellies, wasp-waists and superparamagnetism in magnetic hysteresis. *Journal of Geophysical Research* **101**, 571–83.

Taylor GK (1988) A palaeomagnetic study of a Caledonian Ophiolite. *Geophysical Journal of the Royal Astronomical Society* **94**, 157–66.

Thirlwall MF (1979) *The Petrochemistry of the British Old Red Sandstone Volcanic Province*. Unpublished PhD thesis, University of Edinburgh.

Thirlwall MF (1988) Geochronology of late Caledonian magmatism in Northern Britain. *Journal of the Geological Society of London* **145**, 951–67.

Torsvik TH (1984) Palaeomagnetism of the Foyers and Strontian granites, Scotland. *Physics of the Earth and Planeteriors* **36**, 163–77.

Torsvik TH (1985a) Magnetic properties of the Lower Old Red Sandstone lavas in the Midland Valley, Scotland; palaeomagnetic and tectonic considerations. *Physics of the Earth and Planet Interiors* **39**, 194–207.

Torsvik TH (1985b) Palaeomagnetic results from the Peterhead granite, Scotland: implications for regional late Caledonian magnetic overprinting. *Physics of the Earth and Planetary Interiors* **39**, 108–17.

Torsvik TH, Lovlie R and Storetvedt KM (1983) Multicomponent magnetization in the Helmsdale Granite, northern Scotland; geotectonic implications. *Tectonophysics* **98**, 111–29.

Torsvik TH, Smethurst R, Van der Voo R, Trench A, Abrahamsen N and Halvorsen E (1992) Baltica – a synopsis of Vendian-Permian palaeomagnetic data and their palaeotectonic implications. *Earth Science Reviews* **33**, 133–52.

Trench A and Haughton PDW (1990) Palaeomagnetic and geochemical evaluation of a terrane-linking ignimbrite: evidence for the relative position of the Grampian and Midland Valley Terranes in late Silurian time. *Geological Magazine* **127**, 241–57.

Trewin NH, Gurr PR, Jones B and Gavin P (2012) The biota, depositional environment and age of the Old Red Sandstone of the island of Kerrera, Scotland. *Scottish Journal of Geology* **48**, 77–90.

Turnell HB (1985) Palaeomagnetism and Rb-Sr ages of the Ratagan and Comrie intrusions. *Geophysical Journal of the Royal astronomical Society* **83**, 363–78.

Turnell HB and Briden JC (1983) Palaeomagnetism of NW Scotland syenite in relation to local and regional tectonics. *Geophysical Journal of the Royal astronomical Society* **75**, 217–34.

Van der Voo R (1993) *Palaeomagnetism of the Atlantic, Tethys and Iapetus Oceans*. Cambridge: Cambridge University Press, 411 pp.

Watts DR (1982) A multicomponent, dual polarity palaeomagnetic regional overprint from the Moine of northwest Scotland. *Earth and Planetary Science Letters* **61**, 190–8.

Wellman CH, Lopes G, McKellar Z and Hartley A (2024) Age of the basal 'Lower Old Red Sandstone' Stonehaven Group of Scotland: the oldest reported air-breathing land animal is Silurian (late Wenlock) in age. *Journal of the Geological Society of London* **181**, 138–45.

Wellman CH and Richardson JB (1996) Sporomorph Assemblages from the 'Lower Old Red Sandstone' of Lorne, Scotland. *Special Papers in Palaeontology* **55**, 41–102.

Winchester JA (1973) Pattern of regional metamorphism suggests a sinistral displacement of 160 km along the Great Glen Fault. *Nature Physical Sciences* **246**, 61–64.

Wing-Fatt L and Stacey FD (1966) Magnetic anisotropy of laboratory materials in which magma flow is simulated. *Pure and Applied Geophysics* **64**, 78–80.