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Late Neoproterozoic to Early Palaeozoic palaeogeography of Avalonia: some palaeomagnetic constraints from Nuneaton, central England

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Abstract – Palaeomagnetic studies have been carried out on Neoproterozoic, Cambrian and Ordovician rocks in the Nuneaton inlier, England (52.5° N, 1.5° W). Three magnetic components were recognized, which provide a consistent structural and magnetic history of the inlier. Neoproterozoic volcaniclastic and intrusive rocks acquired a characteristic remanent magnetization (ChRM) dated at 603 Ma. Late Ordovician rocks are represented by lamprophyre and diorite intrusions and their ChRMs were probably imprinted during their emplacement, at about 442 Ma. The Lower Cambrian sedimentary sequence of the Hartshill Sandstone Formation, which unconformably overlies the Neoproterozoic rocks and hosts the Ordovician intrusions, does not preserve a primary magnetization but shows the imprints of the Late Ordovician (442 Ma) remagnetization, as well as a probable end-Carboniferous remagnetization. Palaeolatitudes calculated for the late Neoproterozoic rocks and Ordovician intrusions are in good agreement with other palaeolatitudes calculated for Avalonia during those times. Both the late Neoproterozoic and Late Ordovician rocks additionally show ChRMs with declination anomalies indicating a large tectonic rotation of the Nuneaton area, possibly during one of the Caledonian phases of deformation affecting southern Britain.

Keywords: Avalonia, palaeogeography, palaeomagnetism, Neoproterozoic, Ordovician.

1. Introduction

A coherent history for the development of the Iapetus Ocean and the elongate microcontinent of Avalonia is now emerging from multidisciplinary studies that integrate palaeontological and sedimentological data with palaeomagnetically determined palaeolatitudes (McCabe, Channell & Woodcock, 1992; Torsvik *et al*. 1993; Van Staal *et al*. 1998; Mac Niocaill, 2000; Cocks, 2000; Cocks & Torsvik, 2002). Despite this broad convergence of views, there remains a paucity of reliable palaeomagnetic data for parts of Avalonia during latest Neoproterozoic and Early Palaeozoic times, a problem exacerbated by the complex arrangement of the peri-Gondwanan terranes that originally made up Avalonia (e.g. Murphy *et al*. 2000), as well as the fact that Avalonia has been dismembered by subsequent plate movements, with its components now lying on opposite sides of the Atlantic Ocean (Fig. 1, inset). In particular, there are rather sparse data for the latest Neoproterozoic of eastern Avalonia where, as this study will show, the Neoproterozoic and Early Palaeozoic rocks of central England have experienced complex structural and remagnetization histories.

The main objective of this paper is to report reliable palaeomagnetic data for late Neoproterozoic and Late Ordovician rocks from Eastern Avalonia. In order to eliminate the potential ambiguities of such data, the field sampling has been conducted on a wide age-range of rocks that have been the subject of recent detailed geological study (Bridge *et al*. 1998). These are rocks well exposed in large quarries around Nuneaton (Fig. 1), and their ages have been either determined radiometrically, or can be reasonably constrained biostratigraphically. With this chronological framework in place, we were able to calculate late Neoproterozoic and Late Ordovician palaeolatitudes which are consistent with those obtained from rocks of similar ages in Newfoundland (Hodych & Buchan, 1998; McNamara *et al*. 2001).

It is noteworthy that declination anomalies, implying significant and variable tectonic rotations about vertical axes, have also been reported in palaeomagnetic studies of eastern Avalonian rocks (Torsvik *et al*. 1993; Torsvik, Trench & McKerrow, 1994; Channell, McCabe & Woodcock, 1993; Piper, 1997;

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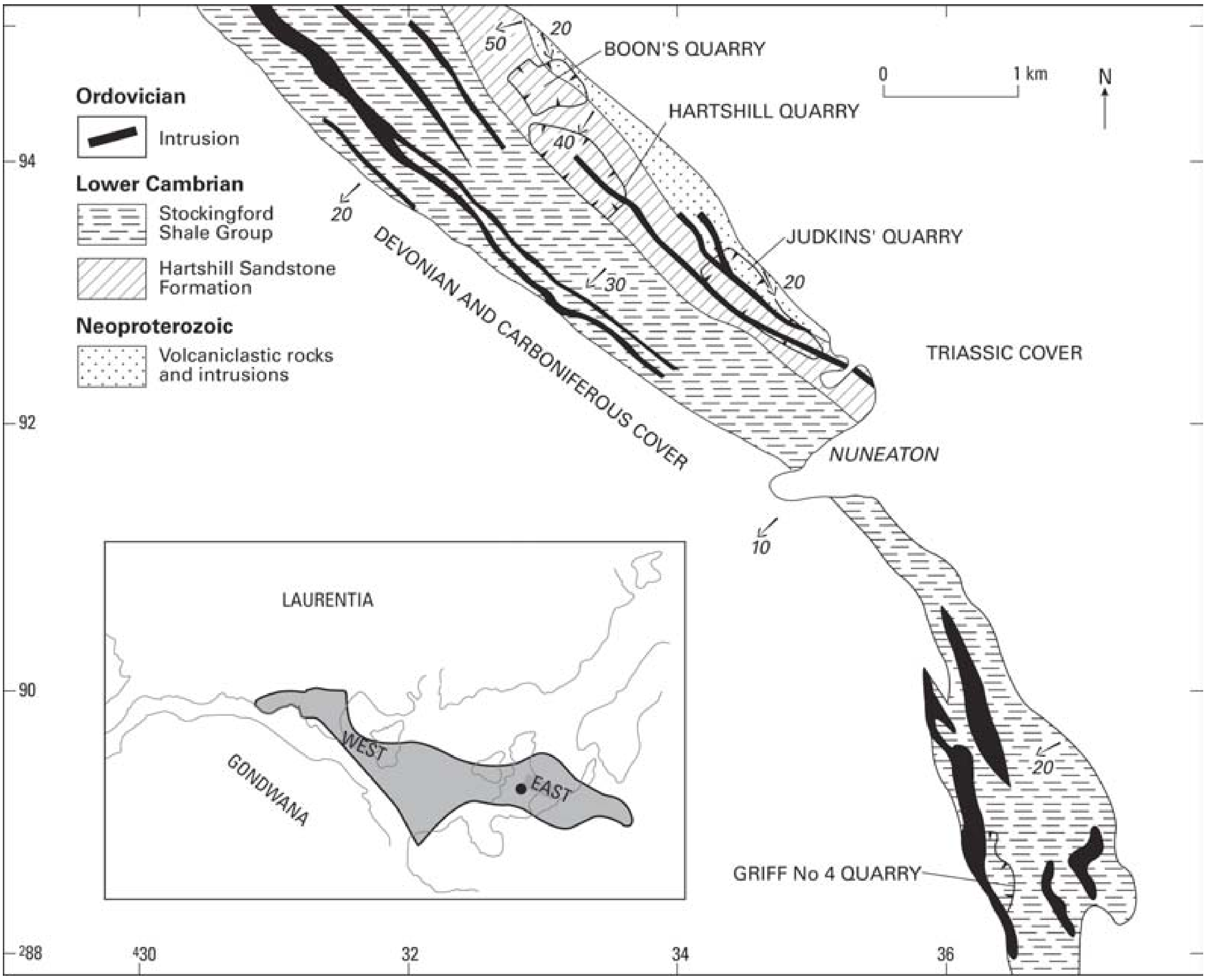

Figure 1. Geology of the Nuneaton inlier, showing the quarries in which palaeomagnetic sampling was undertaken (from Carney, 1995). The inset shows the reconstructed position of Avalonia (shaded) and its various components in a Pangea fit (Bullard, Everett & Smith, 1965). The grid shown on this diagram and on Figure 2 is the National Grid taken from the Ordnance Survey map with the permission of The Controller of Her Majesty's Stationery Office; licence no. GD272191/2003.

Mac Niocaill, 2000). The data reported here confirm that there has been a large tectonic rotation of the sampling locality about a vertical axis in post-Ordovician times.

2. Geology of the sampling locality

Palaeomagnetic sampling was carried out in Boon's, Hartshill and Judkins' quarries (Fig. 2), and in Griff No. 4 Quarry (Fig. 1), the geology of which is described by Bridge *et al*. (1998).

The oldest sampled rocks belong to the Caldecote Volcanic Formation (Fig. 2a,b), of latest Neoproterozoic (Neoproterozoic III) age. This is a stratified sequence of island arc-derived volcaniclastic rocks dominantly composed of massive to thickly bedded, dacitic crystal–lapilli tuffs. Interbedded with them are strata belonging to a tuffaceous siltstone facies grouping (Bridge *et al*. 1998), composed of alternations between laminated tuffaceous mudstone, siltstone, sandstone and vitric tuff.

Intrusions of basaltic and dioritic compositions in the Caldecote Volcanic Formation were also sampled. They are truncated by a major erosional unconformity, on which rest the Lower Cambrian strata (Fig. 2a,b), demonstrating their Neoproterozoic age. The earliest intrusives are swarms of dykes or steeply inclined sheets of basalt, andesite and microdiorite, characterized by rounded to acicular iron–titanium oxides. They are parallel to, or coincident with, northerly trending faults that displace the Caldecote Volcanic Formation but not the overlying Cambrian strata. A single, homogeneous body of granophyric diorite represents the final product of Neoproterozoic intrusive magmatism. Radiometric (U–Pb zircon) dating of this intrusion in Judkins' Quarry (Fig. 2a) has yielded an age of 603 ± 2 Ma (Tucker & Pharaoh, 1991), which is

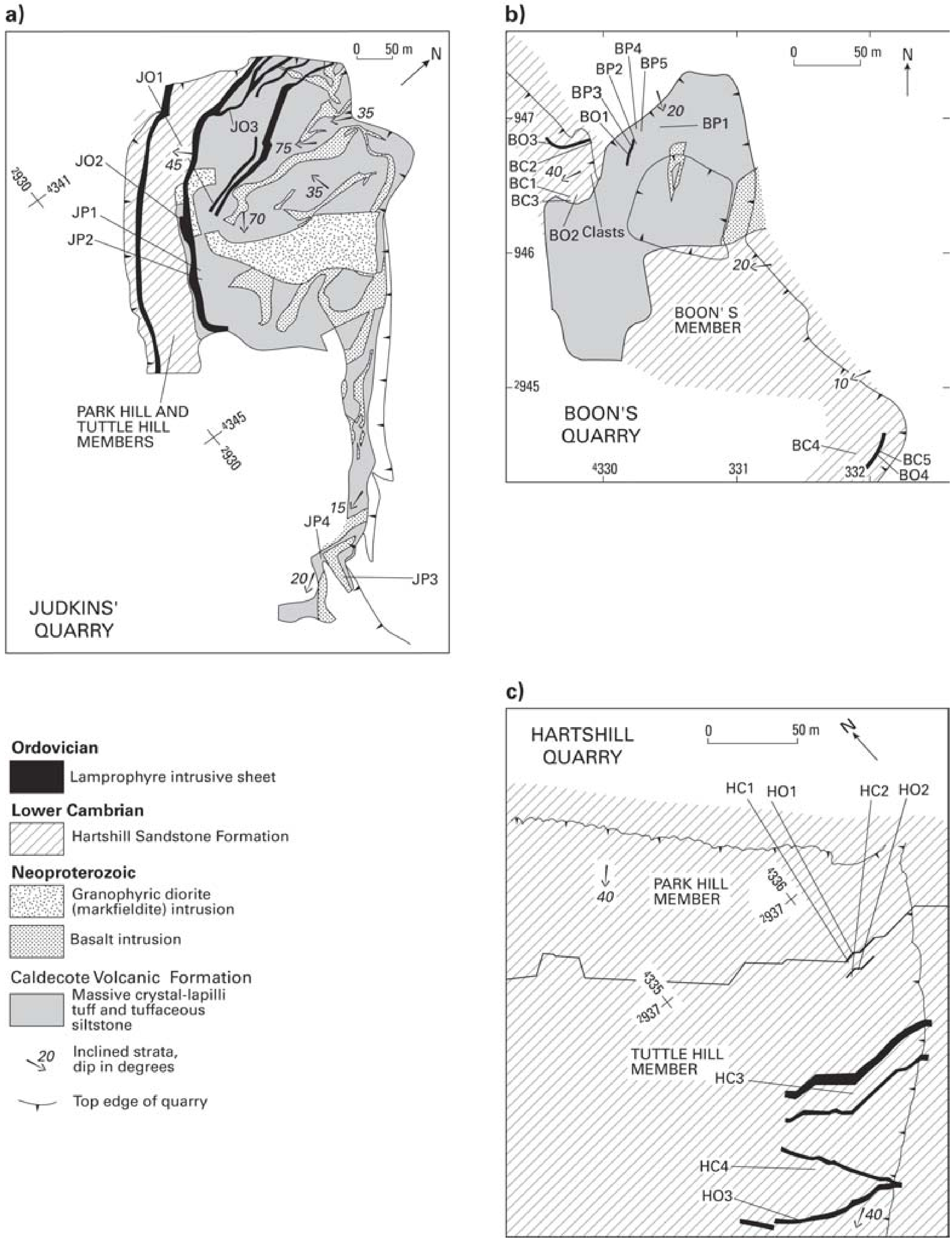

Figure 2. Locations of the palaeomagnetic samples (a) at Judkins' Quarry and (b) Boon's Quarry (modified from Bridge *et al*. 1998), and (c) at the southeast end of Hartshill Quarry (modified from Carney, 1995).

considered to represent the time of magmatic cessation in this particular sector of the Neoproterozoic volcanic arc system.

The Cambrian samples were collected from the Hartshill Sandstone Formation, which represents mainly a transgressive marine sequence. All of the

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samples (Fig. 2b,c) were from stratigraphic levels beneath the Home Farm Member ('Hyolithes Limestone'), the age of which is constrained by its fossils to the uppermost Tommotian and lowermost Atdabanian stages of the Lower Cambrian Series (Brasier, Anderson & Corfield, 1992) or about 520 Ma (Landing *et al*. 1998). Several of the Cambrian samples were from a distinctive association of basal red beds, named as the Boon's Member (Carney, 1995; Bridge *et al*. 1998), and found only in the eponymous quarry (Fig. 2b). This member comprises an association of bouldery breccio-conglomerate and granule-sandstones with breccia layers, representing deposition from debris flows. Its clasts are exclusively composed of material from the Caldecote Volcanic Formation and the associated Neoproterozoic intrusions, and the member is seen to rest with an angular and erosional unconformity on the Neoproterozoic rocks. Within 2 m of that unconformity, the Neoproterozoic rocks become reddened and develop a spheroidal weathering structure of clay mineral-mantled corestones, some of which, as noted by other workers (e.g. Brasier & Hewitt, 1979), are detached as large rounded boulders within the Boon's Member. In addition to sampling the Boon's Member, palaeomagnetic samples were also taken from the overlying Lower Cambrian marine sequence to compare results. These samples, in Hartshill Quarry (Fig. 2c), were taken from mudstone-draped sandstone beds of the Tuttle Hill Member, which is a stratigraphically higher component of the Hartshill Sandstone Formation deposited in tidal or current-agitated, near-shore environments (e.g. Brasier, Hewitt & Brasier, 1978; Bridge *et al*. 1998).

The third grouping of sampled rocks comprises sheet-like bodies of the Midlands Minor Intrusive Suite (Bridge *et al*. 1998). The Late Ordovician, latest Ashgill age of these intrusions is based on a U–Pb zircon and baddeleyite radiometric determination of 442 ± 3 Ma (Noble, Tucker & Pharaoh, 1993) from a pegmatitic segregation in a diorite sill at Griff No. 4 Quarry, south of Nuneaton (Fig. 1). Most of these intrusions are concordant with bedding in the host Cambrian succession and either occur as thin sheets of lamprophyre or single, much thicker (up to 60 m) bodies of hornblende diorite (e.g. at Griff No. 4 Quarry). They show very low-grade regional metamorphism, which indicates thermal alteration at temperatures of between 130° and 260° (R. J. Merriman *in* Bridge *et al*. 1998).

3. Palaeomagnetic sampling and methodologies

Palaeomagnetic investigations were made on a total of 29 sampling sites in the quarries around Nuneaton, the location and geological setting of most being shown in Figure 2a–c. A further site was sampled in Griff No. 4 Quarry (Fig. 1), on rocks of the Midland Minor Intrusive Suite from which the U–Pb radiometric age discussed in the previous section was obtained. Oriented block samples were collected at each site; no drilling was permitted. In the laboratory, cylindrical rock specimens of 2.4 cm diameter and 2.2 cm length were cut from each block, perpendicular to the face that in the field was orientated with respect to north.

The natural remanent magnetization (NRM) of the samples was measured with an Agico JR-5A or a Digico spinner magnetometer. The stability of the NRM was tested by means of progressive thermal demagnetization experiments. Bulk magnetic susceptibility was measured after each thermal step in order to monitor possible magnetic mineral changes. Isothermal remanent magnetization (IRM), thermomagnetic analysis (J-T curves) and, in some cases, petrographic studies were applied to identify the remanence carriers.

NRM components were identified from least-squares analysis on linear segments of the orthogonal vector trajectories or by best-fit remagnetization circle analysis applied to great circle path trajectories. In a few samples the data seemed to hover around a given direction without a demagnetization trajectory in the orthogonal plots; for these samples a mean direction of the last steps was calculated using the statistical treatment of Fisher (1953).

For each palaeomagnetic site a mean direction of the characteristic remanent magnetizations (ChRMs) of the specimens was determined, either by averaging magnetic components (Fisher, 1953) or combining magnetic components with demagnetization circles (McFadden & McElhinny, 1988).

4. Results

4.a. Neoproterozoic rocks: Caldecote Volcanic Formation and later intrusions

The magnetic behaviour of the Neoproterozoic rocks can be described in terms of different categories (Types 1–4), these being determined either by lithology or by the location of the sample site with respect to Late Ordovician sheets of the Midlands Minor Intrusive Suite.

'Type 1' behaviour (Fig. 3a) was mainly found in samples of crystal lapilli tuff from the Caldecote Volcanic Formation, with recorded NRM intensities of the order of 2 mA/m. The magnetic directions were generally directed downwards with high inclination between the northeast and southeast quadrants. Progressive thermal demagnetization revealed that these rocks are characterized by two components, defined on the basis of their relative unblocking temperatures. The low-temperature component is stable between room temperature and 200–300 °C and constitutes about 20 % of the total NRM. This component has

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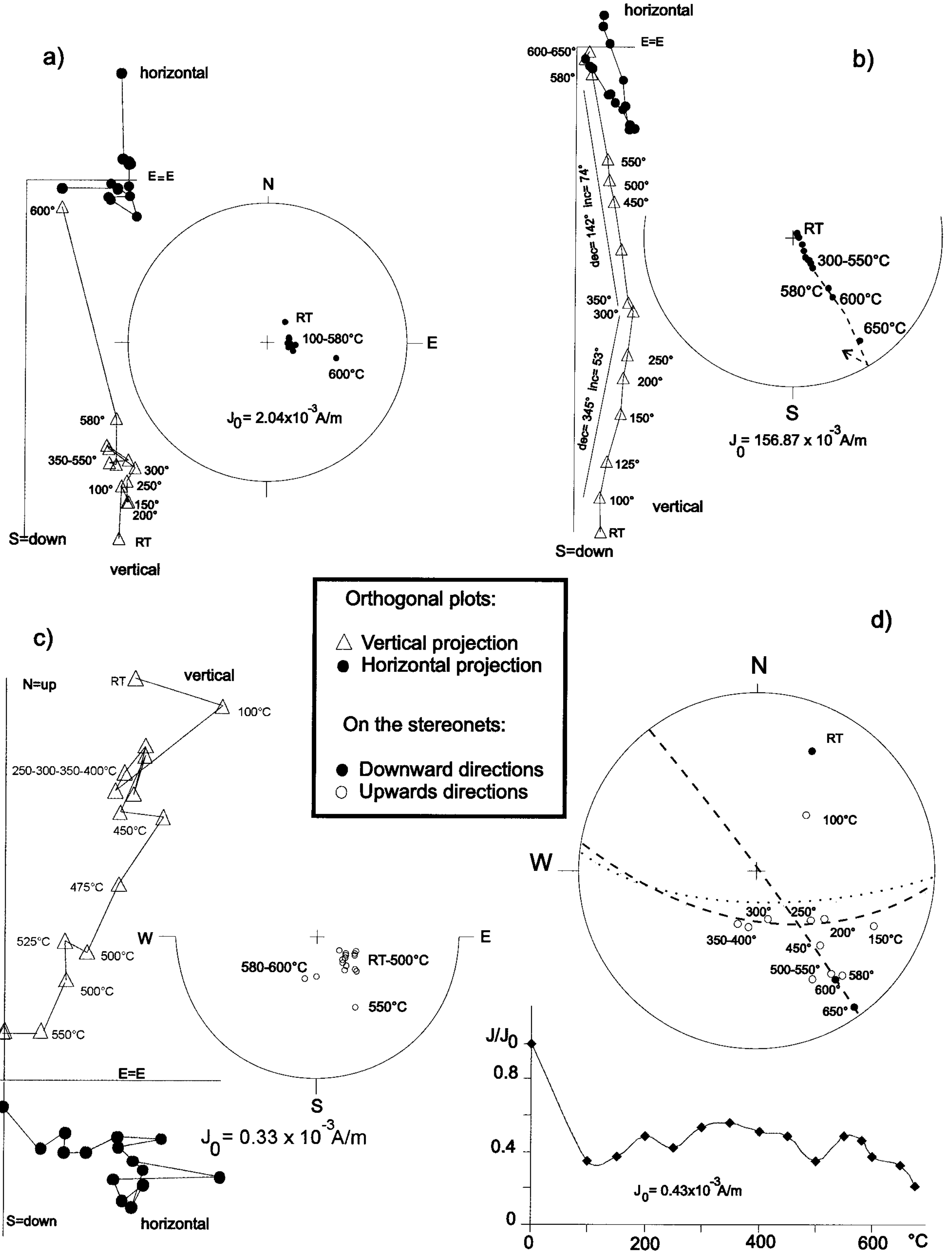

Figure 3. Orthogonal and stereographic projection plots of progressive demagnetization data from specimens of the Neoproterozoic rocks. (a) 'Type 1' magnetic behaviour: specimen of a crystal lapilli tuff from the Caldecote Volcanic Formation in Boon's Quarry. (b) 'Type 2' magnetic behaviour: specimen from a Neoproterozoic intrusion in Judkins' Quarry. (c) 'Type 3' magnetic behaviour: specimen of tuff from the Caldecote Volcanic Formation, at the contact zone of a Late Ordovician intrusion (Boon's Quarry). (d) 'Type 4' magnetic behaviour: specimen from Caldecote Volcanic Formation in Boon's Quarry.

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an *in situ* northerly declination and high to medium positive inclination and probably is a record of the direction of the present-day geomagnetic dipolar field (GDF). The high-temperature component is stable from 300–400 °C up to 580–600 °C and constitutes the dominant proportion of the total NRM. It has an E–SE declination and steep downward inclination before any tilt correction is made. This component unblocked at 580–600 °C, and the implication that magnetite is the main magnetic carrier is in agreement with the acquisition of isothermal remanent magnetization (IRM) of these rocks.

'Type 2' behaviour (Fig. 3b) was mainly found in the Neoproterozoic intrusive rocks, in which NRM intensities are of the order of 150 mA/m. Their directions were generally directed downwards, with high to low inclinations and E–SE declinations. After thermal demagnetization, it was observed that three main components were involved in the NRM. In a few samples, a fourth small and spurious component, that may have been acquired during drilling, was removed at 100 °C. The low-temperature component of the NRM is stable up to 300–350 °C and constitutes about 50 % of the total NRM. This component has an *in situ* declination close to north and has high to medium positive inclinations; suggesting it is a record of the present-day GDF. The intermediate-temperature component is stable between 350 °C and 550 °C and constitutes about 40 % of the total NRM. This component unblocked at 550 °C indicating that (titano)magnetite is its main carrier, which is consistent with the acquisition of IRM of these rocks. The intermediate-temperature component has a SE declination ($D \cong 140°$) and high inclination before any tilt correction ($I \cong 75°$, see Fig. 3b). After 550 °C there is one more component (less than 10 % of the total NRM) that is not completely resolved from the intermediate component. In the stereographic projection of Figure 3b, the data for the steps 580 °C, 600 °C and 650 °C track along a great circle path that also contains the intermediate component. This great circle implies an upward-directed component that is not resolved after 650 °C and is probably carried by haematite. This is supported by petrographic studies of these samples that revealed skeletal magnetite with borders altered to haematite.

'Type 3' magnetic behaviour (Fig. 3c) was mainly observed in rocks of the Caldecote Volcanic Formation at the contact zone of lamprophyre sheets of the Midlands Minor Intrusive Suite. The samples show upward magnetic directions, with medium inclinations and SE declinations. Progressive thermal demagnetization revealed random directions between room temperature and 100–125 °C. After this, the samples were not demagnetized until temperatures higher than 400–450 °C were attained. Following those steps, there was observed a monotonic decay of one component that unblocked at 550 °C indicating that (titano)magnetite is its main carrier. This component constitutes about 70 % of the total NRM and has SE declinations and upward medium inclinations. After a further step at 550 °C, about 10 % of the total NRM remained, however, it was impossible to recognize any other component due to the random behaviour of the samples above temperatures of 580–600 °C.

'Type 4' samples (Fig. 3d) belong to tuffaceous siltstones of the Caldecote Volcanic Formation, with NRM intensities less than 0.5 mA/m that display multi-component magnetization. The Type 4 samples have a low unblocking-temperature component ($Tb \leq 100$ °C) that constitutes more than 50 % of the total NRM. Considering this very low unblocking-temperature, this component probably does not have any geological meaning (*in situ* direction: $D = 20°$, $I = 35°$). Above 150 °C to 350–400 °C on the stereonet the data track along a great circle path, for which a pole to the best-fit plane was calculated ($D = 10°$, $I = -30°$). Vector subtractions between successive data were also calculated and the vectors obtained track along a similar great circle, thereby indicating that just two vectors constitute the first plane. Above 450 °C to 650 °C the data track along another great circle path, the best fit plane having a pole at $D = 235°$, $I = -2°$ in the case of Figure 3d. In short, above 100 °C, the NRM is interpreted to be composed of three components that define two different great circles, the intersection of which yields a vector that is shared by both. The intersection is close to the direction determined in samples with Type 3 behaviour (Fig. 3c), suggesting that both Type 3 and Type 4 behaviours show similar directions with SE declinations and medium upward inclinations. It is difficult to interpret the origin of the other two vectors involved in the great circles of Type 4 behaviour, however, the great circle determined by the highest thermal steps could contain a direction close to that of the present-day GDF. The IRM acquisition of these rocks revealed that both (titano)magnetite and haematite are carriers of remanence. Thermomagnetic analysis identified three Curie points during heating and cooling cycles that are in rough agreement with the unblocking-temperatures of some of these samples. Two unblocking temperatures, at 370 °C and 580 °C, indicate (titano)magnetite and the other, at 680 °C, indicates haematite.

4.b. Cambrian rocks: Hartshill Sandstone Formation

The Lower Cambrian sedimentary rocks have NRM intensities between 0.5 and 10 mA/m and showed various categories of magnetic behaviour during progressive thermal demagnetization. These categories are mainly related to the locations of the Cambrian palaeomagnetic sites with respect to Ordovician rocks of the Midlands Minor Intrusive Suite. Differences in lithological characteristics were also reflected in the magnetic behaviours.

'Type 1' behaviour was found in various Cambrian lithologies located either close to or in the contact zone of the lamprophyre sheets. Figure 4a shows the magnetic behaviour of a sandstone belonging to the Tuttle Hill Member and Figure 4b shows the behaviour of a red bed from Boon's Member. In samples of the Tuttle Hill Member (Fig. 4a) the demagnetization begins after applying steps higher than 250 °C. Between this step and 350 °C, there is a component that constitutes 20 % of the total NRM which is random in direction and hence may not have geological meaning. A high-temperature component, stable from 450–500 °C to 580–600 °C, constitutes the dominant proportion of the total NRM. This component unblocked at 580–600 °C which together with IRM acquisition curves indicates that (titano)magnetite is the main carrier. The directions of the high-temperature component either have SW declinations with low inclinations, or SE declinations with high or moderate upward inclinations. In Boon's Member samples with Type 1 behaviour (Fig. 4b), the demagnetization begins above 300 °C. The dominant high-temperature component of these samples is stable above 450–500 °C and unblocks at temperatures higher than 600 °C, indicating that haematite is a carrier of the NRM. In these rocks the acquisition of IRM shows that both (titano)magnetite and haematite are the carriers of the NRM; this is in agreement with the thermomagnetic analyses that identified Curie points at about 580 °C and close to 700 °C.

'Type 2' behaviour (Fig. 4c) was mainly found in red beds of the Boon's Member that are distant from Ordovician intrusions. These rocks are generally granule sandstones and their magnetic directions have mainly southward declinations and low inclinations. Progressive thermal demagnetization revealed a 'noisy' behaviour upon demagnetization. Despite such behaviour, there is a recognizable component above 200–250 °C. This component unblocks at a temperature higher than 675 °C, indicating haematite as the main carrier of the NRM. This is in agreement with the IRM acquisition of these rocks. Petrographic investigation of these samples shows authigenic overgrowths of haematite and martite.

'Type 3' behaviour (Fig. 4d) was observed in samples from both the Boon's and Tuttle Hill members, and is independent of the location of the rocks with respect to the Ordovician intrusions. Their data track along a great circle path, the pole to the best-fit plane of which was calculated on the basis of their NRM being composed of two magnetic vectors. The example in Figure 4d shows a sample from the Tuttle Hill Member that has one component with a possible low inclination and SW declination and another component with a higher unblocking temperature, that might possibly be the direction of the present-day GDF. Unblocking temperatures and rock magnetic analyses of these samples indicate that (titano)magnetite and haematite are the magnetic carriers of the NRM.

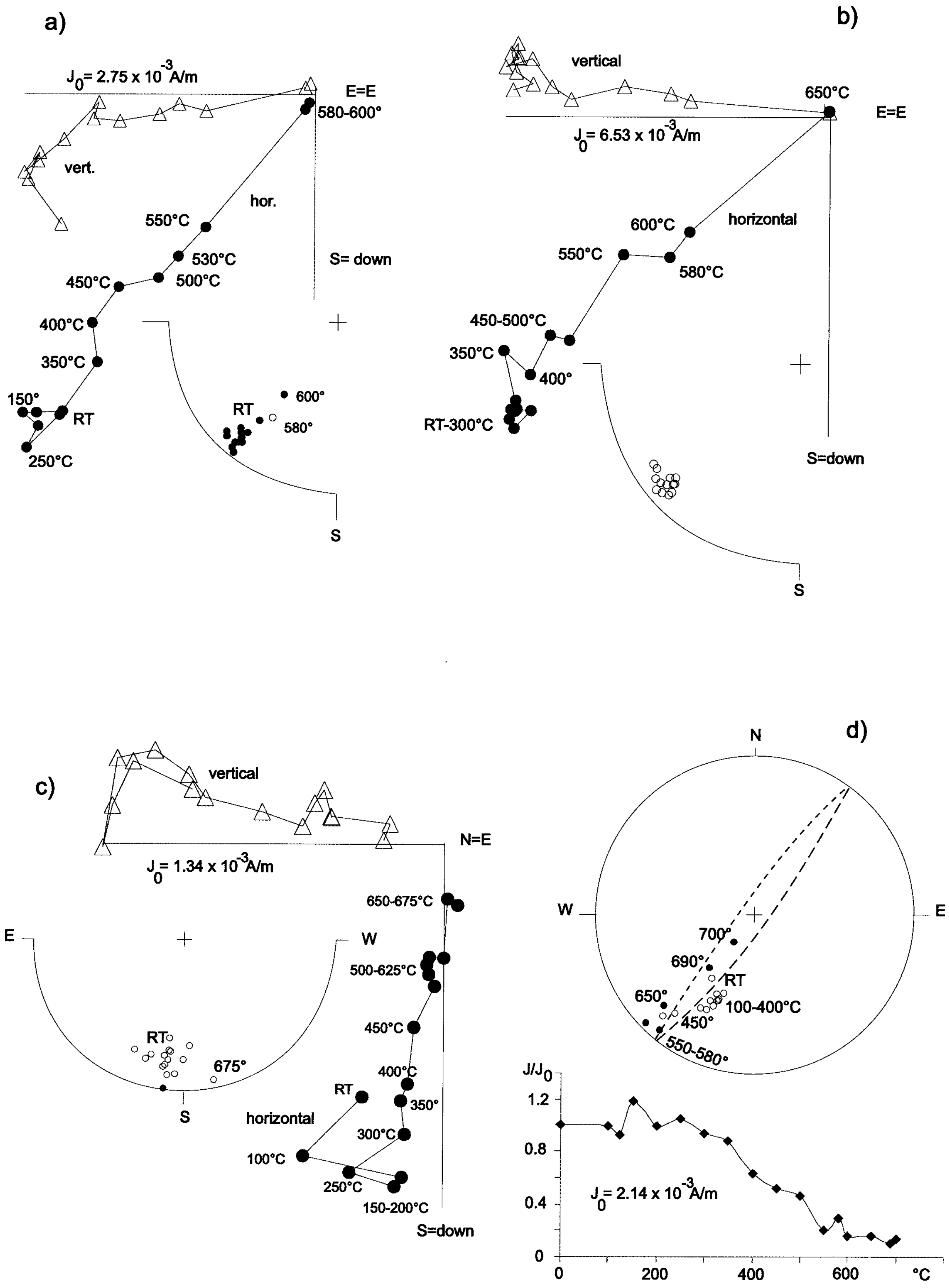
4.c. Late Ordovician rocks: Midlands Minor Intrusive Suite

As with the Neoproterozoic and Cambrian samples, rocks of the Midlands Minor Intrusive Suite showed varying types of magnetic behaviour upon progressive thermal demagnetization.

'Type 1' behaviour (Fig. 5a) was observed in some samples from Griff No. 4 Quarry with NRM intensities of the order of 20 mA/m. These NRMs mainly consisted of one component that unblocks at 350 °C. This unblocking temperature, together with the IRM acquisition of these rocks, indicates that titanomagnetite with high Ti content is the main carrier of the NRM.

'Type 2' behaviour, with NRM intensities between 25 and 35 mA/m, was the most prevalent in the Ordovician intrusions, and was observed in samples showing differing amounts of (titano)magnetite (Fig. 5b,c). A common characteristic is that the data track along a great circle. Figure 5b shows the behaviour of a sample that between 150 °C and 300–350 °C has a stable low-temperature component close to the direction of the present-day GDF. Another direction, with medium upward inclination and SE declination, is identified from a least-squares analysis on linear segments on the orthogonal diagrams between 530 °C and 580 °C. Although there is no intermediate data between 600 °C and 680 °C, it is possible that the same direction is recorded between these steps since the mean direction of these data is similar to that obtained between 530 °C and 580 °C. According to the unblocking temperatures, the magnetic carriers of the NRM are (titano)magnetite, haematite and possibly goethite. This is in agreement with the acquisition of IRM of these rocks, and also accords with the Curie points that were identified from thermal demagnetization of a sample that was first magnetized along two orthogonal axes, applying, respectively, fields of 0.3 and 1.3 Tesla. Another sample displaying Type 2 behaviour is shown in Figure 5c, containing a low-temperature component that coincides with the present-day GDF, defined between 100 °C and 150 °C, and constituting about 40 % of the total NRM. Another component, which constitutes 20 % of the total NRM and has the same direction, is defined between 200 °C and 400 °C. Between 400 °C and 650 °C the data constitute about 20 % of the total NRM that is unblocked at 675 °C without intermediate data in the orthogonal plot (Fig. 5c). For these samples the pole of the best-fit plane defined by the great circle path of the data was calculated. The demagnetization diagram reveals at least two unblocking temperatures, the lowest at about 150–200 °C probably indicating goethite and the highest, at 650–675 °C, indicating haematite. The acquisition of IRM of these samples reveals that haematite and/or goethite are the main carriers of the NRM.

'Type 3' behaviour was found in a sill of the Midlands Minor Intrusive Suite with an intensity of the



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order of 2.5 mA/m. The sample failed to demagnetize and displayed a constant direction (Fig. 5d). This sill is located just above a sampling site in Cambrian rocks, the samples of which showed a demagnetization trajectory (Fig. 4b) with a direction indistinguishable from that of the sill. Thus, the data of the sill and those of the Cambrian site have the same origin. This enables a mean direction to be calculated for the sill, since it is probable that its samples record mainly one component that is not demagnetized. Petrographic studies of a sample from the sill revealed abundant haematite.

5. Field tests

Field tests of palaeomagnetic stability were performed to constrain the timing of the ChRM acquisition in the different geological units. For the tilt tests we applied only the bedding correction recognized from dips measured on the Lower Cambrian strata (Boon's and Tuttle Hill members), and Neoproterozoic volcaniclastic beds (Caldecote Volcanic Formation). No other tectonic corrections were considered necessary, given the structural history of the area which indicates two principal folding episodes: pre-dating and post-dating formation of the local Early Cambrian and Early Ordovician rocks (see Bridge *et al*. 1998).

5.a. Neoproterozoic rocks

Four samples of Neoproterozoic tuffaceous siltstone included as clasts within the basal Cambrian breccias of the Boon's Member were collected for the conglomerate test. After thermal demagnetization experiments a component was determined for every clast, as shown in Figure 6. The timing of acquisition of these directions is discussed below.

Sites BP2 and BP3 in the Caldecote Volcanic Formation were obtained for the baked contact test, these being located, respectively, at 2.5 m from the contact, and at the actual contact, of a lamprophyre sheet (site BO1) correlated with the Midlands Minor Intrusive Suite (Fig. 7a). An intermediate sample (S) at about 0.7 m from the intrusion, between BP3 and BP2, was also collected. The stereonet in Figure 7a shows that the cone of the 95 % confidence level of the mean ChRM direction for site BO1 overlaps the cone for BP3 (the baked country rock). Both these directions, however, differ from the mean ChRM of BP2 (the unbaked country rock), indicating a positive baked contact test. On the other hand, the NRM of sample 'S' is composed of a mixture of at least three components (Fig. 7b). One of these directions, close to the direction of the present-day GDF, is defined between 150 °C and 200 °C. Another direction, similar to that obtained at the Neoproterozoic site BP2, is defined between 250 °C and 350 °C. Finally, the highest steps define a great circle that contains a direction recorded in the Ordovician intrusions.

For tectonic correction (structural test), site mean directions of the ChRMs recorded in the Neoproterozoic rocks (Table 1 and Fig. 8a–c) are given as *in situ*, and after corrections for post-Cambrian and Neoproterozoic tilting. There is no significant variation in the attitude of the Cambrian strata in Boon's and Judkins' quarries, and consequently the 'fold test' (McFadden, 1990) is statistically inconclusive. However, there is a marginal improvement in the clustering of the downward directions for the Neoproterozoic rocks after the Cambrian bedding correction is made (Fig. 8b). For those sites with downward directions, we then applied a second correction based on the Neoproterozoic folding. There is a significant dispersion of directions after this correction (Fig. 8c), indicating that the directions had been imprinted after Neoproterozoic folding or tilting of the Caldecote Volcanic Formation.

5.b. Cambrian rocks: Hartshill Sandstone Formation

For the tectonic correction (structural) test, site mean directions for the ChRMs of the Boon's and Tuttle Hill members (Table 2 and Fig. 8d,e) indicate that there is a significant dispersion of the directions after applying the tilt correction, and the 'fold test' is therefore statistically negative. It is noteworthy that four *in situ* site mean directions from Cambrian rocks of the Boon's Member form a group, characterized by southward and low inclinations, which is different from the rest of the site mean directions (Fig. 8d).

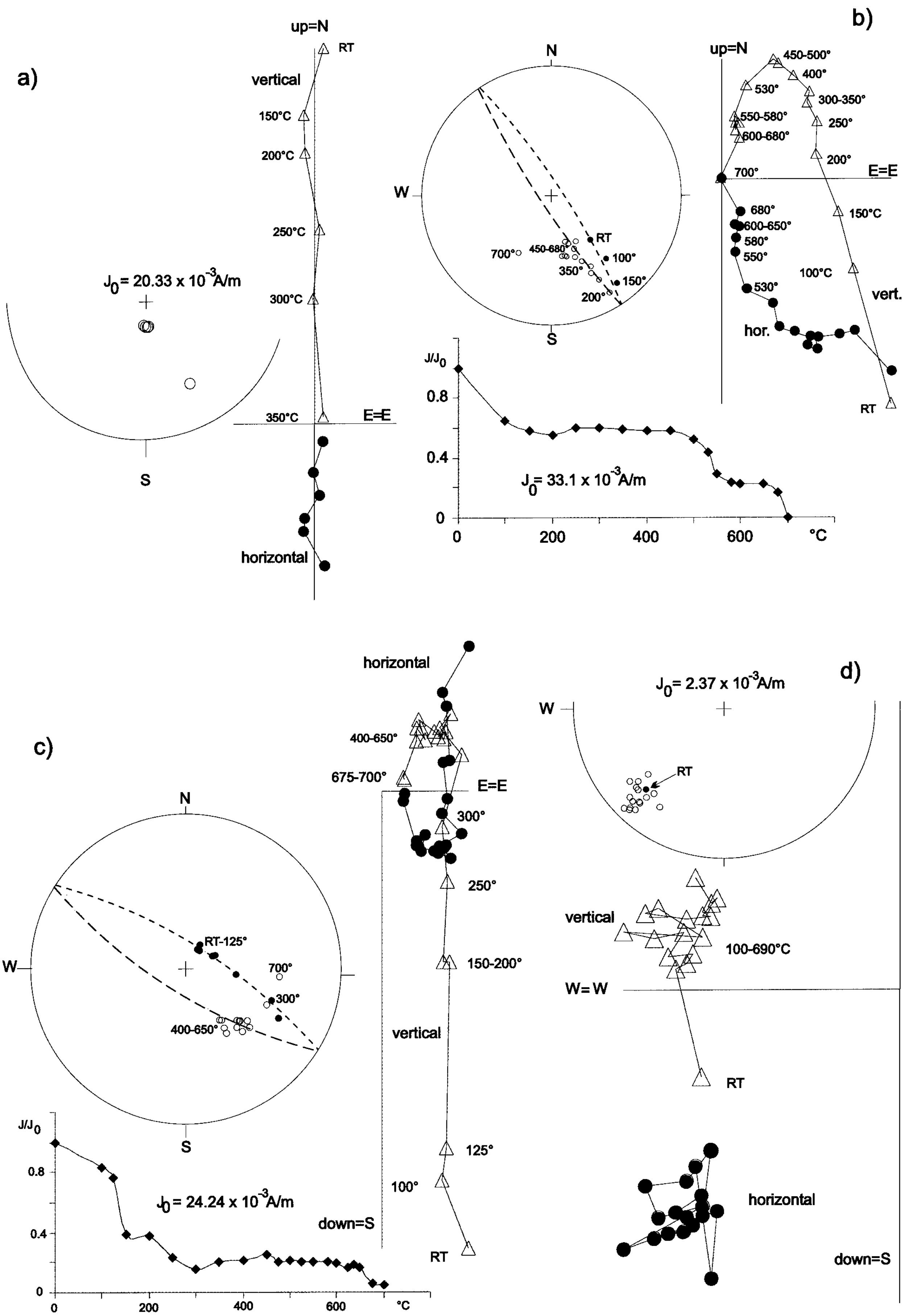
5.c. Late Ordovician rocks: Midlands Minor Intrusive Suite

For the tectonic correction (structural) test, site mean directions of the ChRMs of intrusive lamprophyre sheets (Table 3 and Fig. 8f,g) indicate that there is a higher dispersion of the directions after the Cambrian bedding correction and so the 'fold test' is negative.

6. Interpretation of the palaeomagnetic results

The starting point for a correct interpretation of the site mean directions of the ChRMs of the sampled

Figure 4. Orthogonal and stereographic projection plots of progressive demagnetization data from specimens of the Lower Cambrian Hartshill Sandstone Formation. (a) 'Type 1' magnetic behaviour: specimen of sandstone from the Tuttle Hill Member in Hartshill Quarry. (b) 'Type 1' magnetic behaviour: specimen from a sandstone of the Boon's Member, at the contact of a Late Ordovician intrusion (Boon's Quarry). (c) 'Type 2' magnetic behaviour: specimen of granulestone from the Boon's Member in Boon's Quarry. In the orthogonal projection, the vertical plane is rotated along the vertical axis and N is in coincidence with E. (d) 'Type 3' magnetic behaviour: specimen from sandstone of the Boon's Member in Boon's Quarry. Symbol convention is explained in Figure 3.



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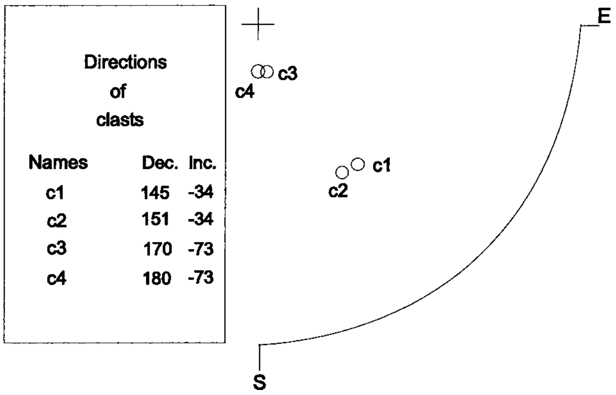

Figure 6. Stereographic projection illustrating the components recorded by four clasts analysed from Lower Cambrian strata of the Boon's Member. Symbol convention on the stereonets is explained in Figure 3.

geological units is the data from Late Ordovician rocks of the Midland Minor Intrusive Suite. This is because the emplacement of these intrusions has thoroughly reset the primary magnetic remanences of the Lower Cambrian sequence, and has partially reset those for the Neoproterozoic rocks.

The *in situ* site mean directions of the ChRMs of the Late Ordovician intrusions (Fig. 8f) are different from Late Palaeozoic, Mesozoic and Cenozoic magnetic directions determined elsewhere in southern Britain (see Van der Voo, 1993). The implication therefore is that these are primary directions, imprinted at the time of emplacement of the Midlands Minor Intrusive Suite at 442 ± 3 Ma.

The 'fold test' further demonstrates that the ChRMs of the Ordovician intrusions are younger than folding of the Lower Cambrian sequence. This is in agreement with the field observation that Ordovician lamprophyre dykes cut the axes of chevron folds in Lower Cambrian strata at Hartshill Quarry (Carney, 1992). The same test also shows that the site mean directions of the ChRMs from the Cambrian strata of the Boon's and Tuttle Hill members were imprinted after the tectonism that folded these beds. It is therefore probable that the site mean directions of the Tuttle Hill Member (HC1, HC2 and HC3) reflect remagnetizations recorded in Late Ordovician times, during emplacement of the Midlands Minor Intrusive Suite (compare Fig. 8d with Fig. 8f). The imprint of the Ordovician remagnetization can also be seen at the Boon's Member sampling site BC5, located close to the margin of a lamprophyre

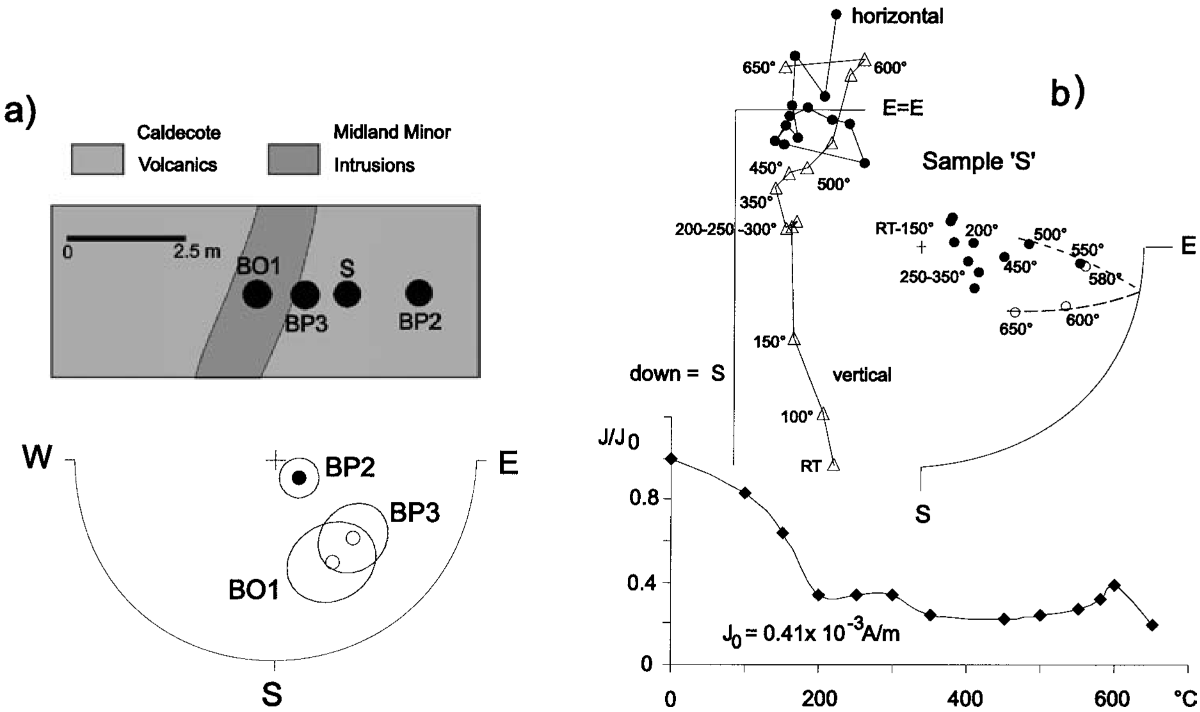

Figure 7. (a) Directions of the Neoproterozoic Caldecote Volcanic Formation and of a Late Ordovician dyke showing a positive baked contact test. (b) Magnetic behaviour of a sample at about 0.7 m from the dyke, from the baked contact test. Symbol convention is explained in Figure 3.

Figure 5. Orthogonal and stereographic projection plots of progressive demagnetization data from the Late Ordovician dykes and sills of the Midlands Minor Intrusive Suite. (a) 'Type 1' magnetic behaviour: specimen from a diorite sill from the Griff No. 4 Quarry. (b) 'Type 2' magnetic behaviour: specimen from a lamprophyre dyke in Hartshill Quarry. (c) 'Type 2' magnetic behaviour: specimen of a lamprophyre sill in Boon's Quarry. (d) 'Type 3' magnetic behaviour: specimen of a sill from Boon's Quarry. Symbol convention is explained in Figure 3.

Table 1. Palaeomagnetic data from the Neoproterozoic rocks

	Tilt correction (Strike/Dip)			*In situ*		Fisher's statistical parameters		After tilt correction			
								Cambrian		Precambrian	
Site	Cambrian	Precamb.	n/n_0(N)	Dec.	Inc.	k	α_{95}	Dec.	Inc.	Dec.	Inc.
BP1	136/43		5/14(4)	160	−54	28	13	101	−49	–	–
BP2	136/43	4/40	9/14(5)	127	78	41	8	208	48	161	48
BP3	136/43		4/9(3)	135	−44	45	14	102	−30	–	–
BP4			0/4(3)	–	–	–	–	–	–	–	–
BP5	136/43	1/40	16/24(8)	112	79	83	4	210	50	156	52
JP1	130/45	14/11	3/6(4)	339	83	88	22	229	48	218	53
JP2	130/45	235/15	13/19(5)	185	82	17	11	214	38	227	42
JP3	130/45	323/35	6/6(3)	125	78	99	7	203	45	160	68
JP4	130/45		4/4(3)	210	−22	47	13	197	−66	–	–

B – Boon's Quarry, J – Judkins' Quarry, P – Precambrian.
The Precambrian (Neoproterozoic) tilt corrections were applied after correction for Cambrian tilting.
n/n_0(N) – n: number of specimens with directions used to calculate the site mean direction, n_0: number of specimens obtained from the samples, N: number of samples at each site. *In situ* – statistical parameters of the mean of all the directions: $\alpha_{95} = 65°$, k = 1.67. Mean of directions with downward inclinations: Dec. = 127.6°, Inc. = 84.7°, $\alpha_{95} = 11°$, k = 73.6. After Cambrian tilt correction – statistical parameters of the mean of all the directions: $\alpha_{95} = 64°$, k = 1.7. Mean of directions with downward inclinations: Dec. = 212.9°, Inc. = 46°, $\alpha_{95} = 8°$, k = 96.8. After Precambrian tilt correction – Mean of directions with downward inclinations: Dec. = 187°, Inc. = 57°, $\alpha_{95} = 22°$, k = 12.6.

Table 2. Palaeomagnetic data from Lower Cambrian strata of the Hartshill Sandstone Formation

Site	Cambrian tilt correction (Str./Dip)	n/n_0(N)	*In situ* Dec.	*In situ* Inc.	Fisher's statistical parameters K	Fisher's statistical parameters α_{95}	After tilt correction Dec.	After tilt correction Inc.
BC1	136/43	14/16(5)	180	−10	17	10	164	−36
BC2	166/22	5/7(7)	198	−14	30.5	13.2	191	−25
BC3	156/36	4/4(3)	169	−1.5	48	18.2	165	−9
BC4	150/12	4/4(3)	189	−1.4	22.5	26.8	188	−9
BC5	150/12	2/2(2)	228	−11	–	–	227	−22
HC1	159/42	4/5(3)	192	−76	361	5.6	88	−54
HC2	159/42	7/8(3)	217	5.1	33.9	11	211	−30
HC3	150/44	3/7(3)	156	−44	126	7.7	119	−33
HC4		0/5(2)	–	–	–	–	–	–

B – Boon's Quarry, H – Hartshill Quarry, C – Cambrian.
n/n_0(N) – n: number of specimens with directions used to calculate the site mean direction, n_0: number of specimens obtained from the samples, N: number of samples of each site. *In situ* – Mean of all the site directions: Dec. = 192.15, Inc. = −19.35, $\alpha_{95} = 25.8$, k = 5.58. After tilt correction – Mean of all the site directions: Dec. = 176.33, Inc. = −33.5 $\alpha_{95} = 29.4$, k = 4.51.

Table 3. Palaeomagnetic data from Late Ordovician rocks of the Midlands Minor intrusive suite

Site	Cambrian tilt correction (Str./Dip)	n/n_0(N)	*In situ* Dec.	*In situ* Inc.	Fisher's statistical parameters K	Fisher's statistical parameters α_{95}	After tilt correction Dec.	After tilt correction Inc.
BO1	135/27	3/3(2)	151	−41	53.7	17	126	−43
BO2	136/43	2/2(2)	163	−32	–	–	131	−41
BO3	155/16	3/3(3)	169	−50	43	19.2	150	−51
BO4	150/12	2/2(2)	225	−9	–	–	224	−21
JO1	130/45	3/3(3)	145	−55	48	11	89	−43
JO2	130/45	5/7(3)	119	−45	402	4	89	−24
JO3	130/45	3/3(3)	136	−52	41	14	90	−37
HO1	159/42	6/6(3)	166	−35	58	6.6	138	−29
HO2	159/42	2/2(2)	161	−51	–	–	121	−36
HO3	138/42	3/4(3)	170	−72	26	25	75	−55
G	129/9	6/6(3)	167	−70	22	17	141	−74

B – Boon's Quarry, J – Judkins' Quarry, H – Hartshill Quarry, G – Griff No. 4 Quarry, O – Ordovician.
n/n_0(N) – n: number of specimens with directions used to calculate the site mean direction, n_0: number of specimens obtained from the samples, N: number of samples of each site. *In situ* – Mean of the site directions (without BO4): Dec. = 154°, Inc. = −51.3°, $\alpha_{95} = 10.4°$, k = 22.71. After tilt correction – Mean of the site directions (without BO4): Dec. = 113.6°, Inc. = −46°, $\alpha_{95} = 14.2°$, k = 12.5. BO4 direction was not averaged because it is at more than 40° from the mean.

intrusion. The event that folded the Lower Cambrian strata, pre-dating as it does the emplacement of the Midlands Minor Intrusive Suite (442 Ma), could be related to one of the phases of the Caledonian Orogeny as defined by McKerrow *et al*. (2000), the Penobscotian (∼Tremadoc) or Shelveian (∼Ashgill) episodes being possible candidates.

Four site mean directions of the ChRMs from the Boon's Member do not record this Late Ordovician remagnetization. These granule sandstones are instead characterized by 'noisy' magnetic behaviours (Fig. 4c). Their thin sections show the presence of authigenic overgrowths of haematite and martite that were not observed in the other rocks. The *in situ* mean directions of these four sandstone sites were compared with a mean Carboniferous direction for the sampling area (Fig. 9), obtained from five Carboniferous palaeopoles listed by Trench & Torsvik (1991). They are statistically indistinguishable at the 95 % of confidence level, and therefore at these sites the ChRMs probably reflect Carboniferous remagnetization of the Boon's Member. It is therefore suggested that the Type 2 remagnetization of the Cambrian strata was accomplished during the end-Carboniferous phase of the Variscan Orogeny, most probably by migrating fluids that altered original magnetic minerals and precipitated haematite. Such a type of remagnetization has been observed in other parts of southern Britain (e.g. Channell, McCabe &

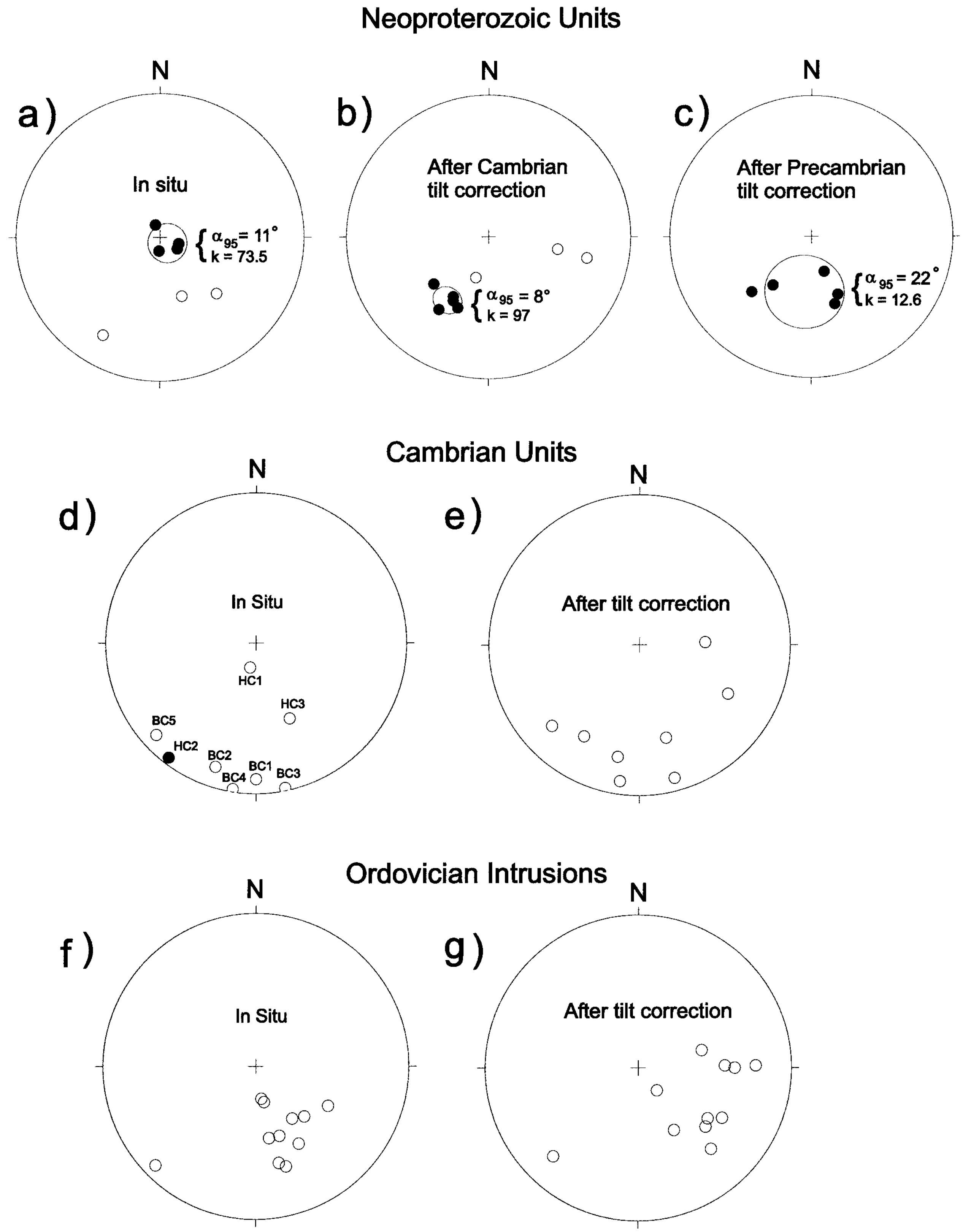

Figure 8. Stereographic projections of site-level characteristic remanent magnetization directions from Caldecote Volcanic Formation and Neoproterozoic intrusive rocks: (a) *in situ* coordinates. (b) Cambrian tilt-corrected coordinates. (c) Neoproterozoic tilt-corrected coordinates. Stereographic projections of site-level chracteristic remanent magnetization directions from Boon's and Tuttle Hill Member (Hartshill Quarry): (d) *In situ* and (e) tilt-corrected coordinates. Stereographic projections of site-level characteristic remanent magnetization directions from Midlands Minor Intrusive Suite: (f) *in situ* coordinates and (g) after tilt correction on the Cambrian strata. Symbol convention on the stereonets is explained in Figure 3.

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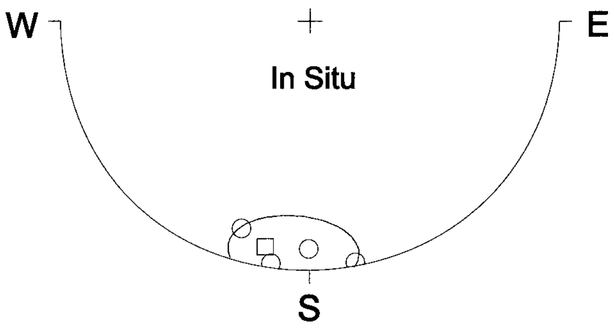

Figure 9. Stereographic projection of four site-level characteristic remanent magnetization directions from the Lower Cambrian, Boon's Member (open circle). A calculated direction with Carboniferous poles is also shown (open square). Note that this direction is contained by the interval of confidence of the mean of the four site-level directions from the Boon's Member sample. Symbol convention on the stereonet is explained in Figure 3.

Woodcock, 1992; Trench *et al.* 1992; Torsvik *et al.* 1993). Its preferential development at Nuneaton, in the Boon's Member only, may reflect the coarse grain size and consequent inherent permeability to hydrothermal fluids of those strata.

For the Neoproterozoic rocks, five *in situ* site mean directions of the ChRMs show steep downward inclinations (Fig. 8a). The positive baked contact test indicates that these directions were recorded prior to emplacement of the Ordovician intrusions. By contrast, the site mean directions with upward inclinations are interpreted as remagnetizations caused by these intrusions (compare Fig. 8a with Fig. 8f). Furthermore, the magnetic components determined in the Neoproterozoic clasts of the Cambrian conglomerates also reflect the Late Ordovician remagnetizations. It is likely that this Late Ordovician remagnetization was mainly thermal in origin, although there may also have been some chemical remagnetization. The incompletely resolved component in the Neoproterozoic intrusive rocks, after the heating step of 550 °C (Fig. 3b), is also probably Late Ordovician, recorded by the secondary haematite alteration that borders the magnetite crystals observed in these rocks. Following corrections based on the attitudes of the Cambrian beds (Fig. 8a,b), it is seen that the site mean directions of the Neoproterozoic ChRMs with downward inclination were possibly imprinted before deformation of the Cambrian strata, as also suggested by the positive baked contact test. These ChRMs do not reflect the primary directions of the Caldecote Volcanic Formation, however, because the 'fold test', based on the attitudes of these tuffs, indicates that they were recorded after Neoproterozoic tectonism. It is possible to attribute remagnetization of the Caldecote Volcanic Formation to the emplacement of the Neoproterozoic intrusive rocks because there is no difference between the ChRMs obtained in the volcanic rocks and the intrusions (Fig. 3a,b). The late-stage granophyric diorite phase of intrusion has yielded a radiometric age of 603 ± 2 Ma and this value therefore constrains the age of the Neoproterozoic remagnetization.

6.a. Comparison with previous work

The data and interpretations reported here reveal a more complex history of magnetization and remagnetization than has previously been considered for this fragment of Avalonia. They are in conflict, for example, with previous findings from the Nuneaton area by Piper & Strange (1989), who briefly described palaeomagnetic results from six sites within the Caldecote Volcanic Formation, on samples that included pyroclastic rocks, dolerite sheets and dykes and porphyritic basalt. They applied alternating field and thermal cleaning to determine two groups of *in situ* directions. One was formed by SW-downward components with directions sporadically represented. A mean direction of declination of 235°, inclination 35°, $\alpha_{95} = 11°$ based on ten samples was obtained for this group. The other is a well-defined SSE-upward component group with a mean direction of declination 182°, inclination −44°, $\alpha_{95} = 6.5°$, based on 45 samples. Piper & Strange (1989) considered that the SSE-upward component was recorded during the early history of these rocks, whereas the SW-downward direction was compared with Siluro-Devonian field directions.

In the light of the new data reported here, a revised interpretation of the findings of Piper & Strange (1989) is presented. The SSE-upward component they identified is comparable with the mean direction for the Late Ordovician intrusions (Fig. 10a). The SW-downward component they recognized is more difficult to correlate; there is, however, a SW direction with low inclination in one site that sampled a Late Ordovician intrusion (BO4 in Table 3). There are also similar directions obtained from some Neoproterozoic and Cambrian sites (JP4, BC5, HC2) that are interpreted here as having been remagnetized during the Late Ordovician. The mean of these directions and that of the present-day GDF describe a great circle path that contains the SW-downward component of Piper & Strange (Fig. 10b). Possibly the SW component of Piper & Strange (1989) represents a composite magnetization direction, dominated by the Late Ordovician SW direction with low inclination but with a recent component of the present-day GDF.

7. Palaeolatitude calculations

The field tests show that the Caldecote Volcanic Formation and Neoproterozoic intrusions recorded positive or downward magnetic directions at ~ 603 Ma. The resulting mean inclination of these five tilt-corrected site means, using only the Cambrian bedding correction, is 46° ($\alpha_{95} = 8°$) implying that the sampling area (now at 52.5° N, 1.5° W) was positioned at 27.5° S + 7°/−6° at about 603 Ma. Such a location,

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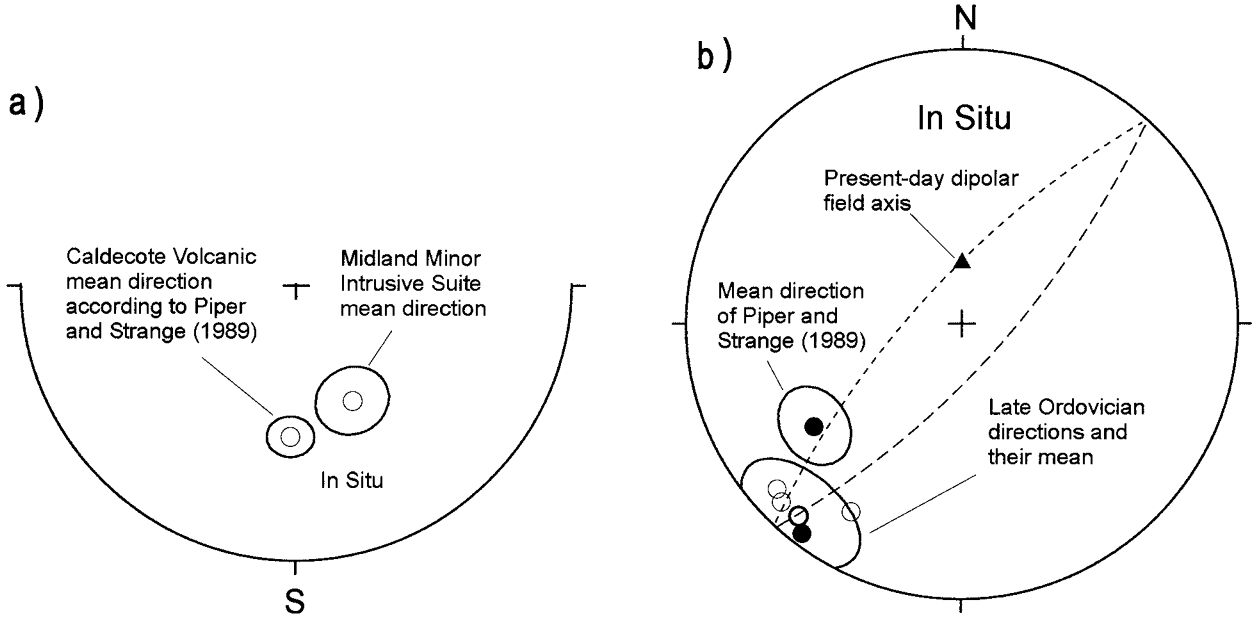

Figure 10. (a) Stereographic projection of one of the mean directions calculated by Piper & Strange (1989) from Neoproterozoic (Caldecote Volcanic Formation) samples and the mean direction calculated here for the Late Ordovician Midlands Minor Intrusive Suite. (b) Stereographic projection of the other mean direction calculated by Piper & Strange (1989) from Caldecote Volcanic samples, compared with the directions considered here to be of Late Ordovician inheritance. Symbol convention on the stereonets is explained in Figure 3.

just outside of the modern southern tropic, and most probably in a maritime situation (McNamara *et al.* 2001), may have supported oceanic and atmospheric circulation systems that produced a warm, humid climatic regime at one stage during the 603–520 Ma period of erosion that preceded deposition of the Lower Cambrian Hartshill Sandstone Formation. Under those conditions, the Neoproterozoic rocks were reddened and subjected to silicate weathering, producing the clay mineral-mantled spheroidal corestones that are preserved beneath the Boon's Member at Boon's Quarry. The Neoproterozoic palaeopole (CV), based on the five tilt-corrected site means using only the Cambrian bedding correction, is located at 329.7° E, 5.0° S (dm/dp = 10°/6°). It is not possible to compare the CV palaeopole with elsewhere in southern Britain because there are no other reliable Neoproterozoic palaeomagnetic data from this continental block.

For bodies of the Midlands Minor Intrusive Suite, the upward-inclined magnetic components represent the magnetic directions recorded at ~442 Ma (Ordovician, latest Ashgill), the age of emplacement. To calculate the palaeolatitude of the sampling area during this event, the site mean directions were averaged *in situ*, with the exclusion of that for site BO4 which is more than 40° away from the mean of the others. This anomalous direction perhaps records a transitional state of the Late Ordovician geomagnetic field. The resulting mean inclination is 51.3° ($\alpha_{95} = 10.4°$), implying that at about 442 Ma the central England part of Avalonia was positioned at latitude 32° S + 11°/−8.5°. The calculated palaeopole (MIS) is located at 51.1° E, 62.2° S (dm/dp = 14°/10°). This palaeopole actually lies off any of the apparent polar wander paths calculated for southern Britain or Baltica (e.g. Trench & Torsvik, 1991; Torsvik *et al.* 1993; Channell, McCabe & Woodcock, 1993). The offset is a feature that may be related to the major declination anomaly revealed by the Late Ordovician data, which will be discussed in Section 8.

7.a. Comparisons with other palaeolatitude data

Figure 11a shows the palaeolatitudes derived from the CV pole in comparison with others of palaeolatitudes obtained in Avalonia and the Sahara Craton for the time span 605–575 Ma (Table 4). In similar fashion, Figure 11b shows the palaeolatitude derived from the MIS pole and compares it with the palaeolatitudes of poles obtained in Avalonia and Laurentia for the time span 450–415 Ma (Table 4). To calculate these other palaeolatitudes the selected palaeopoles of the Sahara Craton and those of Laurentia were averaged (Fisher, 1953) and each calculated mean was considered to be the representative pole position for each time-interval (Table 4). Where no accurate radiometric data existed, the ages were determined stratigraphically to approximate absolute ages using the time-scale of Tucker & McKerrow (1995). It should be noted that Table 4 includes the confidence interval of the calculated palaeolatitudes, but for reasons of clarity that parameter is not shown on Figure 11.

For the Sahara Craton poles the calculated palaeolatitude was in keeping with reconstructions showing

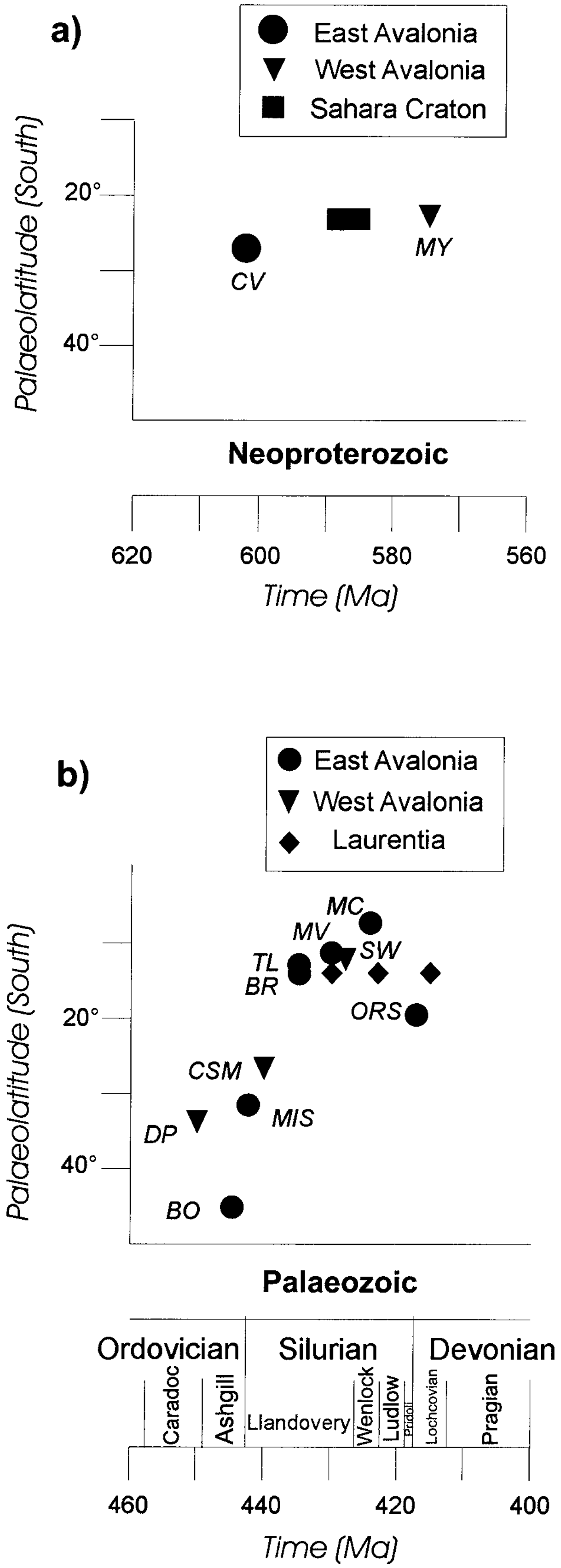

Figure 11. Palaeolatitudes for elements of the Avalonia microcontinent: (a) compared with the palaeolatitudes expected if Avalonia had been attached to Gondwana (time span 615–575 Ma); (b) compared with palaeolatitudes expected if Avalonia had collided with Laurentia (time span 450–415 Ma). The expected palaeolatitudes are calculated using as a reference the location of Nuneaton (52.5° N, 1.5° W). Timescale after Tucker & McKerrow (1995). The data from this study are CV (Caldecote Volcanic Formation) and MIS (Midlands Minor Intrusive Suite). Sources and references used for the other data featured in this compilation, and explanations of abbreviations, are given in Table 4.

Avalonia attached to northwest Africa, as probably occurred during Neoproterozoic and Cambrian times. The expected palaeolatitude was calculated for the same reference location of 52.5° N, 1.5° W, using a relative reconstruction between Avalonia and Africa similar to that of Torsvik & Rehnström (2001) (here the rotation parameter was: Lat. = 2.72° N, Long. = 31.14° E, angle of rotation = 53°). With the Laurentian palaeopoles, the calculated palaeolatitudes were those that would be expected if Avalonia had been attached to Laurentia, as was the case during Late Palaeozoic times (Bullard, Everett & Smith, 1965). These expected palaeolatitudes were calculated for a reference location of 52.5° N, 1.5° W (the sampling area). For the poles of Avalonia, palaeolatitudes were calculated for the sampling locality and the data of Western Avalonia were first transferred to southern Britain co-ordinates using the rotation parameter of Bullard, Everett & Smith (1965).

Figure 11a shows a good agreement between the Nuneaton palaeolatitude and those calculated for the Sahara Craton and Avalonia from 605 Ma to 575 Ma. At that time Avalonia lay outboard of Western Gondwana (Fig. 12b), with 'eastern' Avalonia closer to the northwest coast of Africa than to South America as recently pointed out by McNamara *et al*. (2001). Of further note is the similarity between the palaeolatitude obtained using Caldecote Volcanic Formation data and that obtained by McNamara *et al*. (2001) in Newfoundland (Western Avalonia) for 575 Ma.

The Ordovician to Early Silurian palaeomagnetic data from Avalonia, which include those calculated for the Midlands Minor Intrusive Suite, yield fairly consistent palaeolatitudinal variations. They define (Fig. 11b) a continuous northward drift of Avalonia, commensurate with narrowing of the Iapetus Ocean, from high to low latitudes during the period ~450 Ma to ~435 Ma (see also Mac Niocaill, 2000; Cocks & Torsvik, 2002). The Midlands Minor Intrusive Suite has yielded a palaeolatitude (Fig. 11b) in agreement with that deduced from Western Avalonia on the Cape St Mary's sills (Hodych & Buchan, 1998), which also have a similar radiometric age. Both of these intrusive rock assemblages recorded palaeomagnetic directions with normal polarity, which according to Trench, McKerrow & Torsvik (1991) dominated the Late Ordovician geomagnetic field. The palaeolatitude estimate embodied in Figure 11b is compatible with the

Table 4. Summary of data and references used to compile Figure 11

Rock unit	Code	Age (Ma)	Plat. (°)	Plong. (°E)	Palaeolat. (°S)	Author(s)
Continent: Avalonia						
Time-span: 612–575 Ma						
Caldecote Volcanics	CV	603	5.01 S	329.6	27 ± 8	This study
Marystown Group	MY	575	62.17 S	51.14	23 ± 10	McNamara *et al.* (2001)
Continent: Avalonia						
Time-span: 450–417 Ma						
Dunn Point	DP	450	2.83 S	348.0	34 ± 4	Johnson & Van der Voo (1990)
Mid. Minor Intrusive S.	MIS	442	62.17 S	51.14	32 ± 12	This study
Borrowdale Volcanics	BO	445	8.1 N	6.2	45 ± 7	Channell & McCabe (1992)
Cape St Mary's Sills	CSM	440	10.73 S	358.1	27 ± 10	Hodych & Buchan (1998)
Browgill Redbeds	BR	435	14.0 S	314.0	13 ± 12	Channell, McCabe & Woodcock (1993)
Tortworth Lavas	TL	435	7.0 S	304.0	15 ± 5	Torsvik, Trench & McKerrow (1994)
Mendips Volcanics	MV	430	13.0 S	271.0	12 ± 9	Torsvik *et al.* (1993)
Springdale & Wigwam	SW	428	10.81 S	306.67	13 ± 14	Stamatakos *et al.* (1995)
Millcove Redbeds	MC	424	18.0 S	310.0	8 ± 8	Mac Niocaill (2000)
Lower ORS, Wales	ORS	417	7.0 S	307.0	16 ± 8.5	Channell, McCabe & Woodcock (1992)
Continent: Western Gondwana (Sahara Craton)						
Time-span: 589–586 Ma						
Nabati Complex	NC	589	67.9 S	134.1		Saradeth *et al.* (1989)
Bir Safsaf Dykes	BS	586	80.0 S	69.7		Saradeth *et al.* (1989)
Mean: N = 2, Plat. = 75.95° S, Plong. = 114.96° E, Palaeolat. = 23.6° S						
Continent: Laurentia						
Time-span: 430–415 Ma						
Foyers Granite	FG	420	26.15 S	307.77		Torsvik (1984)
Strontian Granite	SG	430	20.13 S	305.84		Torsvik (1984)
Helmsdale Granite	HG	420	30.23 S	316.66		Torsvik, Løvlie & Storetvedt (1983)
Wabash Reef Ls.	WR	420	17.0 S	305.0		McCabe *et al.* (1985)
Ratagen Complex	RG	415	14.16 S	308.88		Turnell (1985)
Peterhead Granite	PG	415	20.27 S	319.77		Torsvik (1985)
Mean: N = 6, Plat. = 21.41° S, Plong. = 310.56° E, α_{95} = 7°, K = 98.05, Palaeolat. = 14.8° ± 7°						

The palaeolatitudes are calculated using palaeopoles and considering as a reference the location of Nuneaton (52.5°N, 1.5°W).
Plat. and Plong.: Coordinates of palaeopoles (PPs). PPs of Northern Britain in Laurentia coordinates (rotation parameter of Bullard, Everett & Smith 1965). PPs of Western Avalonia in Southern Britain coordinates (rotation parameter of Bullard, Everett & Smith, 1965). Codes of Avalonia PPs shown as labels on palaeolatitudes on Figure 11.

close approach between Laurentia/Baltica and Avalonia in Ashgill times envisaged by Williams *et al*. (2001) on faunal grounds, and also by Cocks & Torsvik (2002).

8. Implications for Palaeozoic block rotations in southern Britain

The ChRMs recorded at the time of emplacement of the Midlands Minor Intrusive Suite show a considerable anomaly in the declination. This anomaly was determined by comparing the Late Ordovician data with three different references, these being: (1) a Borrowdale Volcanic palaeopole, from the English Lake District (Channell & McCabe, 1992; see our Table 4), imprinted at ∼445 Ma; (2) the palaeopole for the Cape St Mary's Sills (Hodych & Buchan, 1998, CMS: Table 4), with an age of ∼440 Ma; and (3) the calculated pole for 'Balonia' (Torsvik *et al.* 1993), with an age of 441 Ma. The latest Ordovician MIS palaeopole is discordant with respect to all these reference palaeopoles. Using the restoration method of Beck (1989), three values of clockwise tectonic rotation were calculated (Table 5). Figure 12a shows that the Late Ordovician mean direction for the sampling area is rotated by about 160° with respect to the reference directions.

Table 5. Rotations calculated for the mean palaeomagnetic data of Late Ordovician rocks of the Midlands Minor Intrusive Suite

Calculation with respect to	Rotation (R ± ΔR)	Flattening (F ± ΔF)
Borrowdale Volcanics	165° ± 16°	13° ± 12.5°
Cape St Mary Sills	154° ± 14.5°	5.2° ± 12.5°
'Balonia 441 Ma'	158° ± 14°	9.8° ± 12.5°

The same declination anomaly should also be found in the Neoproterozoic rocks of Nuneaton, however, there is no reliable palaeomagnetic data of that age from southern Britain to use as a point of reference. Furthermore, the data from Western Avalonia could also include rocks with declination anomalies (McNamara *et al.* 2001). A comparison with Neoproterozoic data from the Sahara Craton (NC and BS in Table 4) seemed more promising, but in order to do this, it is necessary to assume a position for Avalonia with respect to northwest Africa. Since such an assumed reconstruction of Avalonia would in turn influence the calculation of a declination anomaly, it was decided to adopt the palaeoreconstruction that has already

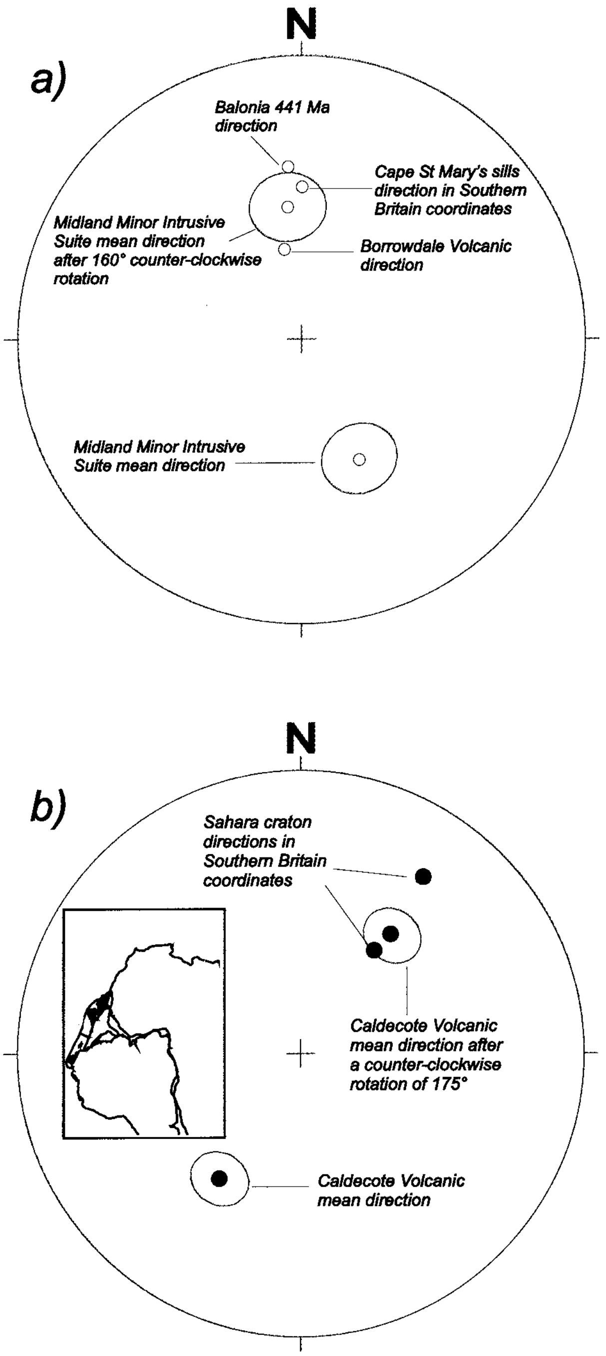

Figure 12. (a) Stereographic projection of the Midlands Minor Intrusive Suite mean direction and directions calculated with the palaeopoles of Borrowdale Volcanics, Cape St Mary's Sills and Balonia (441 Ma pole). Notice the declination anomaly that shows the Midlands Minor Intrusive Suite direction with respect to the others. (b) Stereographic projection of the Neoproterozoic mean direction and directions calculated with palaeopoles from the eastern Sahara craton. The declination anomaly for Nuneaton disappears after restoration for rotation.

been used in this study (Section 7: rotation restoration parameter: 2.72° N, 31.14° E, angle of rotation: 53°). In Figure 12b the mean direction of Caldecote Volcanic Formation is shown together with the directions of those African poles in the co-ordinates of our sampling area. This diagram indicates that a counter-clockwise restoration rotation of 175° of the CV Neoproterozoic mean direction would align this direction into the other reference directions. Therefore, given the uncertainties in the calculated rotations for the Late Ordovician data (Table 5), the Neoproterozoic and the Late Ordovician declination anomalies at Nuneaton together indicate a clockwise tectonic rotation along a vertical axis, probably of the order of 165°.

The timing of this rotation is constrained between the latest Ordovician emplacement of the Midlands Minor Intrusive Suite, and the suggested Variscan remagnetization of the Boon's Member. Tectonic events to which it may be attributed were possibly associated with one of the phases of the Caledonian Orogeny (*sensu* McKerrow *et al.* 2000), perhaps a late episode of the Shelveian (~Ashgill) Caledonian phase, or the Acadian Phase (Emsian). Movements related to the mainly Carboniferous-age Variscan Orogeny are less likely to have caused such a radical rotation, in this part of central England. The possibility of an Acadian age for at least some of the rotation is supported by the tectonic interactions that may have occurred between Gondwana and the Laurentia margin and its accreted terranes (which included Avalonia) during Silurian to Early Devonian times (Van Staal *et al.* 1988). Moreover, within the Ordovician intrusions at Nuneaton there has been detected a thermal resetting of K–Ar isotope systems at about 411–405 Ma, or earliest Devonian times (geochronological information from C. Rundle, 1990; cited in Bridge *et al.* 1998), although the nature of the event that caused this is not known.

One consequence of this block rotation is that palaeogeographic reconstructions of pre-Carboniferous rocks in southern Britain that are based on vector data, such as palaeocurrent directions, may be unsafe.

9. Magnetic and geological history of Nuneaton Inlier

The multi-event geological and magnetization history that has been established for Avalonian basement rocks of the Nuneaton inlier is summarized in Table 6. Many ambiguities were revealed by the palaeomagnetic work, but our interpretations are well constrained within a robust geological framework (see Bridge *et al.* 1998) that has resulted from field-based lithostratigraphic and structural surveys in conjunction with previous geochronological and biostratigraphic dating of the sampled rocks.

10. Conclusions

(1) Neoproterozoic rocks of the Nuneaton Avalonian basement underwent folding, and were then intruded and magnetized during a major thermal event dated at 603 Ma. At this time Nuneaton lay off the western Gondwana margin. A subtropical maritime location, at 27.5° S +7°/−6°, possibly accounts for the climatic regime that caused the reddening and silicate weathering

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Table 6. Summary of geological and magnetic events in the Nuneaton basement inlier

Age	Geological event recognized	Magnetization
Carboniferous to Permian (*c*. 290 Ma)	End – Variscan uplift, tilting and block faulting, followed by deep weathering and erosion	Selective remagnetization of the basal Cambrian succession (Boon's Mbr)
?Early Devonian (*c*. 411–405 Ma)	?Acadian Orogeny; thermal alteration and tectonism involving block rotation	No obvious remagnetization, but probable cause of a major declination anomaly
Latest Ordovician Ashgill (442 Ma)	Emplacement of Midlands Minor Intrusive Suite	Primary magnetization of intrusions; pervasive remagnetization of Cambrian succession and of Neoproterozoic rocks at intrusivecontacts
Late Tremadoc to Ashgill	Unspecified ?Caledonian event involving folding of Cambrian succession	None recognized
Early Cambrian (*c*. 520 Ma)	Probable commencement of marine transgression and deposition of the Hartshill Sandstone Formation	No primary magnetization is preserved
Neoproterozoic to Early Cambrian (603–520 Ma)	Erosion and silicate weathering of land surface developed on Neoproterozoic rocks	No primary magnetization is preserved
Late Neoproterozoic (603 Ma)	Emplacement of intrusive basalts and diorites	Primary magnetization of intrusions; Caldecote Volcanic Formation pervasively remagnetized
Late Neoproterozoic (pre-603 Ma)	Volcanism, and deposition of Caldecote Volcanic Formation, followed by mild folding and faulting	No primary magnetization is preserved

that is locally preserved on the Neoproterozoic palaeolandsurface at Nuneaton.

(2) Following a long erosional and/or non-depositional hiatus (*c*. 70–80 Ma), spanning the Neoproterozoic/Cambrian boundary, a Lower Cambrian to Tremadoc-age marine transgressive sequence (the Hartshill Sandstone Formation and Stockingford Shale Group) was deposited. An unspecified period of time elapsed before this sequence was folded.

(3) Remagnetization of the folded Cambrian strata, and elements of the underlying Neoproterozoic basement, coincided with emplacement of the Midlands Minor Intrusive Suite in latest Ashgill time (442 Ma). Nuneaton was then positioned at latitude 32° S $+11^\circ/-8.5^\circ$, at the southern margin of a narrowed Iapetus, and in close approach with Baltica and Laurentia.

(4) The Nuneaton area subsequently experienced a clockwise block rotation of $\sim 165^\circ$ about a vertical axis. The timing of the event that caused this is constrained to between the late Ashgill and a final remagnetization that occurred in Carboniferous times.

(5) The postulated Carboniferous remagnetization is most intensely imprinted upon lithologies of the Boon's Member, a coarse, bouldery, red-bed sequence at the base of the Lower Cambrian succession.

(6) No primary magnetization can be determined for the Lower Cambrian strata at Nuneaton.

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