Ordovician magnetostratigraphy: a correlation of global data

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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 1991a) 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-seeking geomagnetic field coincides with the south geographic pole. The present study assumes a paleogeography 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. (1990a). 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
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-labeling.

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. 1990b, 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 1991a). 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 (1991a). 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, Llwyd 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 (1991a) are as follows: D, Dalby Limestone; R, Ryd Limestone; G, Gullhögen Limestone; S, Skövde Limestone; V, Vãmb 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 1991b). 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).

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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 sills 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).

**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 Bullth Inlier favours a primary, in this case early Llanvirn, magnetization.

**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 *Taihungshanxia 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).

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

Llanweddy 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 remanent 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 volcanic 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 intruder (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, Bachadse et al. 1987; the Tumblagooda Sandstone, Western Australia, Embleton & Giddings, 1974; the Descon Formation, Alexander terrane, Van der Voo et al. 1980; the Erquy splitite 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-Mangazelka 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.
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 Llyn 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 Alleghanian 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.


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