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The polarity of the Silurian magnetic field: indications from a global data compilation

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Abstract: Silurian palaeomagnetic data from all continents are compiled in an attempt to define the polarity history of the Earth's magnetic field during the period. Data sets from Llandovery, Ludlow, and Pridoli strata often display evidence of field reversals (i.e. the presence of both normal and reverse polarity magnetization directions) despite the fact that the palaeomagnetic sample collections may cover only a limited stratigraphic range in each case. Palaeomagnetic data from rocks of Wenlock age are exclusively of normal magnetic polarity. A comparison of the available Silurian data with published Ordovician palaeomagnetic results suggests that the frequency of magnetic field reversals increased from Ordovician to Silurian times. Palaeomagnetic data sets are not yet available from a continuous Silurian stratigraphic sequence of any great duration, so the Silurian magnetostratigraphy is still at a much more preliminary stage than that for the Ordovician. Apart from the Wenlock, all Silurian series have some intervals with frequent (<2 Ma) polarity reversals. Constant polarity (for durations in excess of 2 Ma) in the Ordovician and Silurian are only apparent during the Arenig (reverse), the early Caradoc (normal), the late Caradoc (reverse), the Ashgill (normal) and the Wenlock (normal). Data are still particularly sparse in Tremadoc and Llandovery rocks.

Magnetostratigraphy utilizes the polarity history of the Earth's magnetic field, when recorded within rocks, as a basis for geological correlation (Hailwood 1989). The distinct advantage of magnetostratigraphy over lithological and biostratigraphic correlation methods is that polarity reversals can be considered as absolute 'time-planes'. Furthermore, the transition period over which magnetic reversals occur (typically 5000 years; Prevot *et al.* 1985) can be regarded as instantaneous on a geological timescale. As a result, magnetostratigraphic studies have been widely employed for the geological correlation of disparate sections of both Cenozoic and Mesozoic rocks (e.g. Townsend & Hailwood 1985; Lowrie *et al.* 1980).

Palaeozoic examples of magnetostratigraphy are less numerous, reflecting the prevalence of complete remagnetization of sediments during orogeny (McCabe & Elmore 1989). Several magnetostratigraphic studies have met with considerable success, however, within Cambrian, Ordovician, Carboniferous and Permian stratigraphic sections (e.g. Kirschvink *et al.* 1991, Torsvik & Trench 1991; Palmer *et al.* 1985; DiVenere & Opdyke 1991; Molina-Garza *et al.* 1989). A clearer understanding of the polarity history of the Earth's magnetic field during Palaeozoic time is, therefore, gradually emerging. A recent correlation of published polarity data was attempted for the Ordovician period (Trench *et al.* 1991*a*). That investigation was able to define a generalized pattern of Ordovician reversals. The aim of the present paper is to investigate the nature and polarity of the Silurian magnetic field according to a compilation of palaeomagnetic data from Silurian rocks.

Methodology

Three levels of data quality were used by Trench *et al.* (1991*a*) when compiling magnetic polarity data for the Ordovician period. Data sets were classified as follows.

(i) Fundamental data obtained from continuous, well-controlled stratigraphic sections with a duration of several zones or stages (i.e. ≫2 Ma) and with the palaeomagnetic data displaying bedding-parallel reversals (i.e. reversals boundaries can be demonstrated to concur with stratigraphic boundaries).

(ii) Supplemental data from well-dated rocks covering a more limited stratigraphic interval (one or two zones, i.e. probably <2 Ma). In the Ordovician, the data from each interval generally display only a single magnetic polarity.

(iii) Unconstrained data, where there is either inadequate biostratigraphic control or where there is evidence that the magnetization age is not contemporary with sedimentation. Other results which could not be placed within a reliable stratigraphic framework (e.g. data from plutonic rocks) are also included in this category.

We found no data sets in the literature which can be regarded as Silurian fundamental data. Nevertheless, a number of investigations in Silurian rocks yielded strong evidence for polarity reversals, even though the palaeomagnetic sites cover only a limited stratigraphic range. Therefore, in our assessment of Silurian results, we chose to sub-divide the supplemental data sets between two groups; those which have mixed magnetic polarity, and those with a single magnetic polarity.

Given the shortage of very well constrained Silurian magnetostratigraphic records, we must also consider whether data which fall into our 'supplemental' category can provide useful information on the polarity history of the Earth's magnetic field. As

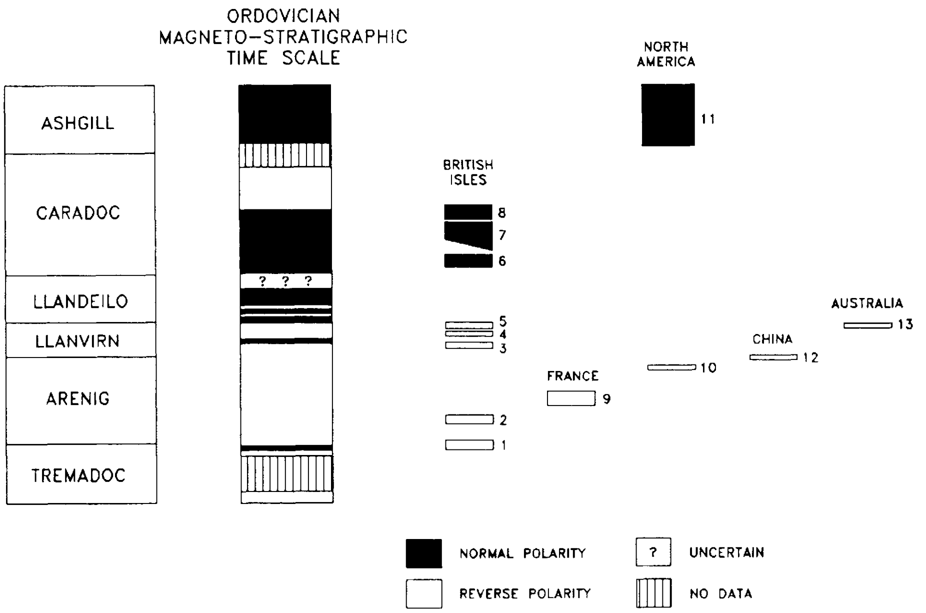

Fig. 1. Comparison of Ordovician supplemental magnetic polarity data with the polarity scale defined by the fundamental data. Note that the dominance of reverse polarity in the Early Ordovician and normal polarity in the Late Ordovician can be seen from the supplemental data alone. Listed Ordovician data are as follows: 1, Treffgarne Volcanics, SW Wales (Trench *et al.* 1992*a*); 2, Slockenray Formation, SW Scotland (Trench *et al.* 1988); 3, Shelve volcanics, Wales (McCabe & Channell 1990); 4, Mweelrea Formation, Ireland (Morris *et al.* 1973); 5, Builth Volcanics, Wales (Trench *et al.* 1991*b*); 6, Tramore Volcanics, Ireland (Deutsch 1980); 7, Borrowdale Volcanics, England (Faller *et al.* 1977); 8, Llanbedrog and Mynytho Volcanic Groups, Lleyn Peninsula, North Wales (Thomas 1976); 9, Moulin de Chateaupanne Formation, France (Pęrroud *et al.* 1986); 10, Moreton's Harbour Group, Canada (Johnson *et al.* 1991); 11, Juniata and Dunn Point Formations (Miller & Kent 1989; Van der Voo & Johnson 1985); 12, Hongshiya Formation, South China (Fang *et al.* 1990); 13, Stairway Sandstone, Australia (Embleton 1972).

an example, we compare Ordovician supplemental data with the composite magnetostratigraphy determined from Ordovician fundamental data (Fig. 1). Although the details of the polarity history are obscured, one can still draw useful conclusions from the supplemental data alone:

(i) Tremadoc–Llanvirn times were dominated by a reverse polarity field;
(ii) Llandeilo–Ashgill times were dominated by a normal polarity field;
(iii) the reversal frequency in Ordovician times was relatively low as few studies show evidence of both polarities.

From this analysis, we conclude that the Silurian polarity data should record at least the generalized pattern of the Silurian magnetic field and that useful inferences can be drawn from the collective data.

Stratigraphic assignments within the Silurian period have been made on the basis of local biostratigraphic evidence pertaining to each study area. The time-calibration of our polarity observations is therefore limited by these constraints. Our omission of data constrained solely by isotopic dating renders the polarity interpretation independent of the various absolute time-scales for the Lower Palaeozoic (e.g. McKerrow *et al.* 1985; Harland *et al.* 1990). Formal magnetostratigraphic nomenclature (Hailwood 1989) has not been employed at this preliminary stage. Informal names have therefore been used for the polarity intervals depending on the epoch in which they occur e.g Ludlow/Pridoli 'mixed' polarity interval etc.

Palaeomagnetic polarities were assigned according to reference apparent polar wander paths (APWPs) for the various palaeocontinents. Pole positions from the respective APWPs yield a Silurian palaeogeography as in Fig. 2 (also see Li *et al.* 1992).

Calibration of Silurian palaeomagnetic data using biostratigraphically-constrained rock-ages carries the assumption that 'magnetization-age' and 'rock-age' coincide. This relationship can be particularly difficult to demonstrate and has been the focus of considerable attention in sedimentary palaeomagnetism (e.g. Lovlie *et al.* 1984). Several of the poles considered here to represent a 'near-primary' remanence might equally be contended to represent later remagnetization events therefore (e.g. Schmidt *et al.* 1987 for the SE Australian poles). Unequivocal evidence for a primary remanence can be established using either a positive slump-fold test or an intra-formational conglomerate test (e.g. Schmidt *et al.* 1991; Trench *et al.* 1992*a*). We note, however, that it is only occasionally possible to apply either test.

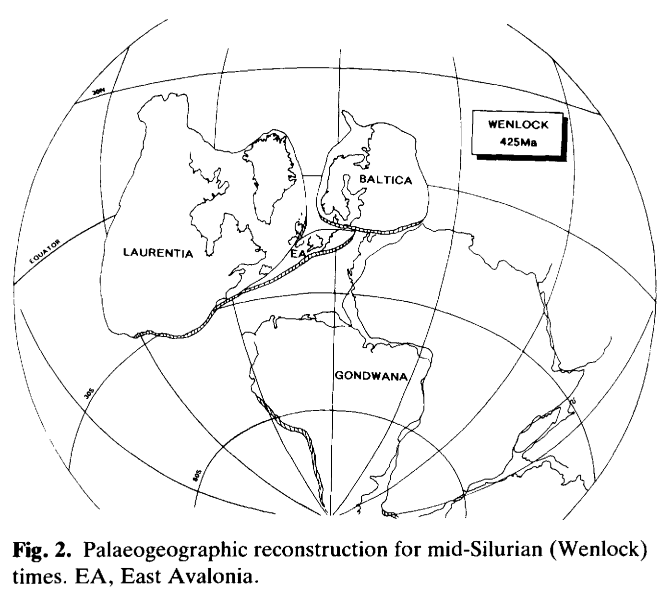

Fig. 2. Palaeogeographic reconstruction for mid-Silurian (Wenlock) times. EA, East Avalonia.

Silurian Palaeomagnetic Data

Essential palaeomagnetic and stratigraphic details of each of the Silurian data sets displaying single and mixed polarity are recounted below. The stratigraphic positions of Silurian palaeomagnetic data are shown in Fig. 3. Data sets within each category are discussed in order of decreasing number of palaeomagnetic sampling sites.

Data sets of single magnetic polarity

(i) Western Ireland sediments, Galway and Mayo, Eire. Smethurst & Briden (1988) describe multicomponent magnetizations from 39 palaeomagnetic sites within Late Silurian sediments of northwest Galway (Salrock Formation) and South Mayo (Clare Island succession), western Ireland. A Silurian magnetization revealed by detailed stepwise-thermal demagnetization predates late-Caledonian deformation of both areas. The Silurian component, termed H, displays an exclusively normal polarity within all sites yielding stable directions. Unpublished data from the latest Llandovery Lough Mask Formation also display normal polarity (M. A. Smethurst pers. comm. 1992; stratigraphic age after Graham *et al.* 1989).

A Wenlock age is probable for the Salrock Formation (Laird & McKerrow 1970). The Clare Island Silurian rocks are probably Wenlock or Ludlow in age (Palmer *et al.* 1989) and may be contemporaneous with the Salrock Formation (Phillips 1974; Smethurst & Briden 1988).

(ii) Andesitic lavas, East Mendips Inlier, SW England. Piper (1975) reported initial palaeomagnetic results from four sites within andesitic lavas of the East Mendips Silurian inlier. All samples were subjected to blanket alternating-field demagnetization to peak fields of 50–100 mT. Following tectonic correction, the lower two sites were regarded as of reverse polarity whilst the upper two sites were of normal polarity. In resampling the sequence (15 sites, 2 in agglomerates), Torsvik *et al.* (1993) identified two stable magnetization components during stepwise thermal demagnetization. These magnetizations were attributed Permo–Carboniferous and Silurian remanence ages respectively. A positive intra-formational palaeomagnetic agglomerate test confirms the primary nature of the Silurian magnetization. Only normal-polarity Silurian magnetizations were identified. The previous 'reverse' polarity sites of Piper (1975) are interpreted by Torsvik *et al.* (1993) as being Permo–Carboniferous overprints which had been erroneously corrected for tectonic dip.

The interpretation of Hancock (1982) suggests that the volcanics (in Moon's Hill Quarry) all young to the north and are underlain by lower Wenlock shales (*M. riccartonensis* Zone) with probable conformity: they are thus now considered to be Wenlock in age.

(iii) Ainslie Volcanics, Australian Capital Territory, Australia. Seven palaeomagnetic sites from the Ainslie volcanics yielded stable magnetizations of normal magnetic polarity (Luck 1973). The sample collection spanned approximately 170 m of a 210-thick sequence of interbedded acid to intermediate flows and pyroclastic rocks. The rock succession is 'mostly sub-horizontal' (Luck 1973). Samples were demagnetized to peak fields/temperatures of 50 mT/550 °C. Although originally attributed to the Early

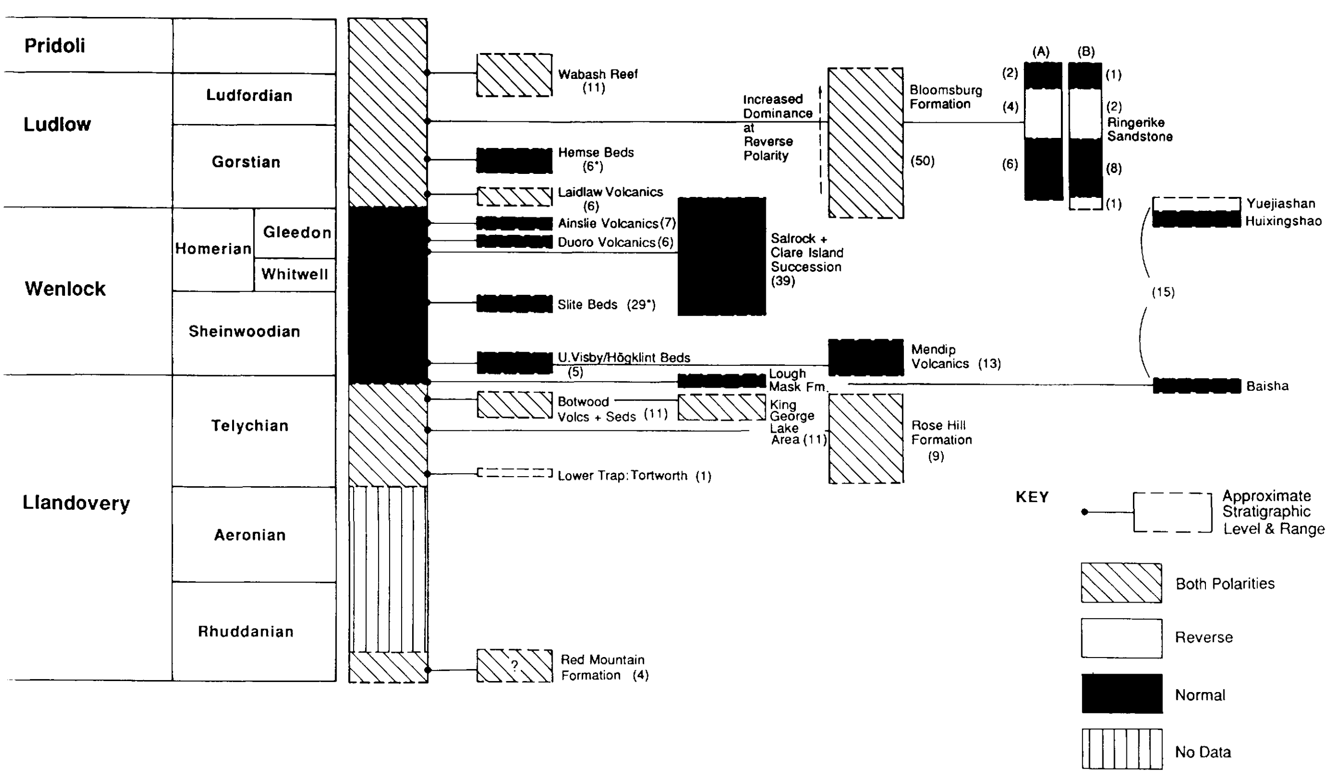

Fig. 3 Magnetic polarity data for the Silurian Period. Individual datasets are discussed in the text. Stratigraphic divisions taken from Harland *et al.* (1990). Numbers in brackets next to each data set indicate the number of palaeomagnetic sample sites; (those with asterisks refer to numbers of samples). Black, normal polarity; hatched, mixed polarity.

Devonian (Opik 1958), the volcanics have been re-assigned a Late Wenlock age based upon a revised stratigraphic correlation (Owen, in Goleby 1980; Walley *et al.* 1990).

(*iv*) *Douro volcanics, Yass district, New South Wales, Australia.* Luck (1973) reports results from six palaeomagnetic sites of the Duoro volcanics following alternating-field demagnetization to peak fields of 50 mT. All six sites, which are spread over an area of approximately 25 km^2, display a normal polarity magnetization. Stratigraphic considerations suggest a Wenlock age for the Duoro volcanics (Packham 1969) based upon graptolite faunas (Browne 1954). An earliest Ludlow age is attributed to the overlying Yass Sub-Group (Link 1970; Link & Druce 1972) based upon an abundant conodont assemblage in the Cliftonwood Limestone. Luck (1973) also reports a single normal-polarity site from the Hawkins volcanics of Late Wenlock age (Owen & Wyborn 1979) in the Yass area.

(*v*) *Upper Visby/Höglint Beds, Gotland, SE Sweden.* Five palaeomagnetic sample sites (49 samples) within flat-lying muddy limestones of the Upper Visby/Höglint beds, Gotland, carry a characteristic remanence of normal polarity (Trench & Torsvik 1991). A conglomerate test failed to yield stable directions of magnetization. The characteristic magnetization unblocks between 250–400 °C/10–35 mT and is carried by magnetite. Although no palaeomagnetic field test is available, extremely low conodont alteration indices (1–1.5; R.J. Aldridge pers. comm.) suggest that viscothermal remagnetization of the limestones is unlikely to have taken place. Conodonts in the limestones indicate an Early Wenlock age (Lower Sheinwoodian; Jeppsson 1983).

(*vi*) *Hemse and Slite Beds, Gotland, SE Sweden.* Following an extensive sampling of Gotland limestones (84 sites), Claesson (1979) obtained stable, normal polarity magnetizations, from only 35 palaeomagnetic specimens. Of these, 29 were recovered from the Slite beds and six from the Hemse beds. As noted above, remagnetization is considered unlikely based upon low conodont alteration indices. The stratigraphic age of these units is constrained to Lower Wenlock (Upper Sheinwoodian) and Lower Ludlow (Eltonian–Leintwardinian) respectively (Jeppsson 1983).

(*vii*) *Lower Trap lava, Tortworth inlier, SW England.* Piper (1975) reports a single reverse polarity site (9 samples) from the Lower Trap lava at the base of the Damery Beds of the Tortworth inlier, Gloucestershire (Curtis 1972). Samples were demagnetized to peak alternating-fields between 50 and 100 mT. An Upper Llandovery (Telychian) age is attributed to the lava based on fauna from the overlying sediments (Curtis 1972; Zeigler *et al.* 1974).

Data sets of mixed magnetic polarity.

(*i*) *Bloomsburg Formation, Central Appalachians, USA.* Four palaeomagnetic investigations of the Bloomsburg redbeds have been published to date; namely by Irving & Opdyke (1965), Roy *et al.* (1967), Kent (1988) and Stamatakos & Kodama (1991). We consider the results of the latter two investigations here as contemporary demagnetization procedures were applied in these studies.

Kent (1988) identifies a possible Silurian remanence (component C) from the effects of Alleghenian remagnetization at 17 sites around the Pennsylvania salient. The statistical precision of this component peaked at approximately 80% unfolding. Stamatakos & Kodama (1991) explain this 'syn-deformational' peak as resulting from the grain-scale deformation of a pre-folding remanence. A primary remanence-age can therefore be contended for the Bloomsburg Formation. In Kent's (1988) study, all eight sites from the northern limb of the Pennsylvania salient yield consistent normal polarities of component C. Conversely, all but two of the nine sites to the south of the salient display reverse polarity. A similar trend is observed in the data of Stamatakos & Kodama (1991) in that only normal polarities occur on the northern limb of the salient (Delaware Water Gap and Montour Ridge localities) but both polarities are evident in the south (Round Top locality). These differences are likely to result from diachroneity in the Bloomsburg Formation.

Palaeontological evidence favours a Latest Wenlock to Early Přídolí stratigraphic range for the Bloomsburg Formation of south Pennsylvania (Berry & Boucot 1970).

(*ii*) *Ringerike Group, Oslo region, Southern Norway.* Douglass (1988) reports multicomponent palaeomagnetic data from two stratigraphic sections (A & B) of the Ringerike Sandstones in the Oslo area of Norway. Conodont Alteration Indices of 3–4 (Aldridge pers. comm.) suggest palaeotemperatures in the order of 110–300 °C (Epstein *et al.* 1977). These temperatures are linked to a partial remagnetization of Permo-Carboniferous age which fails a fold test in the area. Principal deformation is most likely Early Devonian in age (Ramberg & Spjeldnaes 1978). A dual-polarity, high-temperature magnetization passes a fold test at the 95% confidence level. The high-temperature magnetization unblocks above the Curie point of magnetite and is thought to reside in specular hematite (described by Turner 1974). Bedding-parallel reversals are observed in both sections. In section A, the magnetostratigraphy (base to top) is Normal (6 sites)–Reverse (4 sites)–Normal (2 sites). In section B, the sequence is Reverse (1 site)–Normal (8 sites)–Reverse (2 sites)–Normal (1 site). No correlation of sections A and B was attempted.

The redbeds of the Ringerike Group overlie marine sediments of the Steinsfjorden Formation. The transition from marine to non-marine lithologies is believed to occur at close to the Wenlock–Ludlow boundary (Turner & Turner 1974; Worsley *et al.* 1983).

(*iii*) *Upper Llandovery–Lower Ludlow sediments, Yangtze Platform, South China Block.* Silurian limestones and red siltstones of the Sichuan and Yunnan provinces were sampled for palaeomagnetic investigation by Opdyke *et al.* (1987). Unfortunately, only sites from redbeds provided stable magnetizations. Characteristic magnetizations predate Mesozoic deformation of the provinces. Three stratigraphic sections were studied at Songkan, Rongxi and Hongmiao. Stable magnetizations were obtained from the Baisha Formation in the Songkan section (1 site, normal polarity), the Baisha and Huixingshao Formations in the Rongxi section (12 sites, normal polarity) and from the Yuejiashan Formation in the Hongmiao section (2 sites, reverse polarity). Stratigraphic assignments of the formations are as follows (Opdyke *et al.* 1987 fig. 1; based on Lin *et al.* 1982): Baisha

Formation, Upper Llandovery; Huixingshao Formation, Upper Wenlock and Lower Ludlow; Yuejiashan Formation, Lower Ludlow. Polarities were assigned assuming the shortest possible connection of the Silurian data to the Carboniferous, Permian and Triassic apparent polar wander path for South China (Lin *et al.* 1985; Opdyke *et al.* 1986).

(iv) Wabash Formation, Indiana, USA. Eleven (of 25) palaeomagnetic sample sites collected by McCabe *et al.* (1985) from reefal limestones of the Wabash Formation yielded a stable remanence after stepwise demagnetization experiments. Alternating-field treatments were preferred to thermal demagnetization based upon better data quality. Of the stable sites, four reveal exclusively normal polarities, two exclusively reversed, and five both polarities. A palaeomagnetic tilt test, based on the present attitudes of geopetal surfaces, brings the site-mean directions into significantly better agreement.

Stratigraphic evidence suggests a Ludlow–Pridoli age for the Wabash Formation (Pinsak & Shaver 1964) based on the identification of *Kirkidium* of *K. knighti* type and *K. laqueta* type in the lower and upper parts of the formation respectively (Berry & Boucot 1970).

(v) Botwood Group, Central Mobile Belt, Newfoundland. Palaeomagnetic studies from the Botwood Group are reported by Lapointe (1979) and Gales *et al.* (1989). Both papers contend a primary magnetization age. The collective data pass a regional fold test (Siluro–Devonian deformation age) at the 99% confidence level of McElhinny (1964). The resultant pole plots on the mid-Silurian track of the North American apparent polar wander path consistent with a primary age for the magnetization. Gales *et al.* (1989) report seven sites of reverse polarity and a single normal polarity site. Three reverse polarity sites of Lapointe (1979) were also included in the later analysis.

The clastic sediments of the Botwood Group in the vicinity of Grand Falls and the Exploits River have yielded brachiopods ranging from early to latest Llandovery (Berry & Boucot 1970); the samples of Lapointe (1979) are thus likely to be of Llandovery age. The volcanic rocks on and around the Change Islands, sampled by Gales *et al.* (1989) are not precisely dated, but are probably Latest Llandovery or Earliest Wenlock (van der Pluijm *et al.* 1987, locality 90).

(vi) Redbeds and volcanics, King George IV Lake area, Newfoundland. Buchan & Hodych (1989) report palaeomagnetic results from redbeds and volcanics (rhyolite and basalt) of the King George IV Lake area of the Dunnage Zone in southwestern Newfoundland. The characteristic remanence revealed by thermal demagnetization experiments passes a fold test indicating a pre-Acadian (Devonian) magnetization-age. A positive conglomerate test further attests to a primary origin of magnetization. Ten sample sites yield normal polarity magnetizations: A single site shows reverse polarity. Stratigraphic correlatives of the redbeds of the King George IV Lake area yield early Silurian (Llandovery) fauna (Williams 1963).

(vii) Rose Hill Formation, Maryland/West Virginia, USA. French & Van der Voo (1979) obtained palaeomagnetic samples from three lithological sub-divisions of the Rose Hill Formation including the site of the classic Graham (1949) fold test i.e. Lower shales/sandstones, Cresaptown sandstone and Upper shale beds. Stepwise demagnetization experiments yield only normal magnetizations from the Lower Shales which pass a within-site fold test (Late Carboniferous–Permian folding). Red sandstones within the section are dominated by a shallow Alleghenian overprint magnetization. Previously-sampled redbeds indicate the local preservation of a normal polarity remanence however (French & Van der Voo 1977). Dolomitic sandstones of the Upper shale units reveal both remanence polarities although normal magnetizations predominate and were 'virtually the only ones used to calculate the pole position' (French & Van der Voo 1979).

Biostratigraphic constraints place the Rose Hill Formation in the Late Llandovery (Telychian; Schwartz 1923; Berry & Boucot 1970). The Upper shales are overlain by the Keefer sandstone of probable Lower Wenlock age (Berry & Boucot 1970).

(viii) Laidlaw Formation, Yass district, New South Wales. Six (of eight) palaeomagnetic sites within the Laidlaw series (subsequently redefined as the Laidlaw Formation by Pogson & Baker 1974) maintained stable directions of magnetization after cleaning to peak fields of 50 mT (Luck 1973). Of these sites, five display reverse polarity and one is of normal magnetic polarity. No palaeomagnetic field test is reported. An extensive conodont fauna place the Laidlaw Formation within the earliest Ludlow (Link 1970; Link & Druce 1972; Owen & Wyborn 1979).

(ix) Red Mountain Formation, NW Georgia, USA. Morrison (1983) reports a magnetostratigraphic traverse from Upper Ordovician units to overlying Lower Silurian sediments of the Red Mountain Formation at Ringgold Gap, NW Georgia. The Silurian data, summarized in Morrison & Ellwood (1986), comprise the uppermost four sites of the traverse (sites 25–28). Sites 25 and 26 display normal polarity (although with high within-site error) whilst sites 27 and 28 display reverse polarity. A possible influence of Alleghenian remagnetization in the section is not constrained (see Trench *et al.* 1991*a*). Stratigraphic considerations place the Red Mountain Formation within the Llandovery (Rindsberg & Chowns 1986; Berry & Boucot 1970).

Unconstrained data

Data were classified as 'unconstrained' if either biostratigraphic or palaeomagnetic information was insufficient to postulate a stratigraphic position within the Silurian Period. For example, data sets have been omitted as follows.

(i) Intrusive rocks e.g. the Beemerville alkaline complex of New Jersey (Proko & Hargraves 1973), the ring complexes of Niger, West Africa (Hargraves *et al.* 1987), syenites from NW Scotland (Turnell & Briden 1983), the Mount Peyton batholith, Newfoundland (Lapointe 1979).

(ii) Rocks for which the palaeomagnetic polarity of results can be considered equivocal e.g. Mereenie Sandstone, Amadeus Basin, Australia (Li *et al.* 1991).

(iii) Uplift magnetizations regarded as possibly Silurian in age e.g. data from the Scandinavian Caledonides (Piper *et al.* 1990).

(iv) Rocks for which either the stratigraphic age is very poorly determined or the approximate position of the palaeomagnetic sample sites are not determinable e.g.

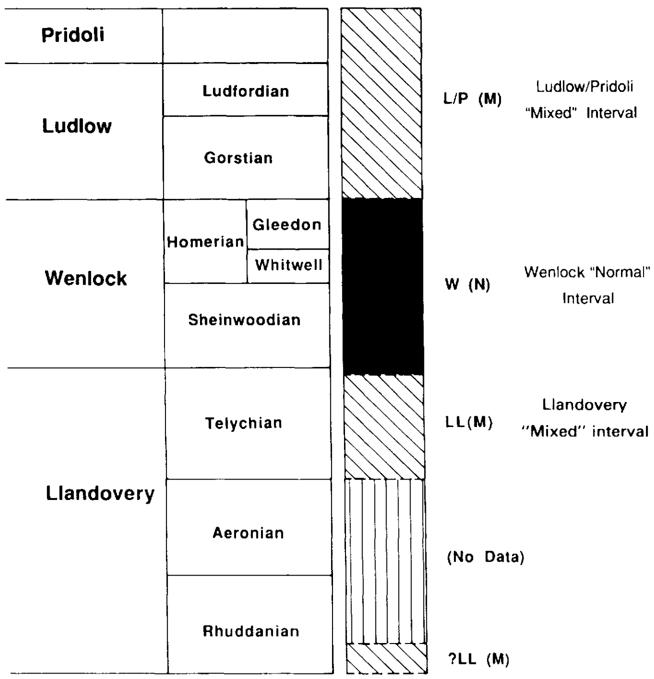

Fig. 4 Composite polarity history for Silurian times. Polarity intervals are informally named after the epochs in which they occur.

Silurian rocks from northwest Siberia (listed by Khramov *et al.* 1965), Cedarburg Shale Formation (?Late Ordovician–Early Silurian; Bachtadse *et al.* 1987), Silurian compilation poles (G2 & G3) from southeast Australia (Goleby 1980).

(v) Silurian rocks suspected as having undergone remagnetization e.g. Becscie Formation, Quebec (Seguin & Petryk 1986), Ludlow/Přídolí sediments of the Russian platform (Smethurst & Khramov 1992), Přídolí sediments from the Yangtze platform (Liu & Liang 1984).

In rejecting palaeomagnetic data from intrusive rocks, we also disregarded results from 'syn-depositional' sills exhibiting soft-sediment deformation at their margins (e.g. andesite and lamprophyre intrusions of western Ireland, Smethurst & Briden 1988). This method removes the problem of establishing whether these sills are truly syn-depositional or whether they represent later intrusions into sediments still to undergo de-watering. Indeed, there is accumulating evidence for the latter origin in many cases, given that several Ordovician–Silurian 'syn-depositional' sills show an opposite magnetic-polarity to their host sediments (see data in Deutsch 1980; Johnson *et al.* 1991, Smethurst & Briden 1988).

Discussion

Available Silurian palaeomagnetic data are unevenly distributed in stratigraphic terms (Fig. 3). Whilst the data-coverage is reasonable for the Wenlock and Ludlow epochs, relatively few data exist for either the Llandovery or Přídolí. A composite polarity history for Silurian times is shown in Fig. 4.

Data are available only for parts of the Llandovery which is regarded as the weakest section of the Silurian record. Ludlow rocks show evidence of several polarity zones i.e. Ringerike, Bloomsburg, Wabash reef, Laidlaw volcanics (Fig. 3). The epoch is therefore regarded as of mixed polarity (Fig. 4). The lack of Přídolí data can be partly overcome in that several Siluro-Devonian redbed sequences, which display dual magnetic polarity, are likely to include Přídolí rocks (e.g. the Midland Valley Lower Old Red Sandstones and lavas of central Scotland, Torsvik 1985, Lower Old Red Sandstones of the Anglo-Welsh cuvette, Channell *et al.* 1992, Andreas redbeds of Pennsylvania, Miller & Kent 1988). The existence of several reversals within the Přídolí, as indicated for the Lower Přídolí by the Wabash Reef, Ringerike and Bloomsburg results, is therefore substantiated.

The most striking feature of the compilation is that all the palaeomagnetic results from the Wenlock are of normal polarity (Fig. 3). We therefore interpret the Wenlock as of normal polarity based upon the present data (Fig. 4). The end of the Llandovery and the start of the Ludlow both mark times of high sea level stands (Johnson & McKerrow 1991); it is perhaps coincidence that these times also appear to coincide with the Wenlock episode of normal polarity, but it is possible that there is some underlying connection, which is not at present understood.

Several of the Llandovery/Ludlow/Přídolí data show a number of polarity reversals even though the palaeomagnetic sample sites cover only a limited stratigraphic interval (e.g. Wabash reef limestone, Ringerike sandstone, Rose Hill Formation). This behaviour contrasts with Ordovician supplemental data which generally show only a single magnetic polarity (Fig. 1; Trench *et al.* 1991*a*). We therefore suggest that field-reversals occurred more frequently during the *c*. 40 million years of Silurian time than during the *c*. 70 million years of the Ordovician Period.

The results of our data compilation are at variance with the polarity history proposed by Khramov & Rodionov (1980) based upon Silurian data from the Russian platform. These authors favoured a prolonged period of reverse polarity from Wenlock to Early Devonian times. In accordance with Smethurst & Khramov (1992), we interpret the apparent 'reverse' polarity data from the Russian Platform to result from pervasive Late Palaeozoic remagnetization. In general terms, our data compilation can be taken to substantiate a dominance of normal polarity in Silurian times as proposed by Irving & Pullaiah (1976).

Conclusions

We present a generalized magnetic polarity history for the Silurian period as constructed from a compilation of global palaeomagnetic data. There are as yet no data sets in the literature which can be regarded as 'fundamental' Silurian data. Data from stratigraphic sections of limited duration exist from the British Isles, Sweden, Norway, Russia, Australia, China, the United States and Canada (Fig. 3). These data are classified as 'supplemental' (after Trench *et al.* 1991*a*) and therefore provide only limited information on the Silurian field. The collective data are drawn from several palaeocontinents i.e. Laurentia, Gondwana, Baltica, South China and Avalonia (Fig. 2).

Preliminary inferences are as follows:

(i) Most of Silurian time was characterized by periods of 'mixed' polarity.

(ii) Wenlock times were mainly characterized by a magnetic field of normal polarity.

(iii) The mean reversal frequency for Silurian times appears to be much higher than that estimated for Ordovician times (1 reversal per 5 Ma; Trench *et al.* 1992b) although much more data are required before precise estimates are possible.

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