Journal of the Geological Society

Ordovician magnetostratigraphy: a correlation of global data

A. TRENCH, W. S. McKERROW and T. H. TORSVIK

Journal of the Geological Society 1991; v. 148; p. 949-957
doi: 10.1144/gsjgs.148.6.0949

Journal of the Geological Society, London, Vol. **148**, 1991, pp. 949–957, 4 figs. Printed in Northern Ireland

Ordovician magnetostratigraphy: a correlation of global data

A. TRENCH,[1] W. S. McKERROW & T. H. TORSVIK[2]
Department of Earth Sciences, University of Oxford, Parks Road, Oxford OX1 3PR, UK
[1]*Present address: Department of Geology, University of Western Australia, Nedlands, Perth, WA 6009, Australia*
[2]*Present address: Geological Survey of Norway, P.B. 3006, Lade, N-7002, Trondheim, Norway*

Abstract: Palaeomagnetic studies where primary magnetizations are established from well-dated rocks have been compiled to construct a magnetostratigraphic time-scale for the Ordovician period. An excellent correlation of magnetozones is observed between independent studies of the Baltic and South Siberian platform sequences. Supplemental datasets from other continents concur with the Baltic and Siberian polarity data.

Early Ordovician times were mainly characterized by a reverse field. Rapid reversals then occurred during Llanvirn and Llandeilo times. Late Ordovician times were dominated by a normal polarity field.

Some gaps remain in the polarity record, notably for late Caradoc–early Ashgill and mid-Tremadoc times.

The combination of biostratigraphic, radiometric and magnetostratigraphic studies within Cenozoic and Mesozoic rocks has aided the definition of a high resolution chronostratigraphy and polarity time-scale for these eras (Harland *et al.* 1989). Additionally, these data can be supplemented by the independent polarity record preserved within the oceanic crust.

For Palaeozoic times however, uncertainties are heightened by the absence of preserved oceanic crust and complicated by the increased effects of later magnetic overprinting in orogenic belts. Magnetic overprinting may be partial, or may have fully reset the original remanence. Nevertheless, primary magnetizations have been recovered from several Palaeozoic orogenic and platform sequences for which biostratigraphic age control is particularly good (e.g. Kirschvink & Rozanov 1984). In western Europe, twenty graptolite zones occur in the *c.* 70 Ma of the Ordovician Period, an average of 3.5 Ma each. Many of these zones can be sub-divided on the basis of conodonts (Bergstrom 1986), local graptolite zones, and on the basis of stages based on benthic faunas. Some stratigraphic intervals may therefore have a duration of as little as 1 Ma. These biostratigraphic constraints make widespread magnetostratigraphic correlation possible.

In this contribution, we have compiled global Ordovician palaeomagnetic data in an attempt to elucidate accurately the polarity history of the geomagnetic field. Previous attempts to define an Ordovician reversal stratigraphy have been made by Khramov and co-workers, based upon palaeomagnetic sections of the Siberian platform (Khramov *et al.* 1965; Rodionov 1966; Khramov & Rodionov 1980). Until recently, these data were unrivalled as a near continuous record of Ordovician polarity changes. However, the identification of a reversal stratigraphy within Ordovician carbonates from the Swedish platform (Torsvik & Trench 1991*a*) significantly increases the available database.

A further problem encountered in addressing the Early Palaeozoic reversal record is that of polarity ambiguity. For example, rocks magnetized near the equator could be interpreted as either normal, or reversely polarized, depending on the inferred orientation of their host continent. Normal polarity indicates that the north geomagnetic and north geographic poles coincide. Conversely, reverse polarity indicates that the north-finding geomagnetic field coincides with the south geographic pole. The present study assumes a palaeogeography as portrayed in Fig. 1 for Early Ordovician times. This scenario is similar to that presented by Scotese & McKerrow (1990) but with Baltica rotated as suggested by Torsvik *et al.* (1990*a*). Note that Siberia is oriented with the Mongolian margin facing north.

Methodology

When compiling the palaeomagnetic data, specific attention was addressed to:

(i) the outcome of any palaeomagnetic field stability tests performed in the original study (i.e. conglomerate, fold, contact and reversal tests);

(ii) available biostratigraphic constraints on the age of the studied rocks.

Magnetostratigraphic analysis requires only that the polarity of the studied rocks need be unequivocally established. Hence, although many early palaeomagnetic studies are based on only limited demagnetization, the polarity is still discernible. On the other hand, magnetostratigraphy makes the assumption that the age of magnetization is the same as the rock-age. This relationship can be particularly difficult to demonstrate in the absence of either sequences of stratigraphically-related reversals, positive intra-formational conglomerate tests or contemporary poles from different regions.

Based on the above considerations, data were loosely classified into three categories: fundamental, supplemental or unconstrained data.

Fundamental data. Stratigraphic sections which display a sequence of polarity reversals which are regarded as primary in origin. Reversal boundaries must be directly related to particular stratigraphic levels and biostratigraphic control must be adequate.

Supplemental data. Studies generally exhibiting a single polarity for which the normal/reverse option is

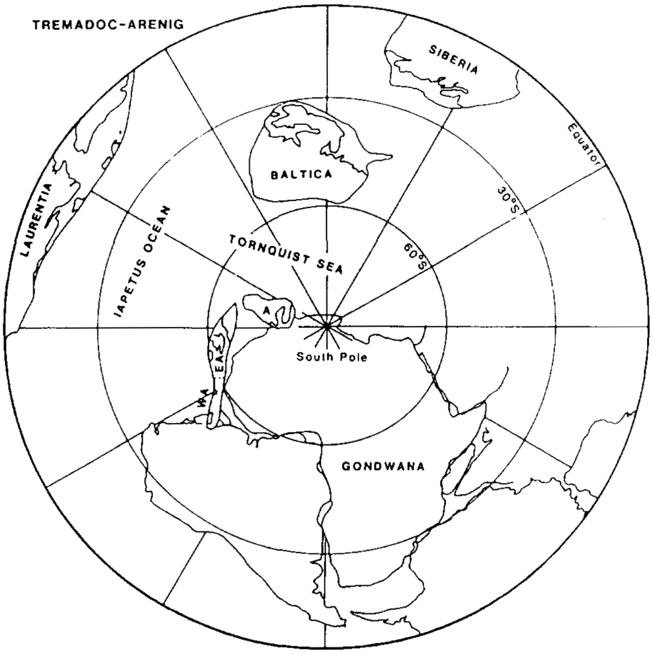

Fig. 1. Palaeoreconstruction for Early Ordovician times. Note that the polarity options adopted in this paper are insensitive to even large changes to this palaeogeographic scenario. To alter the interpreted polarity of a continent, one must rotate the given plate by 180° and move it into the opposing hemisphere. Plate reconstruction shown after Torsvik & Trench (1991*b*).

unambiguously established and for which there is adequate biostratigraphic control.

Unconstrained data. Palaeomagnetic results in this category include studies for which there is either inadequate biostratigraphic control, or for which reversals have no proven stratigraphic link. Some of the data are listed however in the hope that future additional constraints may permit their use.

Magnetostratigraphic nomenclature

We have chosen to name successive reversals depending on the series in which they occur (e.g. A[R] = Arenig, reversed, etc.). If the currently defined polarity record is incomplete, only a limited number of polarity intervals will require re-labelling.

Magnetostratigraphic subdivisions delineated by fundamental and supplemental data are outlined in Figs 2 & 3 respectively. Only the data in Fig. 2 control the interpreted polarity boundaries. Palaeomagnetic and biostratigraphic characteristics of the data are described below.

Fundamental data

South Siberian Platform, USSR

Magnetostratigraphic results reported by Khramov *et al.* (1965) and Rodionov (1966) from the Siberian platform can be correlated with British stratigraphic series (Chugaeva 1976, pp. 286–7.; Moskalenko 1983). Five intervals of normal polarity and six of reverse polarity have been identified within the Ordovician period (Fig. 2). These polarity intervals are reproducible on a regional scale across the platform. Breaks within the Siberian sections are evident for parts of the Tremadoc, the entire Llanvirn series and for segments of the Llandeilo.

Our polarity scale for the Siberian data differs from that presented by Khramov & Rodionov (1980) due to differing correlations between Siberian stages and European series. There may also be some errors incurred in the precise correlation of the broad stages used by Khramov & Rodionov (1980). The most significant difference is the Llanvirn hiatus, which is evident on the Siberian platform and in some adjacent areas (Chugaeva 1976).

The fidelity of the Siberian palaeomagnetic record is also a matter of some concern, and one might question whether the limited magnetic cleaning employed in the 1960s is sufficient to correctly identify the reversal history. For example, samples listed by Rodionov (1966) were heated to only 100 °C or subjected to alternating field treatments of <100 Oersted. Furthermore, there is a notable asymmetry in the directions shown by Rodionov (1966, figs 2 & 3). Nevertheless, the dual polarity nature of the field as recorded by the sediments is clearly evident, and the resulting pole positions do not resemble those of a younger period (see Torsvik *et al.* 1990*b*, fig. 7a). We therefore consider that demagnetization was at least sufficient to delineate the relative polarity of the ancient field.

Västergötland, southern Sweden

A stratigraphically-related sequence of polarity intervals has been described from Ordovician carbonates of Llanvirn to Caradoc age from Gullhögen Quarry, Västergötland (Torsvik & Trench 1991*a*). The reversal stratigraphy is reproducible on both local and regional scales when compared with data reported by Claesson (1977). A total of three normal, and three reverse polarity intervals have been identified. Biostratigraphic age constraints on the various formations are listed by Holmer (1989) and Torsvik & Trench (1991*a*). Stratigraphic breaks within the Gullhögen succession occurred in the mid- and upper Llanvirn and lower Llandeilo series (Holmer 1989).

Extensive sampling of the Orthoceras Limestone facies (Arenig–early Llanvirn) of the Swedish platform has thus far produced only reversely polarized magnetizations (Claesson 1977, 1978; Torsvik & Trench 1990; Perroud *et al.* 1990). These studies have yet to include the sampling of a continuous vertical section however.

Supplemental data

Although they do not display stratigraphically-related reversals, polarity data from Longvillian (middle Caradoc) equivalents of the Snowdon volcanic rocks, Lleyn Peninsula, Wales, are important in the construction of the time-scale as they help to constrain the N–R transition observed within the Dolbor stage on the Siberian Platform. They are therefore included in Fig. 2. Similarly, palaeomagnetic data from the Dunn Point, Juniata and Sequatchie Formations are also shown in Fig. 2 as there is no single continuous magnetostratigraphic section available for Ashgill times. Supplemental data are described in stratigraphic order below and are shown in Fig. 3.

Treffgarne Volcanic Formation, South Wales

Andesitic volcanic rocks and volcaniclastic sediments of the Treffgarne Volcanic Formation display an exclusively

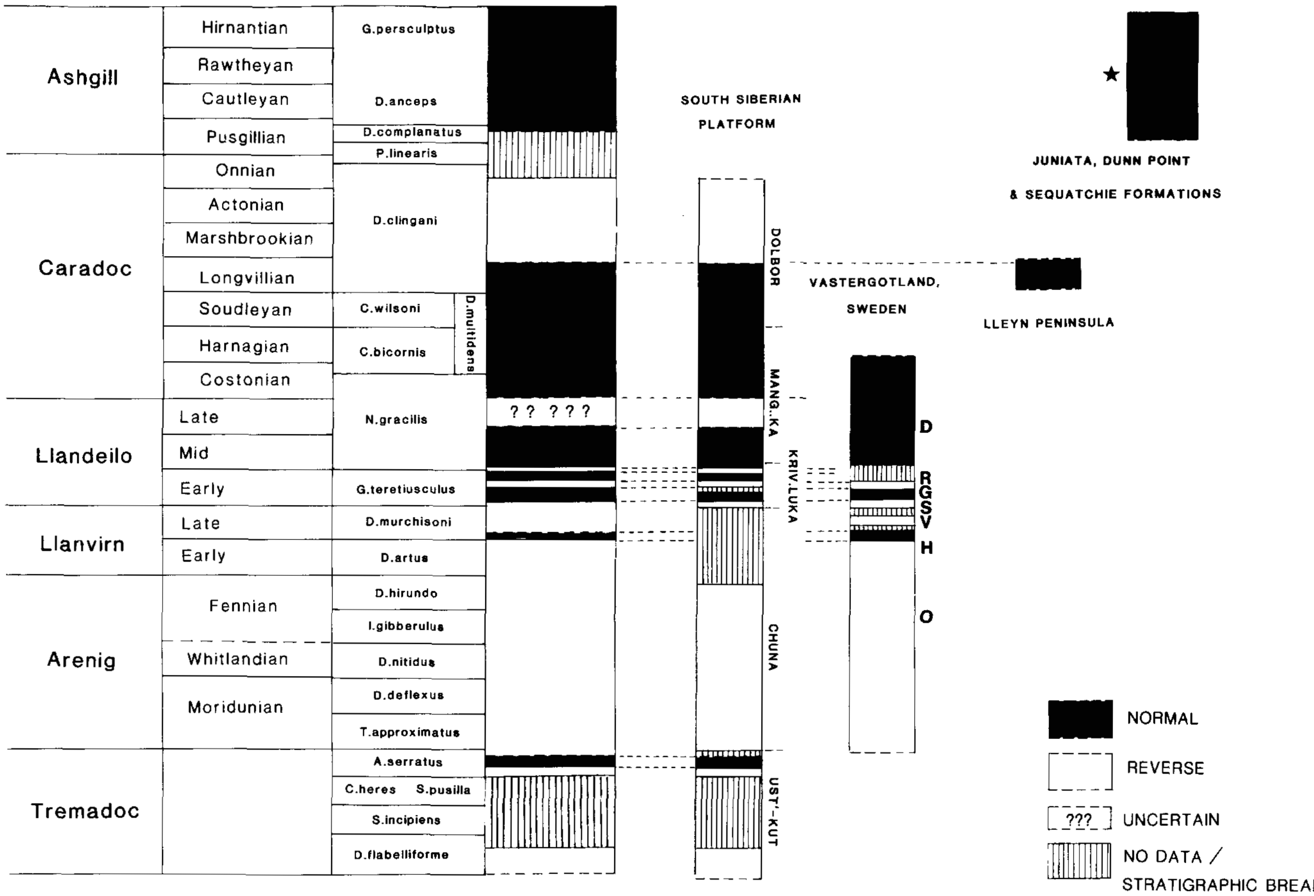

Fig. 2. Magnetostratigraphic correlation of fundamental datasets from Siberia and Sweden. Data from the Lleyn Peninsula, Wales, and the Juniata, Dunn Point and Sequatchie Formations are also included as they further constrain the composite magnetostratigraphy. (★) The inferred polarity for Ashgill time is based on normally polarized palaeomagnetic data from the Dunn Point, Juniata and Sequatchie Formations. If postulated reversely magnetized sites within the Juniata and Sequatchie Formations are truly distinguishable from Alleghenian remagnetizations, then a short period (or periods) of reverse polarity may exist within the Ashgill.

Left-hand columns refer to stratigraphic elements of the Ordovician Period. Faunal sub-divisions are European zones. Sub-divisions of the Arenig series are taken from Fortey & Owens (1987). Siberian stages are indicated next to the appropriate column. Swedish Formations (lettered) from Torsvik & Trench (1991*a*) are as follows: D, Dalby Limestone; R, Ryd Limestone; G, Gullhögen Limestone; S, Skövde Limestone; V, Våmb Limestone; H, Holen Limestone; O, Orthoceras Limestone.

reverse polarity magnetization. A primary magnetic age is established through a positive conglomerate test on an intra-formational conglomeratic facies (Torsvik & Trench 1991*b*). The formation is of late Tremadoc or early Arenig age, and has been suggested as correlative with the late Tremadoc Rhobell Volcanic Group (Traynor 1988). The latter volcanic rocks cut late Tremadoc sediments of the *S. pusilla* Zone and may be as young as the *A. sedwickii* Zone (Kokelaar *et al.* 1982).

Slockenray Formation, Ballantrae Complex, SW Scotland

Pillowed and sheet basalt flows, cherts, mudstones and lithic arenites of the Slockenray Formation display a reverse polarity magnetization (Trench *et al.* 1988, 1990). Arenig graptolites from shales at the base of the Formation are attributed to the *deflexus* Zone (Stone & Smellie 1988). A pre-Llandeilo magnetic age is established by a positive conglomerate test on basalt clasts from the overlying Benan conglomerate (Trench *et al.* 1988). Although the characteristic magnetization fails an intra-formational conglomerate test, it predates obduction-related deformation. The Slockenray section is therefore interpreted to have been magnetized during, or soon after, its formation within an intra-oceanic setting.

Moulin de Chateaupanne Formation, Armorican Massif, France

A steep downward-dipping, reverse-polarity remanence within redbeds of the Moulin de Chateaupanne Formation is interpreted as Ordovician in age by Perroud *et al.* (1986). This interpretation is based on a directional similarity with a suggested primary magnetization from the Ordovician Thouars Gabbro (Perroud & Van der Voo 1985). Brachiopods and conodonts from the Moulin de Chateaupanne Formation indicate an Arenig depositional age, most

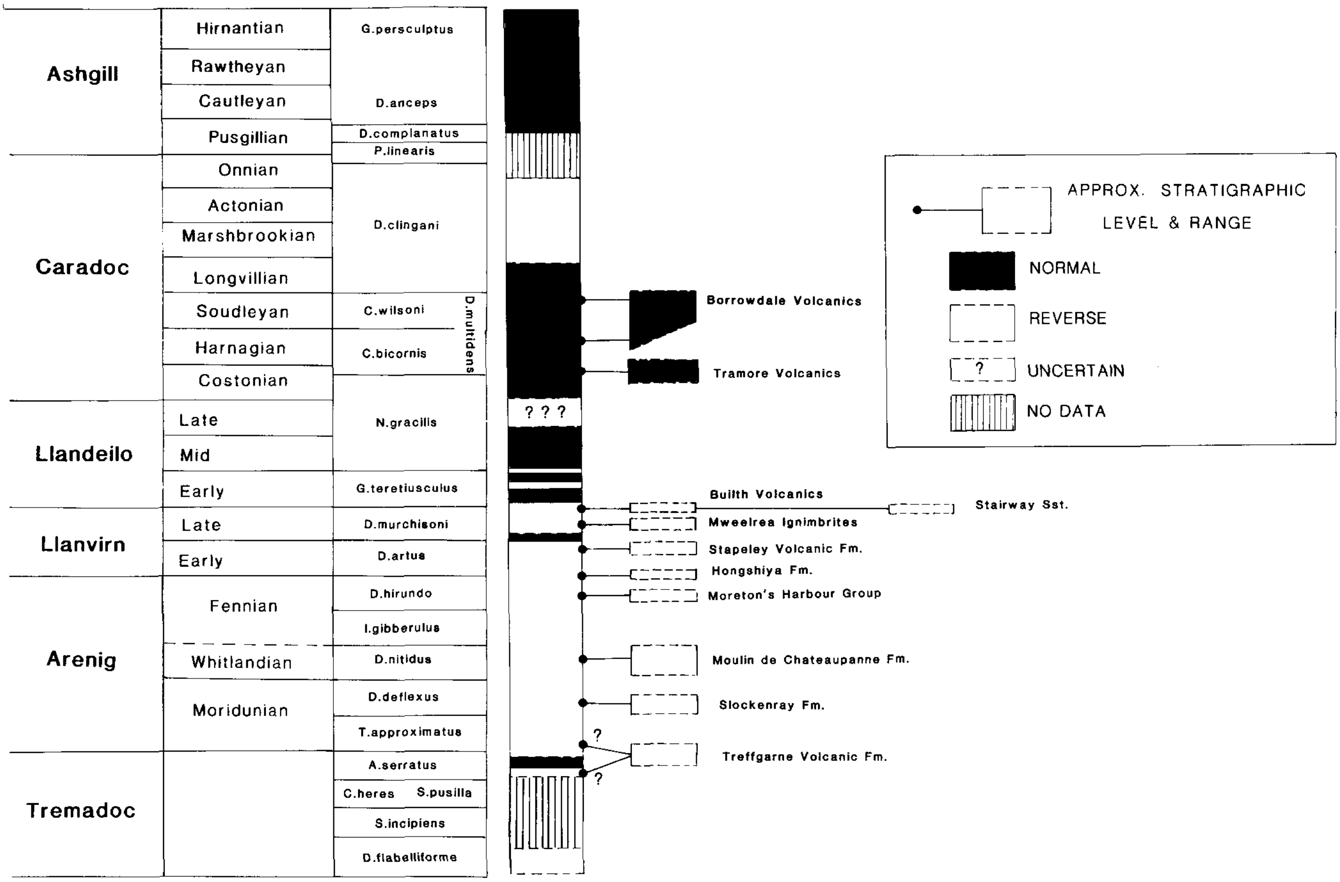

Fig. 3. Composite Ordovician magnetostratigraphy from Fig. 2 with the addition of supplemental datasets. Individual studies are referred to in the text.

probably within the *D. nitidus* Zone. A micro-conglomerate test suggests the natural remanent magnetization (NRM) is of chemical (CRM) rather than detrital origin however (Perroud *et al.* 1986) and may therefore record early diagenesis. Cogne (1988) obtained similar reverse polarity results from the Pont Rean Formation, a suggested correlative of the Moulin de Chateaupanne Formation.

Moreton's Harbour Group, Newfoundland

Johnson *et al.* (1991) report reversely magnetized lava flows (16 sites) from the upper section of the Moreton's Harbour Group within the Notra Dame Bay subzone of the Central Mobile Belt, Newfoundland. These lavas are cut by a dyke and sill which display a later normal polarity. A primary magnetic age is sustained by evidence from a contact test (sill versus surrounding lava), a fold test, and through the demonstration of block rotations related to local sub-vertical axes.

Probable correlatives of the Moreton's Harbour Group have yielded a Lower Ordovician fauna attributed to the *D. hirundo* Zone (Arnott *et al.* 1985; Dean 1978).

Hongshiya Formation, South China Block

Fang *et al.* (1990) report a stable characteristic magnetization from five sites of the Hongshiya Formation, South China. The characteristic magnetization (C component) is inferred to be reversely polarized when comparisons with the biogeographical distribution of the trilobite *Neseuretus* are made (Fortey & Morris 1982). Although the component passes a fold test at the 95% confidence level, this has little direct significance in that the folding is of Tertiary age. The component is interpreted to be primary on the basis that the resulting pole does not resemble that of any younger period on the apparent polar wander path for South China.

The presence of the trilobites *Taihungshania miqueli* (*Bergeron*) and *T. brevica Sun* (Fang *et al.* 1990) indicates a late Arenig to early Llanvirn depositional age (R. A. Fortey pers. comm. 1990).

Stapeley Volcanic Formation, Shelve Inlier, mid-Wales

Eleven palaeomagnetic sites within the Lower Tuff and Shale Member of the Stapeley Volcanic Formation were found to carry a stable, reversely polarized, characteristic magnetization (McCabe & Channell 1990). The formation is established as early Llanvirn (*D. artus* Zone) on faunal grounds (Williams *et al.* 1972). The characteristic magnetization passes a fold test with respect to Ashgill folding (Woodcock 1990) at the 99% confidence level. Although McCabe & Channell initially favoured a pre-Ashgill remagnetization event, a comparison with the Builth Inlier favours a primary, in this case early Llanvirn, magnetization age (Trench & Torsvik, 1991a, b; McCabe & Channell 1991).

Mweelrea Ignimbrites, South Mayo Trough, Ireland

Deutsch & Somayajulu (1970) obtained an exclusively reverse polarity remanence from ignimbrites within the lower parts of the Mweelrea Formation, western Ireland (Dewey 1963). These data were subsequently confirmed by Morris *et al.* (1973). The magnetization passes a fold test and therefore predates the Mweelrea syncline which most likely formed in *N. gracilis* Zone times (Dewey & Ryan 1990). A positive conglomerate test further indicates the magnetization to be primary (Murthy & Deutsch 1971). Faunal evidence places the lower parts of the Mweelrea Formation in the *D. murchisoni* Zone (Dewey *et al.* 1970; Dewey & Ryan 1990), and the ignimbrites therefore date from the earlier part of the zone.

Llanelwedd volcanic rocks, Builth Inlier, mid-Wales

Basalts and keratophyres from the south end of the Builth Inlier show an exclusively reverse polarity of their original magnetization. A primary magnetic age is established by positive agglomerate and conglomerate tests within the volcanic succession (Briden & Mullan 1984, Trench *et al.* 1991; McCabe & Channell 1991). The volcanic rocks directly overlie Lower *D. murchisoni* shales and are succeeded by *G. teretiusculus* shales (Jones & Pugh 1941; 1949; Williams *et al.* 1972; Institute of Geological Sciences 1977).

Stairway Sandstone, Amadeus Basin, Australia

Embleton (1972) obtained a westerly-directed magnetization, oblique to the present geomagnetic field, in nine samples from the Stairway Sandstone of the Amadeus Basin, central Australia. The direction of natural remanant magnetization remained stable during stepwise-thermal demagnetization to 650 °C. The palaeomagnetic pole (2.0°S, 50.5°E) is a south pole in a conventional Gondwana reconstruction (Fig. 1). Palaeontological and stratigraphic evidence favours a late Llanvirn depositional age (see Webby 1978, fig. 5 & p. 52).

Tramore volanic rocks, SE Ireland

Deutsch (1980) reported polarity data from 16 sites (6 Reverse, 10 Normal) within andesitic volcanic rocks of the Tramore Volcanic Formation. The six lowermost sites, which display reverse polarity, are from andesitic sills (Schiener 1974) into sediments containing a *D. murchisoni/G. teretiusculus* Zone fauna (Carlisle 1979). As we have omitted data from intrusive rocks (see section on unconstrained data), these lower sites are not incorporated in Fig. 3. The ten normal-polarity sites incorporate andesite flows stratigraphically straddling a limestone facies containing *N. gracilis* Zone fauna (Carlisle 1979). The dual polarity magnetization passes a fold test (determined using an *F*-ratio method, Larochelle 1967) substantiating a pre-'Caledonian' remanence age (Deutsch 1980).

Borrowdale Volcanic Group, English Lake District

Palaeomagnetic data from twenty-seven sites of the Borrowdale Volcanic Group exhibit normal polarity following tilt correction (Faller *et al.* 1977). Biostratigraphic considerations indicate that eruption most likely occurred between end-Llandeilo and early Caradoc times. The volcanic rocks were then uplifted prior to deposition of the Coniston Limestone Group which began in Actonian (late Caradoc) times. The site-means are significantly better grouped after structural correction indicating a pre-Actonian magnetization age (Faller *et al.* 1977).

Llanbedrog and Mynytho Volcanic Groups, Lleyn Peninsula, North Wales

Thomas (1976) obtained normal polarity magnetizations from 13 sites within acid and intermediate volcanic rocks of the Lleyn syncline, North Wales. The volcanic rocks were erupted within the Longvillian stage of the Caradoc series (Williams *et al.* 1972). The magnetization passes a fold test at the 99% confidence level (McElhinny 1964) indicating a pre-Acadian magnetic age (Woodcock *et al.* 1988; McKerrow 1988). A single reverse-polarity site was rejected by Thomas (1976) on the grounds of structural complexity. This reverse polarity site has therefore not been considered in our analysis.

Juniata Formation, Central Appalachians, USA

A palaeomagnetic reinvestigation of the Juniata Formation around the Pennsylvania salient has identified a pre-deformational component of exclusively normal polarity at 13 separate sites (Miller & Kent 1989). A previously reported reverse magnetization (Van der Voo & French 1977) is interpreted as a syn-tectonic overprint related to Alleghenian deformation. This explanation may not explain all reverse polarity sites however and the presence of a short reverse-polarity interval cannot be discounted (e.g. site 1 of Van der Voo & French, see discussion by Miller & Kent). Although the stratigraphic age of the Juniata Formation can be established as Ashgill (probably *D. complanatus* Zone and certainly *D. anceps* Zone; Dennison 1976), the magnetic age of the pre-folding component is only constrained as pre-Alleghenian/Kiaman. For our present purposes, we tentatively assign a magnetization age equivalent to the Juniata stratigraphic age.

Sequatchie Formation, NW Georgia, USA

Morrison (1983) reports a possible reversal stratigraphy within sediments of the Late Ordovician Sequatchie Formation exposed at Ringgold Gap, NW Georgia. The Sequatchie Formation forms a tectonostratigraphic equivalent to the Juniata Formation (see Dennison 1976). Both magnetite and hematite remanence carriers were identified from blocking temperature analyses. In summarizing the data, Morrison & Ellwood (1986) postulate two zones of normal polarity (sites 16–17, & 19–21) and two of reverse polarity (site 18 & 22–24) within the Sequatchie sediments. Similar to the Juniata Formation; however, doubts exist as to whether the reverse polarity data may reflect a magnetization of Alleghenian age. This uncertainty is noted in Fig. 2.

Rindsberg & Chowns (1986) infer a ?Maysvillian to Richmondian stratigraphic age which is considered equivalent to the Ashgill series (see fig. 5 of Barnes *et al.* 1976).

Dunn Point Formation, Nova Scotia

Van der Voo & Johnson (1985) obtained a generally univectorial, normally-polarized, magnetization following stepwise-thermal treatment of lavas from the Dunn Point Formation, Nova Scotia. The magnetization passes a fold test at the 99% confidence level of McElhinny (1964); indicative of a pre-Acadian magnetization age (Boucot *et al.* 1974). The Dunn Point lavas are overlain by silicic volcanic rocks of the McGillivray Brook Formation, which are in turn overlain by the Lower Silurian Arisaig Group (Boucot *et al.* 1974). Stratigraphic constraints therefore favour Late Ordovician (Ashgill) extrusion of the Dunn Point Formation lavas.

Laterites developed between individual flows indicate a sub-aerial exposure at the time of eruption. Preferential hematization of flow-tops supports this contention. Van der Voo & Johnson (1985) infer a primary remanence residing in hematite produced through early oxidation. This conclusion is consistent with the fact that the resulting magnetization direction is unlike that of any younger rocks from the North American craton.

Unconstrained data

Datasets were classified as 'unconstrained' if either the stratigraphic or palaeomagnetic control proved inadequate. Such studies were not used to construct the magnetotstratigraphic time-scale.

In this regard, we omitted all palaeomagnetic results from intrusive rocks, as their magnetization age cannot be easily correlated with biostratigraphic zones. We also omitted all Ordovician uplift magnetizations for the same reason (e.g. Watts & Briden 1984). Results from 'syn-depositional' sills which exhibit soft-sediment deformation at their margins were also excluded. This policy removes the problem of establishing whether these intrusions are *truly* syn-depositional, or whether they represent later intrusions into sediments still to undergo de-watering. Data from 'syn-depositional' sills and dykes from the Tramore volcanic rocks (Deutsch 1980), the Breidden Hill inlier (Piper & Stearn 1975) and the Moreton's Harbour Group (Johnson *et al.* 1991) were therefore not considered.

Other datasets omitted from the time-scale are as follows.

(i) Rocks for which either the stratigraphic age is not sufficiently precise or the position of the palaeomagnetic sites within a unit is not constrained (e.g. the Graafwater, Pakhuis and Cedarburg Formations of the Table Mountain Group, Southern Africa, Bachtadse *et al.* 1987; the Tumblagooda Sandstone, Western Australia, Embleton & Giddings, 1974; the Descon Formation, Alexander terrane, Van der Voo *et al.* 1980; the Erquy spilite series, Armorica, Duff 1979; the Cliefden Caves Limestone, Malongulli Formation and Angullong Tuff, SE Australia, Goleby 1980; and the Tzahagaum Formation, Kashmir, India, Klootwijk *et al.* 1983). Palaeomagnetic data from the Eycott Volcanic Group in the English Lake district (normal polarity, Briden & Morris 1973) were omitted as its biostratigraphic age is disputed (cf. Eastwood *et al.* 1968; Downie & Soper 1972; S. G. Molyneux, pers. comm. 1991).

(ii) Rocks yielding palaeomagnetic reversals, but for which a stratigraphic-link has not been proven or is not sufficiently documented e.g. the Walli and Mount Pleasant andesites, Goleby (1980); Bays Formation, Tennessee, Watts & Van der Voo (1979); Oneota Dolomite, Minnesota/Iowa/Wisconsin, Jackson & Van der Voo (1985); Jinduckin Formation, Australia, Luck (1970).

(iii) Ordovician strata suspected as having suffered remagnetization (e.g. FengFeng, Magiagou and Yeli Formations, North China block, Lin 1984, Lin *et al.* 1985; Late Ordovician to Early Silurian platform sediments of Anticosti Island, Quebec, Seguin & Petryk 1986).

Discussion

The fundamental data from the Siberian and Swedish platform sequences are in very good agreement after the correlation between Siberian and European biostratigraphic divisions has been applied (Fig. 2, Chugaeva 1976). The sections both identify the Arenig series as of reverse polarity (A[R], Fig. 4) and indicate short intervals of both polarities in Llanvirn–Llandeilo times (L[N1]–L[N4]).

The only ambiguity occurs for late Llandeilo times (probably *N. gracilis* Zone) when the Siberian sections indicate a brief reverse polarity field (?L[R4]) whilst the Swedish limestones display only normal polarities (L[N4] and/or C[N]). Unfortunately, as the palaeomagnetic sampling level of the reversed interval is poorly constrained in the Siberian sections (mid-Mangazeika stage), we are unable to investigate the discrepancy further. It is possible that the short reverse polarity zone coincides with a hiatus on the Swedish platform. The resulting uncertainty is indicated in Figs 2–4.

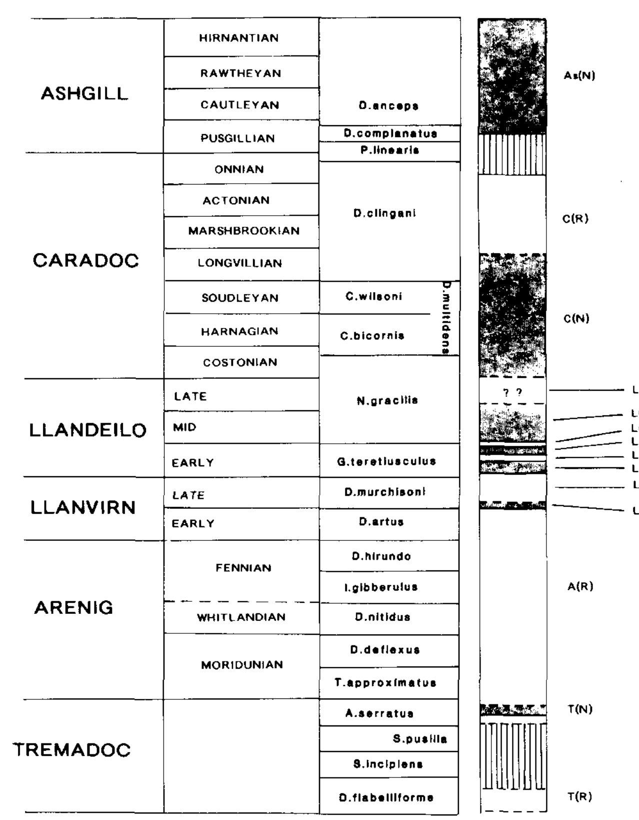

Fig. 4. Interpreted polarity-stratigraphy for the Ordovician Period. Magnetozones have been named according to the stratigraphic series in which they occur i.e. T(N), Tremadoc (Normal); A(R), Arenig (Reverse) etc. For key to polarities see Fig. 2.

The timing of the C[N] to C[R] transition identified within the Caradoc series of the Siberian platform is poorly constrained within the *D. clingani* Zone. The transition is presently indicated near the end of the Longvillian, given that the Lleyn peninsula volcanic rocks display normal polarities. Importantly, if possible reverse polarity data from Soudleyan rocks of the Breidden Hill inlier (2 sites, Piper & Stearn 1975) are confirmed, this would imply an earlier reverse polarity interval within the Caradoc.

The Ashgill series is indicated as having normal polarity based on reliable data from the Juniata and Dunn Point Formations. Possible reverse polarities recorded within the Juniata Formation (Van der Voo & French 1977) and Sequatchie Formation (Morrison 1983; Morrison & Ellwood 1986) are difficult to discriminate from possible Alleghenian remagnetization effects. Given the fact that no continuous section is available, we regard the Ashgill series as the weakest part of the currently defined scale.

Within the compiled data, we have found no evidence for an interval of anomalous field behaviour during Late Ordovician times as proposed by Thomas & Briden (1976).

Conclusions

We present a preliminary polarity time-scale for the Ordovician period constructed on the basis of existing global palaeomagnetic data (Fig. 4). Normal and reverse polarity intervals have been named according to the series in which they occur. The time-scale is primarily based on a correlation of Ordovician sections from Siberia and Sweden (Fig. 2) but is supplemented by additional data from the British Isles, France, Canada, the United States, Australia and China (Fig. 3). The following characteristics of the Ordovician field are evident.

(i) All Arenig rocks have thus far yielded reversely polarized magnetizations.

(ii) Several reversals of the geomagnetic field occurred during Llanvirn–Llandeilo times.

(iii) The early part of the Caradoc series corresponds to an interval of normal polarity. The latter part of this series is characterized by a reversely-polarized field.

(iv) Ashgill rocks have yielded normal polarities to date, although short reverse polarity zones may occur which have yet to be unambiguously identified.

These conclusions imply a geomagnetic field of predominantly reverse polarity during Early Ordovician times (Tremadoc–Llanvirn), succeeded by a predominantly normal polarity field in Later Ordovician times (Llandeilo–Ashgill). The present study also succeeds in identifying areas, in both time and space, for which magnetostratigraphic information is limited and therefore the polarity time-scale is poorly defined. Future research work targeted in these areas should further our knowledge of the Ordovician field pattern.

R. Cocks, R. Fortey, S. Molyneux, D. Harper M. Dentith, S. Greensill, J. Soper, V. Bachtadse, B. Ellwood, J. Briden, G. Taylor, J. Morrison, G. Naslas, T. Chowns and G. Simpson are thanked for their prompt response to specific queries. B. Van der Pluijm provided a manuscript in the process of publication. R. Van der Voo, H. Perroud, M. Smethurst & M. McElhinny are thanked for reviews and comments. A.T. acknowledges a NERC post-doctoral Fellowship (GT5/F88/GS2). T.H.T. thanks the Norwegian Research Council for funds. Norwegian International Lithosphere Program (ILP) contribution 134.

References

Arnott, R. J., McKerrow, W. S. & Cocks, L. R. M. 1985. The tectonics and depositional history of the Ordovician and Silurian rocks of Notre Dame Bay, Newfoundland. *Canadian Journal of Earth Sciences*, **22**, 607–618.

Bachtadse, V., Van der Voo, R. & Halbich, I. W. 1987. Palaeomagnetism of the western Cape Fold belt, South Africa, and its bearing on the Palaeozoic apparent polar wander path for Gondwana. *Earth and Planetary Science Letters*, **84**, 487–499.

Barnes, C. R., Jackson, D. E. & Norford, B. S. 1976. Correlation between Canadian Ordovician zonations based on graptolites, conodonts and benthic macrofossils from key successions. *In*: Bassett, M. G. (ed.) *The Ordovician System*. Proceedings of a Palaeontological Association symposium, Birmingham, September 1974. University of Wales Press, 209–226.

Bergstrom, S. M. 1986. Biostratigraphic integration of Ordovician graptolite and conodont zones—A regional review. *In*: Hughes, C. P. & Rickards, R. B. (eds) *Palaeoecology and Biostratigraphy of Graptolites*. Geological Society, London, Special Publication, **20**, 61–79.

Briden, J. C. & Morris, W. A. 1973. Palaeomagnetic Studies in the British Caledonides—III, Igneous rocks of the Northern Lake District, England. *Geophysical Journal of the Royal Astronomical Society*, **34**, 27–46.

—— & Mullan, A. J. 1984. Superimposed Recent, Permo-Carboniferous and Ordovician palaeomagnetic remanence in the Builth Volcanic Series. *Earth and Planetary Science Letters*, **69**, 413–421.

Boucot, A. J., Dewey, J. F., Dineley, D. L., Fletcher, R., Fyson, W. K., Griffin, J. G., Hickox, C. F., McKerrow, W. S. & Ziegler, A. M. 1974. *Geology of the Arisaig area, Antigonish County, Nova Scotia*. Geological Society of America Special Paper, **139**.

Carlisle, H. 1979. The Ordovician stratigraphy and faunas of the Tramore area of Co Waterford with a revised Ordovician correlation for east and south-east Ireland. *In*: Harris, A. L., Holland, C. H. & Leake, B. E. (eds) *The Caledonides of the British Isles—reviewed*, Geological Society, London, Special Publication, **8**, 545–554.

Chugaeva, M. N. 1976. Ordovician in the North-Eastern USSR. *In*: Bassett, M. G. (ed.) *The Ordovician System*. Proceedings of a Palaeontological Association symposium, Birmingham, September 1974. University of Wales Press, 283–292.

Claesson, K. C. 1977. *Palaeomagnetic studies of Swedish Lower Palaeozoic rocks*. PhD thesis. University of Newcastle.

—— 1978. Swedish Ordovician limestones: problems in clarifying their directions of magnetization. *Physics of the Earth and Planetary Interiors*, **16**, 65–72.

Cogne, J. P. 1988. Strain, magnetic fabric and palaeomagnetism of the Pont Rean Formation, Brittany, France. *Journal of Geophysical Research*, **93**, 13673–13687.

Dean, P. L. 1978. *The volcanic stratigraphy and metallogeny of Notre Dame Bay, Newfoundland*. Memorial University of Newfoundland, Geology Report, **7**.

Dennison, J. M. Appalachian Queenston delta related to eustatic sea-level drop accompanying late Ordovician glaciation centred in Africa. *In*: Bassett, M. G. (ed.) *The Ordovician System*. Proceedings of a Palaeontological Association symposium, Birmingham, September 1974. University of Wales Press, 107–120.

Deutsch, E. R. 1980. Magnetism of the Mid-Ordovician Tramore Volcanics, SE Ireland, and the question of a wide Proto-Atlantic Ocean. *In*: McElhinny, M. W., Khramov, A. N., Ozima, M. & Valencio, D. A. (eds) *Global Reconstruction and the Geomagnetic Field during the Palaeozoic*. *Journal of Geomagnetism and Geoelectricity*, Supplement III, **32**, 77–98.

—— & Somayajulu, C. 1970. Palaeomagnetism of Ordovician ignimbrites from Killary Harbour, Eire. *Earth and Planetary Science Letters*, **7**, 337–345.

Dewey, J. F. 1963. The Lower Palaeozoic stratigraphy of central Murrisk, County Mayo, Ireland, and the evolution of the South Mayo Trough. *Quarterly Journal of the Geological Society of London*, **119**, 313–344.

—— & Ryan, P. D. 1990. The Ordovician evolution of the South Mayo Trough, western Ireland. *Tectonics*, **9**, 887–901.

——, Rickards, R. B. & Skevington, D. 1970. New light on the age of Dalradian deformation and metamorphism in western Ireland. *Norsk Geologiske Tidsskrift*, **50**, 19–44.

Downie, C. & Soper, N. J. 1972. Age of the Eycott Volcanic Group and its conformable relationship to the Skiddaw slates in the English Lake District. *Geological Magazine*, **109**, 259–268.

Duff, B. A. 1979. The palaeomagnetism of Cambro-Ordovician red beds, the Erquy spilite series and the Tregastel-Ploumanach granite complex, Armorican massif (France and the Channel Islands). *Geophysical Journal of the Royal Astronomical Society*, **59**, 345–365.

EASTWOOD, S. E., HOLLINGWORTH, M. A., ROSE, W. C. C. & TROTTER, F. M. 1968. *Geology of the country around Cockermouth and Caldbeck.* Geological Survey of Great Britain, Memoir no. **23**.

EMBLETON, B. J. 1972. The palaeomagnetism of some Palaeozoic sediments from central Australia. *Journal and Proceedings of the Royal Society of New South Wales,* **105,** 86–93.

—— & GIDDINGS, J. W. 1974. Late Precambrian and Lower Palaeozoic palaeomagnetic results from South Australia and Western Australia. *Earth and Planetary Science Letters,* **22,** 355–365.

FALLER, A. M., BRIDEN, J. C. & MORRIS, W. A. 1977. Palaeomagnetic results from the Borrowdale Volcanic Group, English Lake District. *Geophysical Journal of the Royal Astronomical Society,* **48,** 111–121.

FANG, W., VAN DER VOO, R. & LIANG, Q. 1990. Ordovician palaeomagnetism of Eastern Yunnan, China. *Geophysical Research Letters,* **17,** 953–956.

FORTEY, R. A. & MORRIS, S. T. 1982. The Ordovician trilobite Neseuretus from Saudi Arabia, and the palaeogeography of the Neseuretus fauna related to Gondwanaland in the earlier Ordovician. *Bulletin of the British Museum of Natural History,* **36,** 63–75.

—— & OWENS, R. M. 1987. The Arenig in South Wales. *Bulletin of the British Museum of Natural History,* (Geology), **41,** 69–307.

GOLEBY, B. R. 1980. Early Palaeozoic palaeomagnetism in south east Australia. *Journal of Geomagnetism and Geoelectricity,* **32,** 11–21.

HARLAND, W. B., ARMSTRONG, R. L., COX, A. V., CRAIG, L. E., SMITH, A. G. & SMITH, D. G. 1989. *A geologic time scale.* Cambridge University Press, Cambridge.

HOLMER, L. E. 1989. Middle Ordovician phosphatic inarticulate brachiopods from Vastergotland and Dalarna, Sweden. *Fossils and Strata,* Oslo, **26,** 1–172.

Institute of Geological Sciences. 1977. *Classical areas of British Geology, Llandrindod Wells Ordovician Inlier,* 1:25 000 solid geology map.

JACKSON, M. & VAN DER VOO, R. 1985. A Lower Ordovician palaeomagnetic pole from the Oneota Dolomite, Upper Mississippi River Valley. *Journal of Geophysical Research,* **90,** 10449–10461.

JOHNSON, R. J. E., VAN DER PLUIJM, B. A. & VAN DER VOO, R. 1991., Palaeomagnetism of the Moreton's Harbour Group, Northeastern Newfoundland Appalachians: Evidence for an Early Ordovician island arc near the Laurentian margin of Iapetus. *Journal of Geophysical Research,* **96,** 11689–11702.

JONES, O. T. & PUGH, W. J. 1941. The Ordovician rocks of the Builth district. A preliminary account. *Geological Magazine,* **78,** 185–191.

—— & —— 1949. An Early Ordovician shore-line in Radnorshire, near Builth Wells. *Quarterly Journal of the Geological Society of London,* **105,** 65–99.

KHRAMOV, A. N. & RODIONOV, V. P. 1980. The geomagnetic field during Palaeozoic times. *In*: MCELHINNY, M. W., KHRAMOV, A. N., OZIMA, M. & VALENCIO, D. A. (eds). *Advances in Earth & Planetary Sciences,* **10,** Academic Publications, Tokyo, Japan, 99–116.

——, —— & KOMISSAROVA, R. A. 1965. New data on the Palaeozoic history of the geomagnetic field in the U.S.S.R. (Translated from) *Nastoyashcheye i Proshloye Magnitonogo Polia Zemli* [The present and past of the geomagnetic field] Moscow, 'Nauka' press, 206–213.

KIRSCHVINK, J. L. & ROZANOV, A. YU. 1984. Magnetostratigraphy of lower Cambrian strata from the Siberian Platform: a palaeomagnetic pole and a preliminary polarity time-scale. *Geological Magazine,* **121,** 189–203.

KLOOTWIJK, C. T., SHAH, S. K., GERGAN, J., SHARMA, M. L., TIRKEY, B. & GUPTA, B. K. 1983. A palaeomagnetic reconnaissance of Kashmir northwestern Himalaya, India. *Earth and Planetary Science Letters,* **63,** 305–324.

KOKELAAR, B. P., FITCH, F. J. & HOOKER, P. J. 1982. A new K-Ar age from uppermost Tremadoc rocks of North Wales. *Geological Magazine,* **119,** 207–211.

LAROCHELLE, A. 1967. *A re-examination of certain statistical methods in palaeomagnetism.* Geological Survey of Canada Paper, **67/18**.

LIN, J-L. 1984. *The apparent polar wander paths for the North and South China blocks.* PhD thesis, University of California, Santa Barbara.

——, FULLER, M. D. & ZHANG, W-Y. 1985. Preliminary Phanerozoic polar wander paths for the North and South China blocks. *Nature,* **313,** 444–449.

LUCK, G. R. 1970. The palaeomagnetism of some Cambrian and Ordovician sediments from the Northern Territory, Australia. *Geophysical Journal of the Royal Astronomical Society,* **20,** 31–39.

MCCABE, C. & CHANNELL, J. E. T. 1990. Palaeomagnetic results from volcanic rocks of the Shelve Inlier, Wales: evidence for a wide Late Ordovician Iapetus Ocean in Britain. *Earth and Planetary Science Letters,* **96,** 458–468.

—— & —— 1991. Reply to the Comments by A. Trench and T. H. Torsvik on: Palaeomagnetic results from volcanic rocks of the Shelve Inlier, Wales: Evidence for a wide Late Ordovician Iapetus Ocean in Britain. *Earth and Planetary Science Letters,* **104,** 540–544.

MCELHINNY, M. W. 1964. Statistical significance of the fold-test in palaeomagnetism. *Geophysical Journal of the Royal Astronomical Society,* **8,** 338–340.

MCKERROW, W. S. 1988. Wenlock to Givetian deformation in the British Isles and the Canadian Appalachians. *In*: HARRIS, A. L. & FETTES, D. J. (eds) *The Caledonian–Appalachian Orogen.* Geological Society, London, Special Publication, **38,** 437–448.

MILLER, J. D. & KENT, D. V. 1989. Palaeomagnetism of the Upper Ordovician Juniata Formation of the Central Appalachians revisited again. *Journal of Geophysical Research,* **94,** 1843–1849.

MORRIS, W. A., BRIDEN, J. C., PIPER, J. D. A. & SALLOMY, J. T. 1973. Palaeomagnetic studies in the British Caledonides—V Miscellaneous new data. *Geophysical Journal of the Royal Astronomical Society,* **34,** 69–105.

MORRISON, J. 1983. *Palaeomagnetism of the Silurian and Ordovician Red Mountain, Catheys and Sequatchie Formations from the Valley and Ridge Province, northwest Georgia.* MS thesis. Athens, University of Georgia.

—— & ELLWOOD, B. B. 1986. Palaeomagnetism of Silurian–Ordovician sediments from the Valley and Ridge Province, Northwest Georgia. *Geophysical Research Letters,* **13,** 189–192.

MOSKALENKO, T. A. 1983. Conodonts and biostratigraphy in the Ordovician of the Siberian Platform. *Fossils and strata,* **15,** 87–94.

MURTHY, G. S. & DEUTSCH, E. R. 1971. Further palaeomagnetic results from the Killary Harbour folded ignimbrites, Western Ireland (abs.). *Transactions of the American Geophysical Union,* **52,** 189–190.

PERROUD, H. & VAN DER VOO, R. 1985. Palaeomagnetism of the Late Ordovician Thouars Massif, Vendee, Western France. *Journal of Geophysical Research,* **90,** 4611–4625.

——, BONHOMMET, N. & THEBAULT, J. P. 1986. Palaeomagnetism of the Ordovician Moulin de Chateaupanne Formation, Vendee, western France. *Geophysical Journal of the Royal Astronomical Society,* **85,** 573–582.

——, ROBARDET, M. & BRUTON, D. L. 1990. The position of the Baltic shield during the Ordovician. *Annales Geophysicae, Special issue, XV EGS assembly, Copenhagen,* April 1990.

PIPER, J. D. A. & STEARN, J. E. F. 1975. Palaeomagnetism of the Breidden Hill (Palaeozoic) Inlier, Welsh Borderlands. *Geophysical Journal of the Royal Astronomical Society,* **43,** 1013–1016.

RINDSBERG, A. K. & CHOWNS, T. M. 1986. Ringgold Gap: Progradational sequences in the Ordovician and Silurian of northwest Georgia. *Geological Society of America Centennial Field Guide—Southeastern section,* 159–162.

RODIONOV, V. P. 1966. Dipole character of the geomagnetic field in the late Cambrian and the Ordovician in the south of the Siberian Platform. (Translated from) *Geologiya i Geofizika,* **1,** 94–101.

SCHIENER, E. J. 1974. Syndepositional small-scale intrusions in Ordovician pyroclastics, Co. Waterford, Ireland. *Journal of the Geological Society, London,* **130,** 157–161.

SEGUIN, M. K. & PETRYK, A. A. 1986. Palaeomagnetic study of the Late Ordovician—Early Silurian platform sequence of Anticosti Island, Quebec. *Canadian Journal of Earth Sciences,* **23,** 1880–1890.

SCOTESE, C. R. & MCKERROW, W. S. 1990. Revised World maps and introduction. *In*: MCKERROW, W. S. & SCOTESE, C. R. (eds) *Palaeozoic Palaeogeography and Biogeography.* Geological Society, London, Memoir, **12,** 1–21.

STONE, P. & SMELLIE, J. L. 1988. *Classical areas of British geology: the Ballantrae area: a description of the solid geology of parts of 1:25 000 sheets NX 08, 18 and 19.* HMSO for British Geological Survey, London.

THOMAS, C. 1976. *Palaeomagnetic and rock magnetic studies of the Lower Palaeozoic rocks of North Wales.* PhD thesis, Leeds University.

—— & BRIDEN, J. C. 1976. Anomalous geomagnetic field during the Late Ordovician. *Nature,* **259,** 380–382.

TORSVIK, T. H. & TRENCH, A. 1990. The Lower-Middle Ordovician palaeofield of Scandinavia; Southern Sweden 'revisited'. *Physics of the Earth and Planetary Interiors,* **65,** 283–291.

—— & —— 1991*a*. Ordovician Magnetostratigraphy: Llanvirn–Caradoc limestones of the Baltic Platform. *Geophysical Journal International,* in press.

—— & —— 1991*b*. The Ordovician history of the Iapetus Ocean in Britain: New palaeomagnetic constraints. *Journal of the Geological Society, London,* **148,** 423–425.

——, OLESON, O., RYAN, P. D. & TRENCH, A. 1990*a*. On the palaeogeography of Baltica during the Palaeozoic: new palaeomagnetic data from the Scandinavian Caledonides. *Geophysical Journal International,* **103,** 261–279.

——, SMETHURST, M. A., BRIDEN, J. C. & STURT, B. A. 1990*b*. A review of Palaeozoic palaeomagnetic data from Europe and their palaeogeographical implications. *In*: MCKERROW, W. S. & SCOTESE, C. R. (eds) *Palaeozoic Palaeogeography and Biogeography.* Geological Society, London, Memoir, **12,** 25–41.

TRAYNOR, J-J. 1988. The Arenig in South Wales: sedimentary and volcanic processes during the initiation of a marginal basin. *Geological Journal*, **23**, 275–292.

TRENCH, A. & TORSVIK, T. H. 1991*a*. Discussion of 'Palaeomagnetic results from volcanic rocks of the Shelve Inlier, Wales: evidence for a wide Late Ordovician Iapetus Ocean in Britain' by C. McCabe & J. E. T. Channell. *Earth and Planetary Science Letters*, **104**, 535–539.

—— & —— 1991*b*. A revised Palaeozoic apparent polar wander path for Southern Britain (Eastern Avalonia). *Geophysical Journal International*, **104**, 227–233.

——, BLUCK, B. J. & WATTS, D. R. 1988. Palaeomagnetic studies within the Ballantrae Ophiolite; southwest Scotland: magnetotectonic and regional tectonic implications. *Earth and Planetary Science Letters*, **90**, 431–448.

——, TORSVIK, T. H., WALDERHAUG, H. & BLUCK, B. J. 1990. Palaeomagnetic and rock magnetic reliablity criteria in ophiolitic rocks: a case study from the Palaeozoic Ballantrae Ophiolite, Scotland. *In*: VAN DER VOO, R. & SCHMIDT, P. W. (eds) *Reliability of Palaeomagnetic data. Tectonophysics*, **184**, 55–72.

——, ——, SMETHURST, M. A., WOODCOCK, N. H. & METCALFE, R. 1991. A palaeomagnetic study of the Builth Wells—Llandrindod Wells Ordovician inlier, Wales: Palaeogeographic and structural implications. *Geophysical Journal International*, **105**, 447–489.

VAN DER VOO, R. & FRENCH, R. B. 1977. Palaeomagnetism of the Late Ordovician Juniata Formation and the Remagnetization Hypothesis. *Journal of Geophysical Research*, **82**, 5796–5802.

—— & JOHNSON, R. J. E. 1985. Palaeomagnetism of the Dunn Point Formation (Nova Scotia): High palaelatitudes for the Avalon terrane in the Late Ordovician. *Geophysical Research Letters*, **12**, 337–340.

——, JONES, M., GROMME, C. S., EBERLEIN, G. D. & CHURKIN, M. Jr. 1980. Palaeozoic palaeomagnetism and northward drift of the Alexander Terrane, southeastern Alaska. *Journal of Geophysical Research*, **85**, 5281–5297.

WATTS, D. R. & BRIDEN, J. C. 1984. Palaeomagnetic signature of slow post-orogenic cooling of the northwest Highlands of Scotland recorded in the Newer Gabbros of Aberdeenshire. *Geophysical Journal of the Royal Astronomical Society*, **77**, 775–788.

—— & VAN DER VOO, R. 1979. Palaeomagnetic results from the Ordovician Moccasin Bays, and Chapman Ridge Formations of the Valley and Ridge Province, Eastern Tennessee. *Journal of Geophysical Research*, **84**, 645–655.

WEBBY, B. D. 1978. History of the Ordovician continental platform shelf margin of Australia. *Journal of the Geological Society of Australia*, **25**, 41–63.

WILLIAMS, A., STRACHAN, I., BASSETT, D. A., DEAN, W. T. & WHITTINGTON, H. B. 1972. *A correlation of Ordovician rocks in the British Isles*. Geological Society of London, Special Report **3**.

WOODCOCK, N. H. 1990. Sequence stratigraphy of the Palaeozoic Welsh Basin. *Journal of the Geological Society, London*, **147**, 537–547.

——, AWAN, M. A., JOHNSON, T. E., MACKIE, A. H. & SMITH, R. D. A. 1988. Acadian transpression in Wales during the Avalonia/Laurentia convergence. *Tectonics*, **7**, 483–495.

Received 4 February 1991; revised typescript accepted 13 July 1991