AGSO

PHANEROZOIC MAGNETOSTRATIGRAPHY: A CONTRIBUTION TO THE TIMESCALES PROJECT

BY C KLOOTWIJK (COMPILER), M IDNURM, H THEVENIAUT & A TRENCH

RECORD 1994/45

AGSO

AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

1994/45

PHANEROZOIC MAGNETOSTRATIGRAPHY:
A CONTRIBUTION TO THE TIMESCALES PROJECT

Palaeomagnetism Project 224.03

Phanerozoic Timescales Project 111.03

C.T. KLOOTWIJK[1] (Compiler), M. IDNURM[1], H. THEVENIAUT[1] and A. TRENCH[2]

[1] Australian Geological Survey Organisation, GPO Box 378, Canberra, ACT 2601, Australia.
[2] Western Mining Corporation Limited, Kambalda, Western Australia.

DEPARTMENT OF PRIMARY INDUSTRIES AND ENERGY

Minister for Resources: The Hon. David Beddall, MP
Secretary: Greg Taylor

AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

Executive Director: Harvey Jacka, AM

ISSN: 1039-0073
ISBN: 0 642 21320 8

It is recommended that this publication be referred to as:

KLOOTWIJK, C. (Compiler), IDNURM, M., THEVENIAUT, H. and TRENCH, A., 1994. Phanerozoic Magnetostratigraphy: A contribution to the Timescales Project. Australian Geological Survey Organisation, Record 1994/45.

CONTENTS

SUMMARY

A critique of magnetostratigraphic coverage for the Phanerozoic is presented. Cambrian to Early Carboniferous constraints are sparse in the absence of dedicated magnetostratigraphic studies. The Late Carboniferous and Late Permian boundaries of the Permo-Carboniferous Reverse Superchron (PCRS) are better constrained from magnetostratigraphic studies, but limited detail is available on possible normal polarity subchrons in the PCRS. Triassic to Recent constraints are well-established from dedicated magnetostratigraphic studies with adequate biostratigraphic control, and for the Middle Jurassic to Recent from calibration against marine magnetic anomalies.

Follows p. 1

GENERAL INTRODUCTION

Responsibilities

Responsibility for this review of Phanerozoic magnetostratigraphic constraints is shared:

. Cambrian to Silurian: Allan Trench;
. Devonian to Permian: Chris Klootwijk;
. Triassic to Middle Jurassic: Hervé Théveniaut;
. Middle Jurassic to Recent: Mart Idnurm.

Individual contributions were compiled by Chris Klootwijk into a uniform style of presentation. Various approaches to data compilation were followed by the four authors. This variety in approach necessarily reflects variations in data quality and quantity in the Phanerozoic for characteristic events such as the Permo-Carboniferous Reverse Superchron and the Cretaceous Normal Polarity Superchron. The authors describe their individual approaches in the introductions to their respective chapters.

Purpose

This review was undertaken as a contribution to AGSO's Phanerozoic Timescales Project (Young and Laurie,1994). It aims to document magnetostratigraphic correlation and dating constraints, as a complement to, perhaps more, established biostratigraphic, lithostratigraphic and chronostratigraphic correlation and dating tools. Individual authors of the various chapters of AGSO's Phanerozoic Timescales Project have taken care to integrate the magnetostratigraphic constraints with the Period correlation charts, wherever warranted by the available level of detail. Numerical age constraints documented in the reviewed literature, therefore, have been adjusted to key time points of the AGSO Phanerozoic Timescales (Jones,1994).

Methods

Four methods to develop magnetic polarity timescales were discussed in a seminal paper by Irving and Pullaiah (1976): i.e. the *direct method*, *marine method*, *time-scale method*, and *stratotype method*. The *direct method* plots polarities of individual rock units directly against radiometric age of the rocks. The *marine method* compiles polarities from successions of marine magnetic anomalies with, age tie-ins provided by radiometric dating of oceanic basalts or from biostratigraphic control on directly overlying sediments. The *time-scale* method plots polarities of individual rock units through conversion of chronostratigraphic ages into numerical ages according to the preferred timescale of the day. The *stratotype method* plots polarity successions against lithostratigraphic and/or biostratigraphic control.

The *direct method* has limited practical applicability; it is restricted to rocks that can be dated radiometrically and its resolution is limited by the precision and accuracy of radiometric methods. The *marine method* has provided some highly detailed polarity sequences for the Cenozoic and part of the Mesozoic; its applicability is limited by the resolution of marine magnetic modelling techniques, the accuracy and precision of the biostratigraphic and radiometric tie-ins, and the absence of pre-Middle Jurassic ocean floor. The *time-scale method* is a practical way of integrating results from individual studies, and can incorporate results from studies often not designed for magnetostratigraphic purposes. Its applicability is limited, however, because of the absence of unequivocal superposition evidence and, for earlier results in particular, uncertainties about the primary origin of individual results. The *stratotype method* has evolved as the preferred method for development of magnetostratigraphies because highly sensitive cryogenic magnetometers enable magnetizations of virtually any lithology to be measured. It provides unequivocal superposition control, better control on the primary origin of the magnetizations, and its time resolution is limited only by litho- and bio-stratigraphic detail of the studied sections.

Development of a reference magnetostratigraphy for the Phanerozoic, and for the Palaeozoic in particular, is hampered by the limited number of studies to date that are dedicated entirely to magnetostratigraphy. Data from diverse sources and of diverse quality, reliability, and resolution need to be integrated therefore, to develop a reference magnetostratigraphy resulting in a record with various levels of detail and reliability.

In several recent magnetostratigraphic compilations for the early Palaeozoic, Trench and coworkers (Trench *et al.*,1991,1993) classified original data and compiled magnetostratigraphies at three quality levels: *fundamental*, *supplemental* and *unconstrained:*

- *Fundamental* data come from dedicated magnetostratigraphic studies on continuous, well-controlled stratigraphic sections with a duration of several zones or stages (spanning at least several million years), and with reversal boundaries that are demonstrated to represent stratigraphic levels;
- *Supplemental* data come from well-dated rocks that cover only a limited stratigraphic interval and generally display only a single magnetic polarity;
- *Unconstrained* data come from rocks with inadequate biostratigraphic control and indications for a secondary origin rather than primary origin for the magnetization.

Trench et al's *fundamental* and *supplemental* data equate most closely with Irving and Pullaiah's (1976) *stratotype* and *time-scale* data. *Unconstrained* data are not useful for magnetostratigraphic application. The threefold approach to data compilation is equally applicable to the late Palaeozoic, and the essence of the technique has been followed throughout the Palaeozoic.

Nomenclature

The International Subcommission on Stratigraphic Classification of the International Union of Geological Sciences proposed a standard magnetostratigraphic nomenclature (Anonymous,1979; Cox in Harland *et al.*,1982,1990; see Hailwood,1989 for overview). The subcommission recommended against the use of the terms "event" and "epoch" for description of time derived from geomagnetic polarity, and proposed instead the terms *polarity subchron* (10^4-10^5 yr) and *polarity chron* (10^5-10^6 yr), with *polarity superchron* (10^6-10^7 yr) describing a longer polarity interval in time. Corresponding chronostratigraphic terms for description of rocks formed during these time intervals are: polarity *subchronozone*, *polarity chronozone* and *polarity superchronozone*. Corresponding lithostratigraphic terms describing magnetic polarity units within rock units are: *polarity subzone*, *polarity zone* and *polarity superzone*. The term *magnetozone* is currently most commonly used for polarity zone, and *magnetic chron* likewise for polarity chron.

CAMBRIAN TO SILURIAN MAGNETOSTRATIGRAPHY (Allan Trench)

Introduction

The establishment of a magnetic polarity timescale for the early Palaeozoic remains in its infancy although significant progress has been made in recent years. Lower Palaeozoic rocks present a number of problems to magnetostratigraphic work beyond those of younger strata. These difficulties can be summarised as follows:

- The absence of preserved Palaeozoic oceanic crust precludes comparison of palaeomagnetic data with an independent magnetic anomaly pattern from which a high resolution polarity sequence can be deduced. The Mesozoic-Tertiary marine magnetic anomalies have played a vital role in the development of polarity time-scales for these periods (Harland *et al.*,1990).

- The likelihood of magnetic overprinting having completely destroyed the primary magnetic signature of a rock becomes greater with increasing rock age, given the increasingly complex geological history affecting the rock. As such, geologically 'ideal' sections for magnetostratigraphic work may preserve no evidence of the palaeomagnetic field at the time of rock deposition (e.g. Ordovician - Silurian boundary section at Anticosti Island, Quebec; see Seguin and Petryk,1986; Ripperdan,1990).

- Plate configurations have changed dramatically since the early Palaeozoic, making the identification of normal and reverse polarities equivocal for many plates and, in particular, for marginal continental terranes. For example, several competing palaeogeographies exist for late Precambrian to Cambrian times (e.g. Lin *et al.*,1985; Piper,1987; Moores,1991; Kirschvink,1992; McKerrow *et al.*,1992).

Because of these problems, very few dedicated magnetostratigraphic studies have been attempted on lower Palaeozoic rocks. Some notable exceptions include the works of Kirschvink and Rosanov (1984) on Cambrian limestones of the Siberian platform, Ripperdan and Kirschvink (1992) and Ripperdan *et al.* (1993) on the Cambrian-Ordovician boundary carbonates of Black Mountain, Australia and Dayangcha, China, respectively, and Torsvik and Trench (1991) on Lower-Middle Ordovician carbonates from Sweden.

Despite the lack of dedicated magnetostratigraphic studies of lower Palaeozoic rocks, numerous palaeomagnetic studies have been undertaken with the aim of deducing continental palaeopoles for clarifying continental reconstructions. These studies, although designed for other purposes, provide useful ancillary information from which at least the predominant polarity of the early Palaeozoic magnetic field can be deduced. Syntheses of the early Palaeozoic magnetic field polarity have been undertaken by Irving and Pullaiah (1976), Khramov *et al.*(1965), Khramov and Rodionov (1981), Khramov (1987) and Trench *et al.* (1991,1992,1993).

Magnetostratigraphic nomenclature and data quality

Hailwood (1989) has detailed the magnetostratigraphic nomenclature as adopted in studies of Mesozoic, Tertiary and Recent sections. Given our present rudimentary knowledge of the early Palaeozic magnetic field, however, Trench *et al.* (1991,1993) adopted an informal nomenclature for the subdivision of polarity intervals. In this scheme, reversals were named depending on the stratigraphic interval in which they occur (e.g. A[R] = Arenig, Reverse; L[N2] = Llanvirn-Llandeilo, Normal interval 2; W[N] = Wenlock Normal; LL[M] = Llandovery Mixed interval, etc.). On a detailed scale when numerous reversals are present, Kirschvink and Rosanov (1984) opted to name reversals using a sequential lettering (A - T) and sign convention ("+" = normal, "-" = reverse). Data quality for early Palaeozoic magnetostratigraphic purposes has been assessed according to the tripartite division of palaeomagnetic data (after Trench

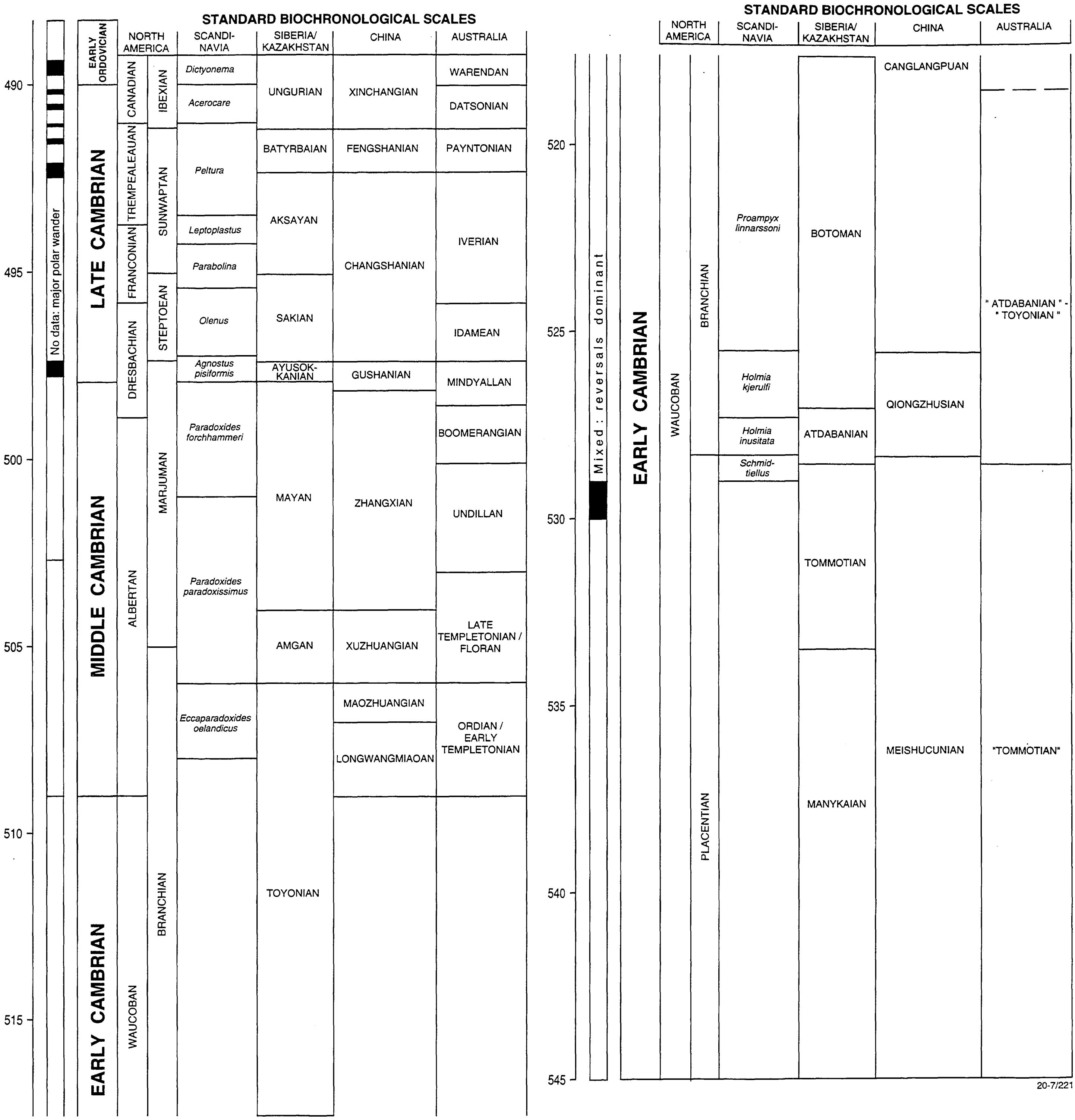


Fig.1 Tentative magnetostratigraphy for parts of the Cambrian after Shergold (1989,1994).

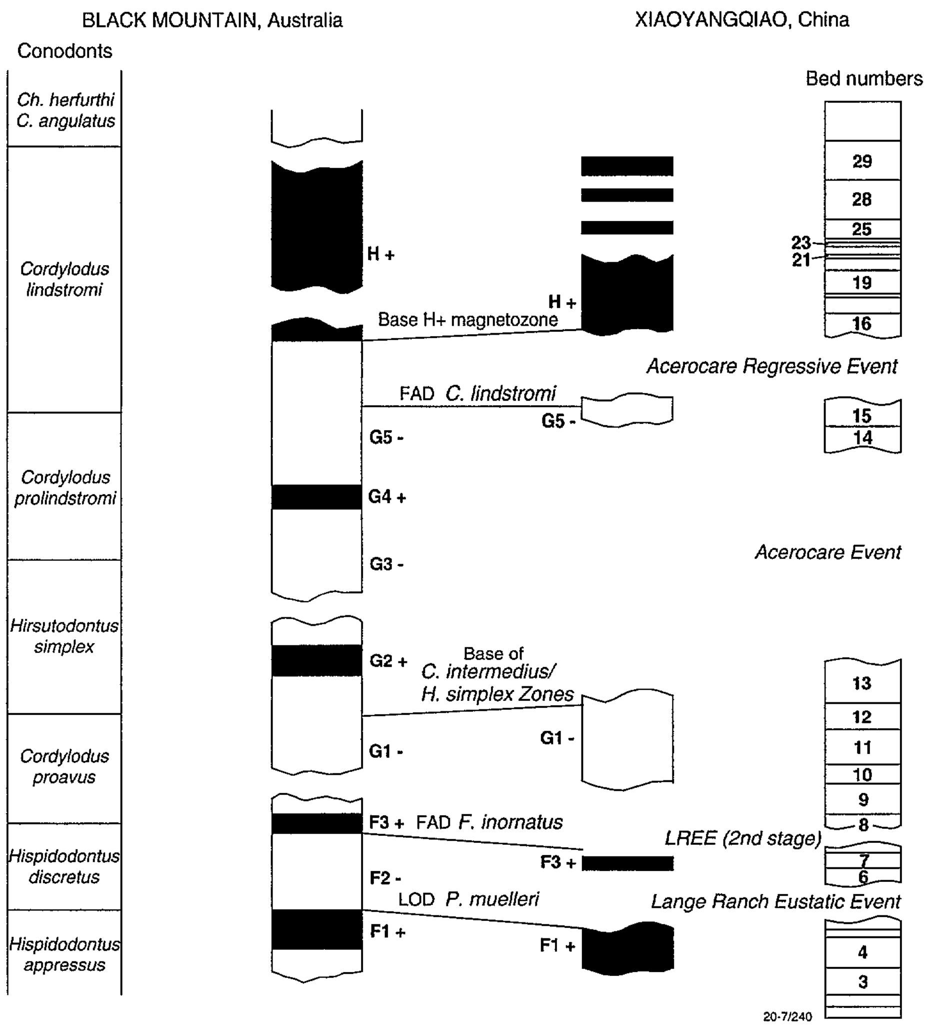


Fig.2 Tentative correlation of magnetostratigraphies for Cambrian-Ordovician boundary sections at Black Mountain, western Queensland, Australia (Ripperdan and Kirschvink,1992; Ripperdan et al.,1992) and at Xiaoyangqiao near Dayangcha, Jilin Province, China (Ripperdan et al.,1993) as proposed in the latter study.

et al.,1991) described in the General introduction.

Cambrian

A detailed compilation of all palaeomagnetic polarity data from Cambrian strata has yet to be carried out and is beyond the scope of the present summary. Although the Precambrian-Cambrian boundary has now been ratified (Landing,1994) and dated (Bowring *et al.*,1993), the Cambrian-Ordovician boundary remains unresolved (Shergold,1994) introducing uncertainty in dating and correlation of Late Cambrian- Early Ordovician magnetostratigraphy. Likewise, palaeogeographic uncertainties are greater in Cambrian time than either Ordovician or Silurian times and preclude unambiguous polarity definition. For example, Kirschvink (1992) has revised the polarity classification adopted during his previous studies

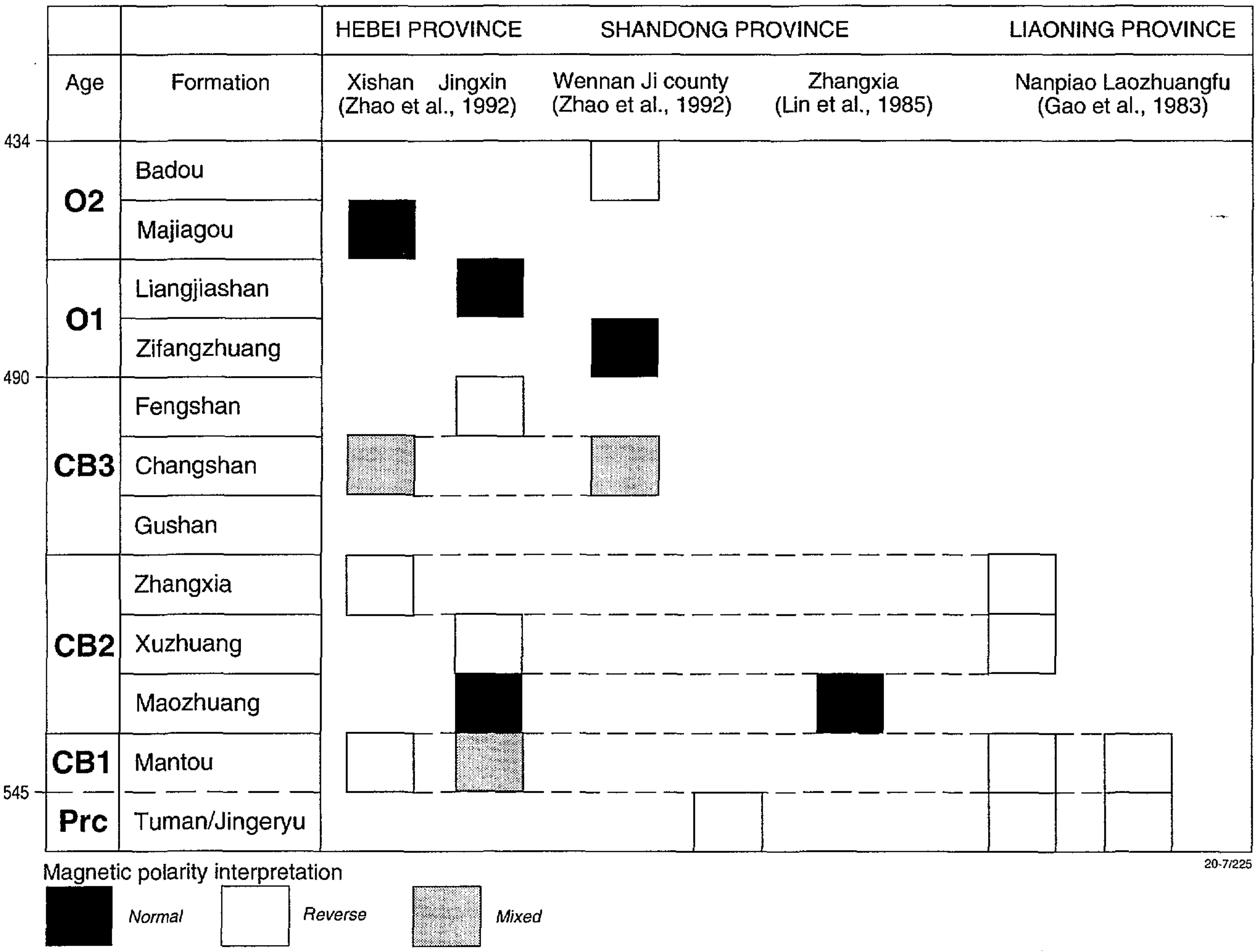


Fig.3 Sketch section showing magnetic polarity zonations observed from Cambrian and Ordovician sediments of the North China Block (after Zhao et al.,1992).

of the Cambrian of the Siberian Platform (Kirschvink and Rosanov,1984). In this regard, no attempt has been made in this summary to reconcile authors' polarity interpretations for Cambrian time with the plethora of Cambrian reconstructions presently available. Instead, we reproduce a polarity interpretation by Shergold (1989,1994) based on magnetostratigraphic studies by Kirschvink (1978a,b) for the base of the Cambrian and by Ripperdan and Kirschvink (1992) and Ripperdan *et al.* (1992) for the Cambrian-Ordovician boundary (Fig.1). Whilst both magnetostratigraphies are well-determined, the Early Cambrian Amadeus Basin succession suffers from an uncertain global correlation and the correlation potential of the Cambro-Ordovician Black Mountain succession is hampered by uncertainty about a Cambro-Ordovician stratotype section (J. Shergold, pers. comm.,1994).

Stratigraphy-parallel polarity reversals within Cambrian rocks have been described as follows:

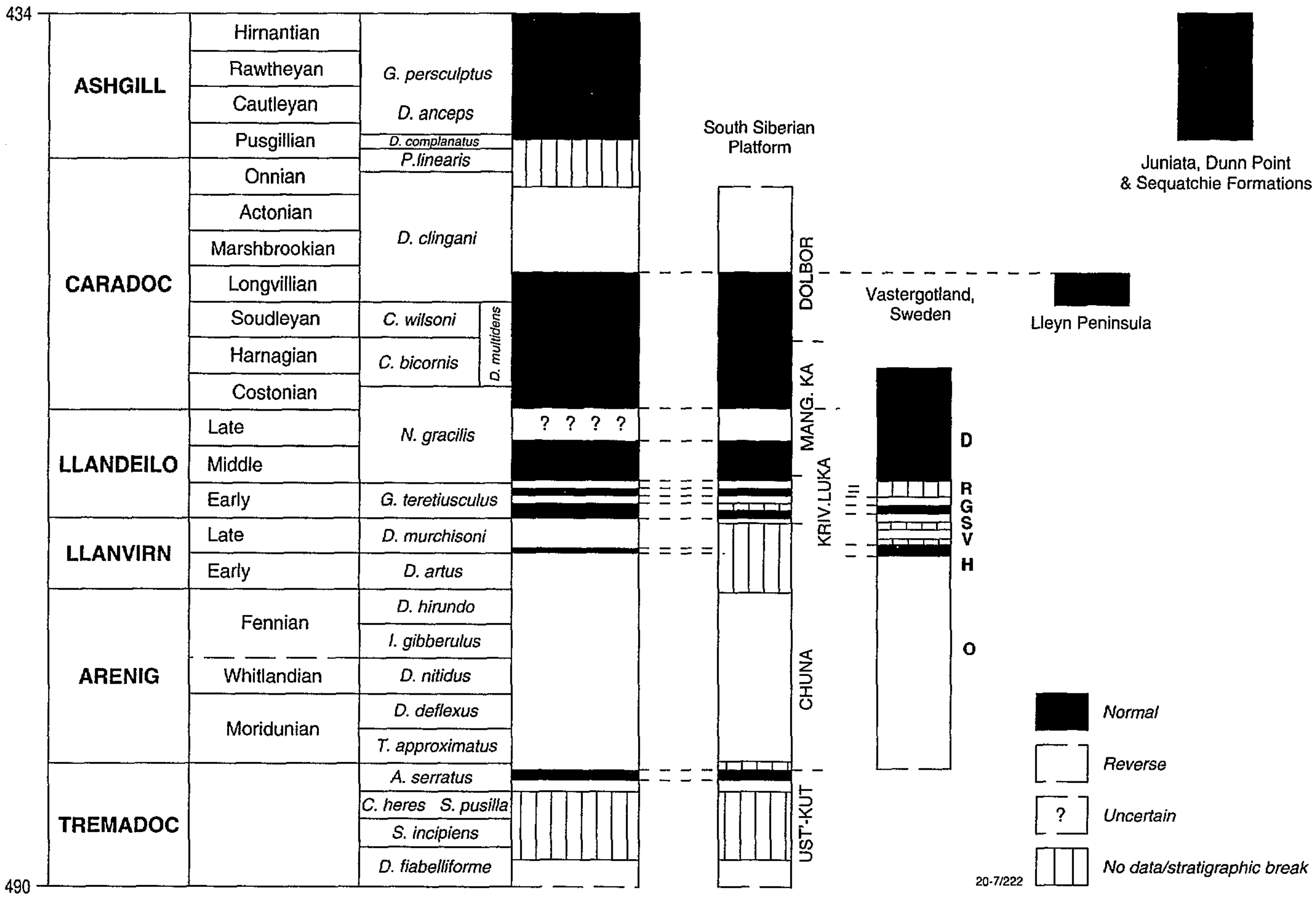


Fig.4 Magnetostratigraphic correlation of Ordovician fundamental datasets from the South Siberian Platform and southern Sweden (after Trench et al.,1991). Data from the Lleyn Peninsula, Wales (Thomas,1976), and the Juniata (Miller and Kent,1989), Dunn Point (Van der Voo and Johnson,1985) and Sequatchie Formations (Morrison,1983; Morrison and Ellwood,1986 of eastern North America are also included as they further constrain the composite stratigraphy. "*" The inferred polarity for Ashgill time is based on normally magnetized palaeomagnetic data from the Dunn Point, Juniata and Sequatchie Formations. If postulated reversely magnetised sites within the Juniata and Sequatchie Formations are truly distinguishable from Alleghenian remagnetisations, then a short period (or periods) of reverse polarity may exist within the Ashgill. Left-hand columns refer to stratigraphic elements of the Ordovician and the adjacent right-hand column represents the composite magnetostratigraphic record. Faunal sub-divisions are European zones. Sub-divisions of the Arenig series are taken from Fortey and Owens (1987). Siberian stages are indicated next to the appropriate column. Swedish formations (lettered) from Torsvik and Trench (1991) are as follows: D, Dalby Limestone; R, Ryd Limestone; G, Gullhogen Limestone; S, Skovde Limestone; V, Vamb Limestone; H, Holen Limestone; O, Orthoceras Limestone.

- Kirschvink *et al.* (1991) report detailed magnetostratigraphic and carbon isotope results from postulated Precambrian-Cambrian boundary sections in Morocco, Siberia and South China.

- Kirschvink (1978a,b) documents palaeomagnetic results from upper Precambrian and Lower Cambrian sediments of the Amadeus Basin, Central Australia. Samples were collected at approximately one metre intervals through an 800 m thick sequence. An "unconformity test" (Kirschvink,1978b) is argued to support a magnetisation age equivalent to the stratigraphic age

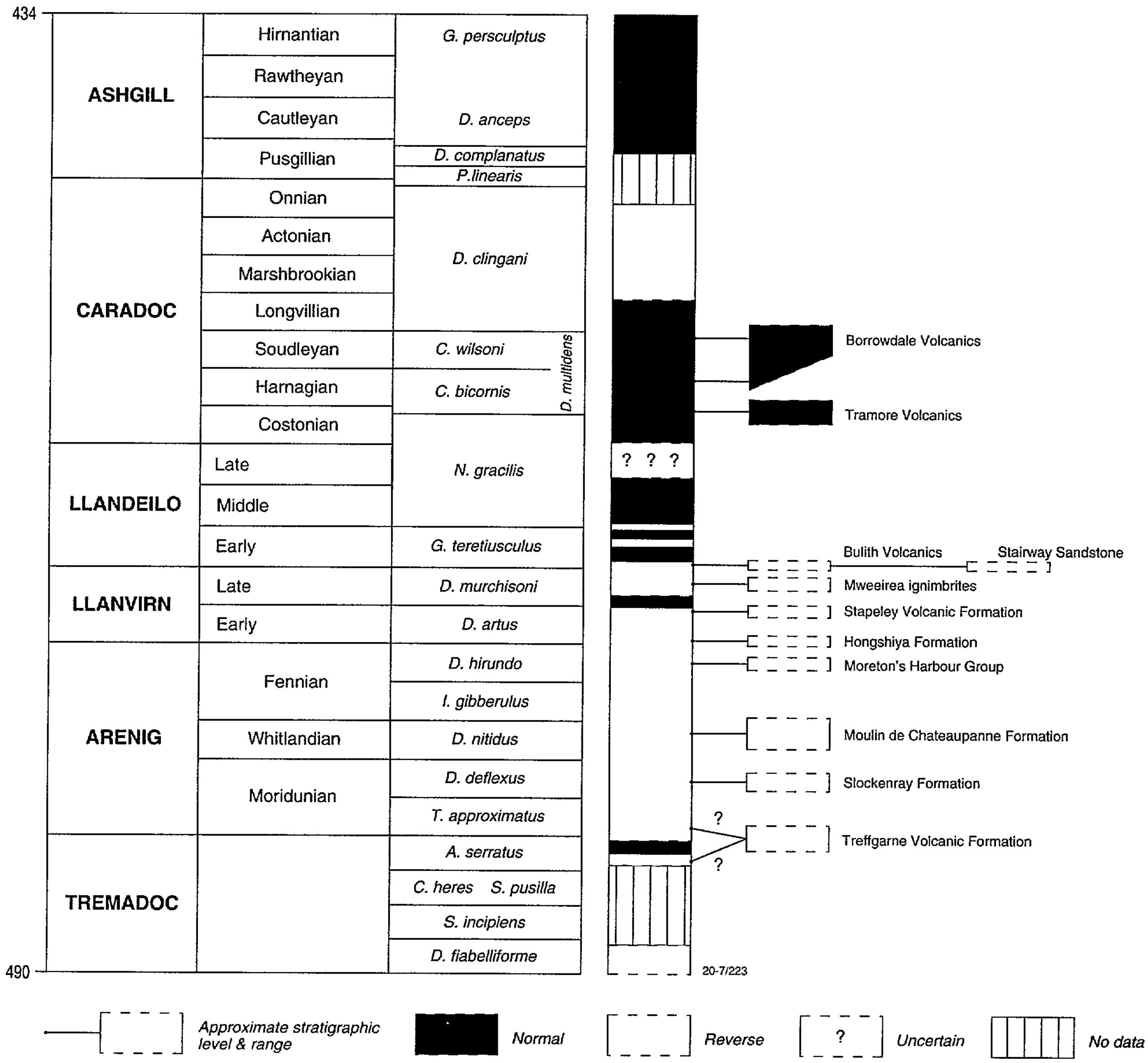


Fig.5 Composite Ordovician magnetostratigraphy (from Figure 4) with the addition of supplementary datasets. Individual studies are as follows: Borrowdale Volcanics (Faller et al.,1977), Tramore Volcanics (Deutsch,1980), Builth Volcanics (Briden and Mullan,1984; Trench et al.,1991), Stairway Sandstone (Embleton,1972), Mweelrea Ignimbrites (Deutsch and Somayajuhu,1973; Morris et al.,1973), Stapeley Volcanic Formation (McCabe and Channell,1990), Hongshiya Formation (Fang et al.,1990), Moreton's Harbour Group (Johnson et al.,1991), Moulin de Chateaupanne Formation (Perroud et al.,1985), Slockenray Formation (Trench et al.,1988), Treffgarne Volcanic Formation (Torsvik and Trench,1991; Trench et al.,1991).

of these rocks. The Early Cambrian interval of the Arumbera Sandstone is represented by mixed polarities which extend upwards into the Todd River Dolomite and Eninta Sandstone, the former having a definite Early Cambrian biostratigraphic age (Shergold,1994).

- Kirschvink and Rosanov (1984) report numerous magnetozones from upper Precambrian and

Lower Cambrian strata of the Siberian Platform. Stratigraphy-parallel reversals were observed that could be correlated with archaeocyathid zones. Reliable correlation of these data with coeval results from Australia remains equivocal.

- Klootwijk (1980) reports magnetic polarity data from Lower Cambrian rocks of the Flinders Ranges of South Australia and Middle to lower Upper Cambrian rocks of the Amadeus Basin. Shergold (1989,1994) summarises the polarities with respect to the biostratigraphic record. Mixed polarities are identified from the Lower Cambrian Ajax Limestone with the possible correlative section, the Wilkawillina Limestone and Oraparinna Shale, displaying only reverse polarity. Results from the Moodlatana Formation are reverse with the Middle Cambrian upper Giles Creek Formation and lower Shannon Formation.

- Ripperdan and Kirschvink (1992) and Ripperdan *et al.* (1992) report on detailed magnetostratigraphic and carbon isotope studies of the Black Mountain section in Queensland and Ripperdan *et al.* (1993) on the Dayangcha section, Jilin Province, China. Both sections are proposed as representative of the Cambrian - Ordovician boundary on biostratigraphic grounds. A tentative correlation of the two magnetostratigraphic sections after Ripperdan *et al.* (1993) is shown in Figure 2.

- Zhao *et al.* (1992) revealed multicomponent magnetisations in Cambrian (and Ordovician) sedimentary units from several localities in the North China Block. The higher unblocking temperature components pass field tests and are interpreted to approximate the depositional age of the sequences. Zhao *et al.* (ibid.) interpret the Cambrian strata to be predominantly reversely magnetized with intermittent zones of mixed polarity (Fig.3), despite problems to unambiguously establish the sign of the polarity.

Ordovician

Magnetic polarity data from Ordovician rocks are summarised in Figures 4 and 5. *Fundamental* data (Fig.4) reveal a probable correlation of polarity results between detailed sections of carbonates on the Baltic (Torsvik and Trench,1991) and south Siberian platforms (Khramov *et al.*,1965; Rodionov,1966). The latter section, along the banks of the Lena River, is currently under reinvestigation using contemporary analytical methods and superconducting magnetometer technology (Torsvik and Tait, pers. comm.,1993). *Supplemental* data (Fig.5) are consistent with the results of the detailed platform successions and yield evidence of the predominant polarity in their own right. An interesting outcome of this analysis suggests that polarity reversals occurred less frequently in Ordovician times than, for example, in Cenozoic times (Fig.6, after Trench *et al.*,1992), although a missing-data problem cannot be excluded.

The following characteristics of the Ordovician magnetic field are evident (Figs 4,5):

- All Arenig rocks, with exception of the successions described in Farr *et al.* (1993), thus far have yielded reverse magnetisations.
- Several reversals of the geomagnetic field occurred during Llanvirn-Llandeilo times.
- The early part of the Caradoc series corresponds to an interval of normal polarity. The later part of the series is characterised by a reversely-magnetized field.

	Reversal Frequency
ORDOVICIAN	**≃ 5 m.y.**
CENOZOIC	**≃ 0.5 m.y.**

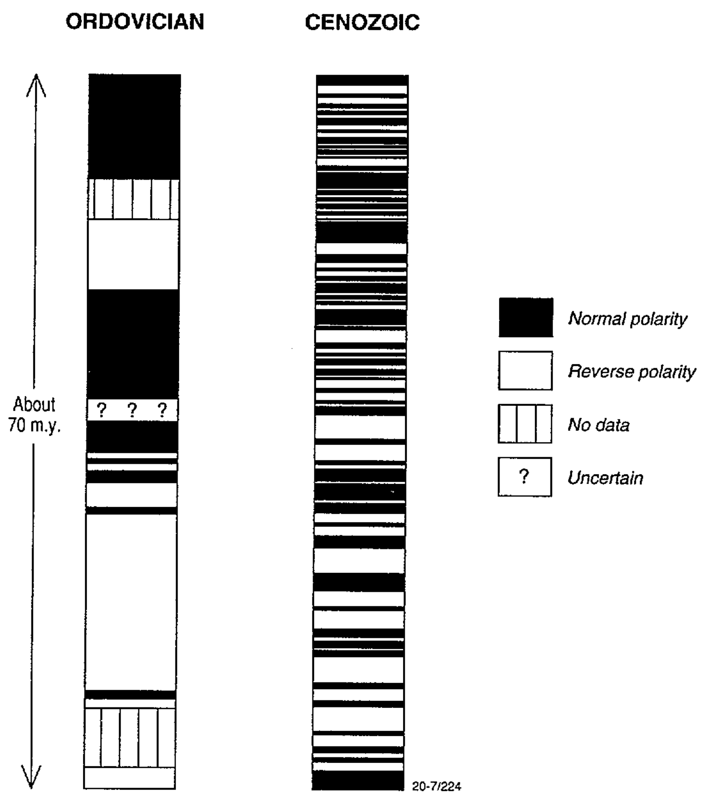


Fig.6 **Comparison of Ordovician reversal pattern with Cenozoic reversal pattern indicating the relative simplicity of Ordovician polarities as presently determined.**

- Ashgill rocks have yielded normal polarities to date, although short reverse polarity zones may occur that have yet to be unambiguously identified.
- The above observations 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).

Magnetic polarity data that have recently become available from Ordovician strata include results from shales and limestones of the North China block (Zhao *et al.*,1992), the Bluffer Pond Formation of the northern Appalachians (Potts *et al.*,1993), and carbonates and sandstones of the Powell, Everton and St Peter Formations of northern Arkansas (Farr *et al.*,1993). The data from the North China Block pass reversal, baked contact, and fold tests (Mesozoic folding) and demonstrate evidence of an overall similarity in the magnetic polarity pattern for the stratigraphic sequence between sampled localities

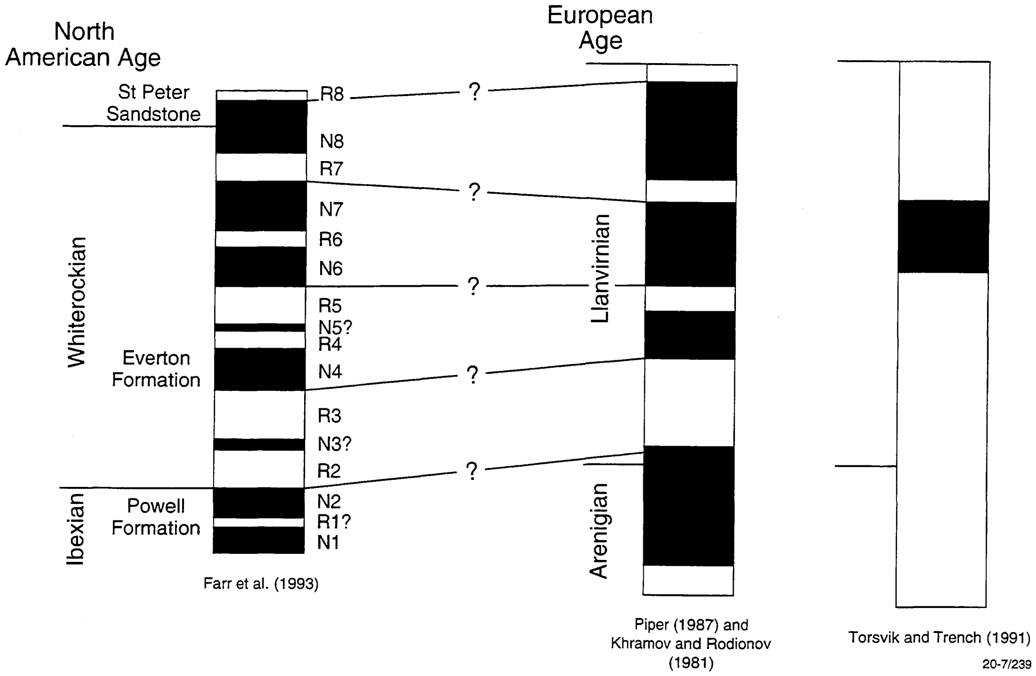


Fig.7 Comparison of a tentative reversal pattern from Lower to Middle Ordovician rocks from northern Arkansas (Farr et al.,1993) with compilations by Piper (1987), as modified from Khramov and Rodionov (1981), and Torsvik and Trench (1991).

(Fig.3). Unfortunately, the apparent polar wander path for the North China Block is poorly constrained for the early Palaeozoic and Zhao *et al.* (1992) were unable to unambiguously establish the magnetic polarity of their data. Comparison of their results (Fig.3) to the composite Ordovician polarity pattern (Fig.4) points to the North China data displaying the opposite polarity to that put forward by Zhao *et al.* (1992). Potts *et al.* (1993) subsequently presented evidence for normal polarity of the Caradocian (Late Ordovician) palaeofield, consistent with the synthesis of previous studies presented by Trench *et al.* (1991). Farr et al., (1993) present a detailed magnetostratigraphic record of Lower to Middle Ordovician (Ibexian and Whiterockian) rocks from northern Arkansas (Fig.7). The record is most probably of primary origin as evidenced from correlations between sampled sections and a positive conglomerate test. The reversal record is more complex, but may be crudely correlatable to the compiled reversal record from Piper (1987). It is considerably more complex than the Baltoscandian compilation by Torsvik and Trench (1991) and the global compilation by Trench *et al.* (1991,1992, Figs 4,5).

Silurian

Magnetic polarity data for Silurian times are summarised in Figure 8 (after Trench *et al.,*1993). The following points of interest are noted:

- Palaeomagnetic data sets of primary origin are not yet available from a continuous Silurian stratigraphic succession of any great duration (i.e. there are no *fundamental* data), so a composite Silurian magnetostratigraphy is still at a much more preliminary stage than that for

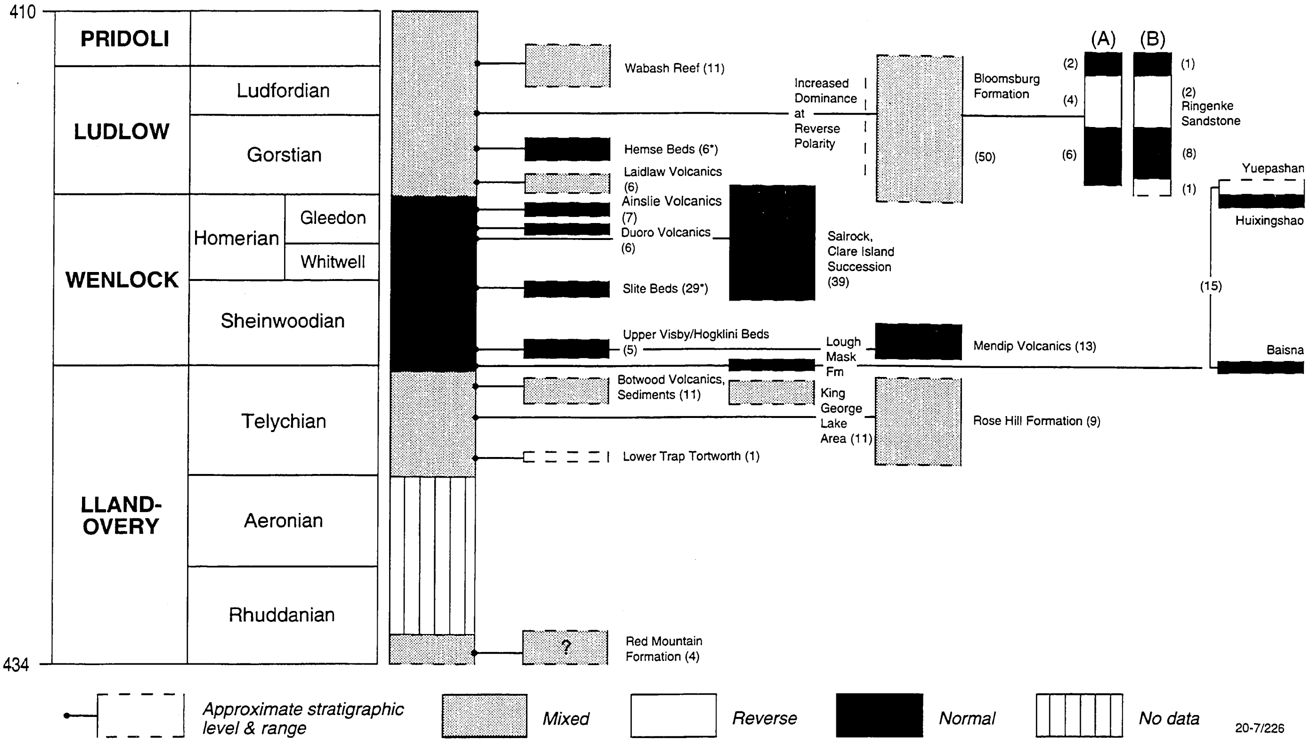


Fig.8 Magnetic polarity data for the Silurian. Individual datasets are as follows: Wabash Reef, USA (McCabe et al.,1985); Hemse Beds, Sweden (Claesson,1979); Laidlaw Volcanics, Australia (Luck,1973); Ainslie Volcanics, Australia (Luck,1973); Douro Volcanics, Australia (Luck,1973); Slite Beds, Sweden (Claesson,1979), Upper Visby/Hoglint Beds, Sweden (Trench and Torsvik,1991); Botwood Volcanics and sediments, Canada (Gales et al.,1989); Lower Trap, Tortworth, U.K. (Piper,1975); Red Mountain Formation, USA (Morrison,1983); Salrock, Clare Island and Lough Mask Formation, Ireland (Smethurst and Briden,1988); King George IV Lake area, Canada (Buchan and Hodych,1989); Bloomsburg Formation, USA (Kent,1988); Mendip Volcanics, England (Torsvik et al.,1993); Rose Hill Formation, USA (French and Van der Voo,1977,1979); Ringerike Sandstone, Norway (Douglass,1988); Yuejiashan, Huixingshao and Baisha sections, South China (Opdyke et al.,1987).

the Ordovician.

- The majority of the Silurian was characterised by periods of mixed polarity (i.e. intervals of high reversal frequency).

- Wenlock times were mainly characterised by a magnetic field of normal polarity based upon single polarity studies of red mudstones from western Ireland (Smethurst and Briden,1988), andesitic volcanics from southwest England (Torsvik *et al.*,1993), carbonates and mudstones from southeast Sweden (Trench and Torsvik,1991) and volcanics from southeast Australia (Luck,1973; Klootwijk, unpublished data).

Conclusions

When compared with equivalent studies of Cambrian and Silurian rocks, Ordovician strata reveal fewer reversals of the Earth's magnetic field. This can be interpreted to indicate a lower reversal frequency during the Ordovician than either the Cambrian or Silurian. A preliminary estimate of reversal frequency for the Ordovician is of the order of one reversal per five million years (Trench *et al.*,1992).

The variation in reversal frequency identified between segments of Cambrian, Ordovician and Silurian age indicates that magnetostratigraphy will serve as a high precision correlation tool for only part of the of the early Palaeozoic, during times of rapid reversals of the Earth's magnetic field (e.g. Precambrian-Cambrian boundary). Conversely, the comparative simplicity of some segments of the early Palaeozoic polarity record suggests that correlation of disparate sections with the appropriate magnetozone should be possible with relative ease. Further refinement of the Cambrian, Ordovician and Silurian magnetostratigraphic timescale and subsequent correlation of sections should resolve palaeogeographic uncertainties affecting many early Palaeozoic continental blocks.

DEVONIAN TO PERMIAN MAGNETOSTRATIGRAPHY (Chris Klootwijk)

Data quality

Data quality for the Devonian, Carboniferous and Permian is variable. Considerable progress has been made over the past five years in defining the base and top of the Permo-Carboniferous Reverse Superchron (PCRS). Some high-quality magnetostratigraphic profiles for the mid-Carboniferous and the latest Permian are now available, but the boundaries of the PCRS are as yet not defined within zone level. The reversal stratigraphy within the PCRS has not yet been studied at the high-resolution standards that are the current norm. The few earlier reported observations of normal polarity intervals within the PCRS remain to be confirmed and detailed regarding their primary origin and stratigraphic level. The magnetostratigraphy of the, pre-PCRS, Early Carboniferous and Devonian is poorly known. A few isolated studies have provided magnetostratigraphic detail for successions covering limited timespans. Some magnetostratigraphic compilations have been carried out on available palaeomagnetic data that were mainly acquired for other purposes. Many of these data were obtained prior to the recognition of the pervasiveness and wide areal extent of reverse polarity overprints of PCRS origin in Permo-Carboniferous fold belts and adjacent basins. The primary origin of many of these results, in particular the reverse polarity interpretations, remain to be confirmed, so the compilation presented should serve as no more than a guide to further detailed studies. Extensive and important magnetostratigraphic studies were carried out by Russian workers on late Palaeozoic stratotype sections in Russia and Tatarstan. Most of these studies were originally published in the nineteen-seventies and early nineteen-eighties in Russian literature. Details of the studies and results are not easily accessible, although subsequent compilations were published more widely. A further impediment to scrutiny of the results is their acquisition using methods that are largely unfamiliar to workers outside the former USSR. The studied stratotype sections no doubt have great potential for development of a magnetostratigraphic timescale, but the extent to which available results can be used must await further evaluation in view of the well-documented evidence for widespread late Palaeozoic remagnetisation.

Nomenclature: from "Kiaman" to "PCRS"

A long interval of reverse polarity, from about the Middle Carboniferous to the latest Permian, was first defined by Irving and Parry (1963) and named, in a rather informal way, the "Kiaman Magnetic Interval", with the "Kiaman Magnetic Division" as the corresponding "time-rock unit". They defined the "Kiaman"

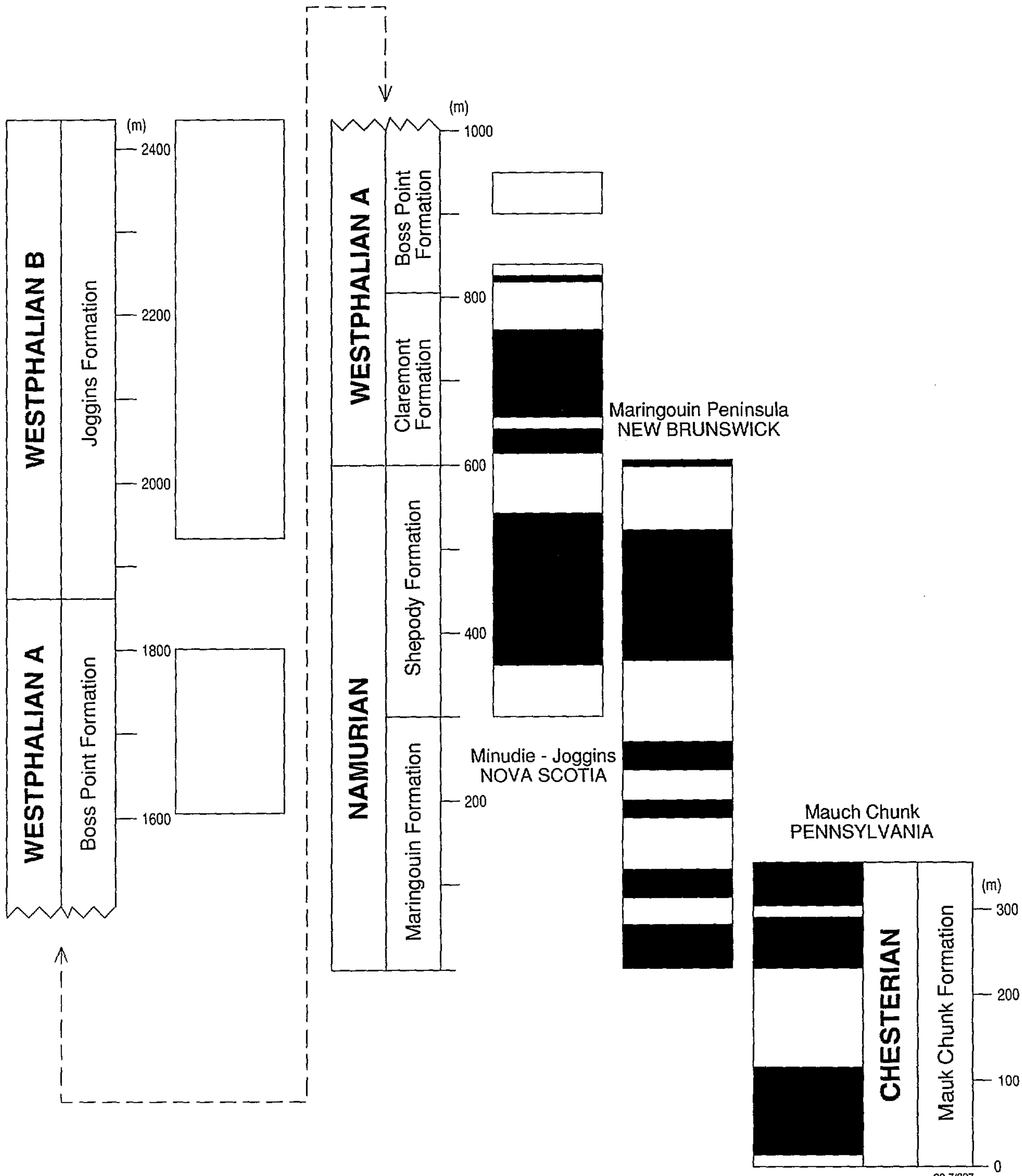


Fig.9 Composite mid-Carboniferous magnetic polarity sequence based on a tentative correlation of results from the Mauch Chunk Formation (Pennsylvania) and from the Cumberland Basin (Nova Scotia, New Brunswick), redrawn after DiVenere and Opdyke (1991a, fig.10,1991b, fig.6).

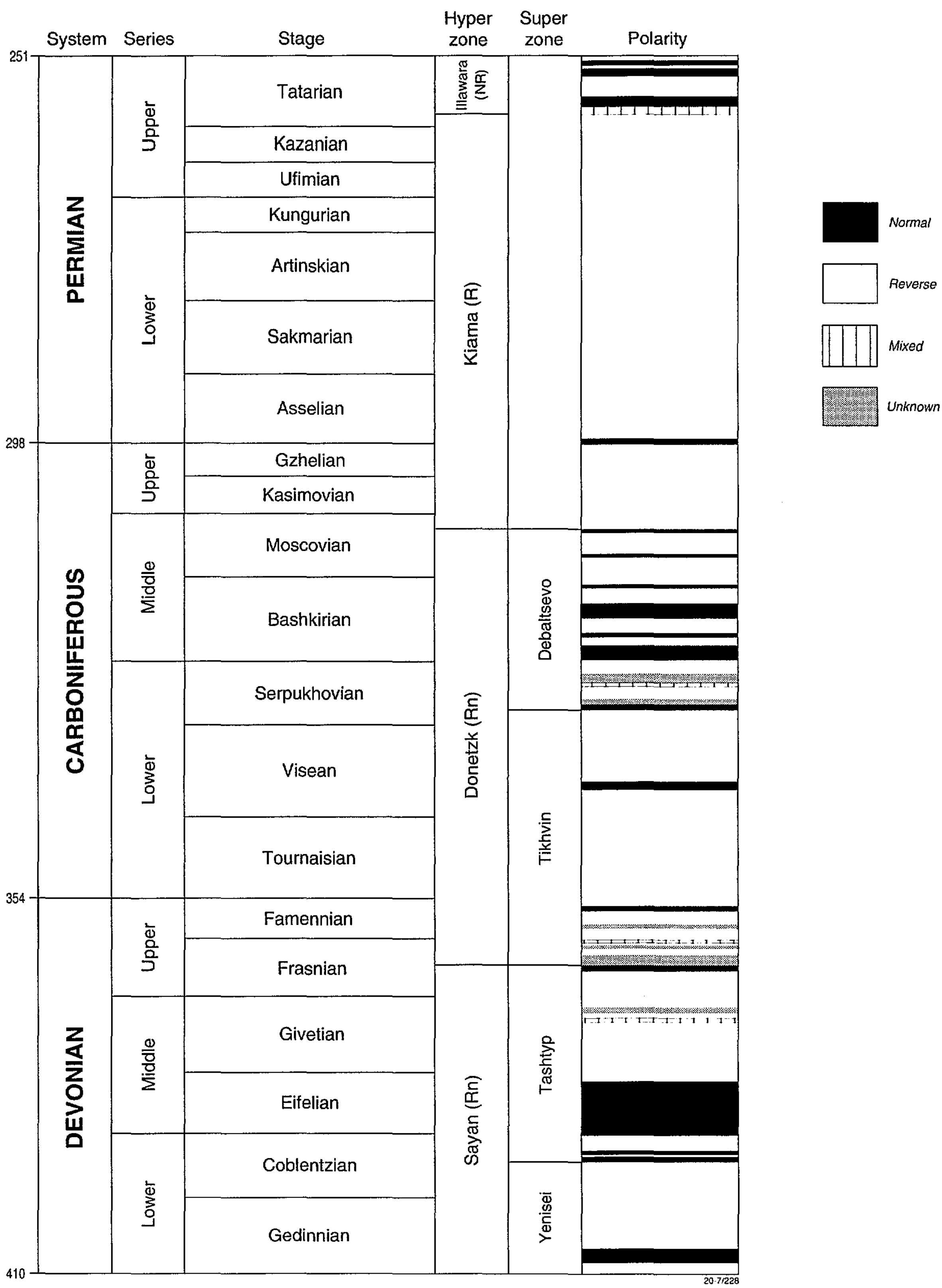


Fig.10 Magnetic polarity scale for the late Palaeozoic of the former USSR, redrawn after Khramov and Rodionov (1981, fig.1).

on the basis of earlier observations of a prolonged interval of reverse polarity in Europe, North America, and in the Permian stratotype sections in Russia and Tatarstan (see Irving and Pullaiah,1976), and in particular on the basis of their own observations in the Hunter Valley and Sydney Basin. The older boundary of the "Kiaman Magnetic Interval" was defined as the "Paterson Reversal" (Irving,1966) at the change from normal polarity in the underlying Paterson Volcanics ("Paterson Toscanite") to reverse polarity in the overlying Seaham Formation ("Upper Kuttung Glacial Sediments"). The younger boundary was defined as the "Illawarra Reversal", then no better located than above the Gerringong Volcanics ("Upper Marine Latites") and below the Narrabeen Group (Irving,1963)("Narrabeen Chocolate Shales"), which left its position undefined within the uppermost Permian coal measures of the Sydney Basin.

Two problems soon became apparent to Irving and coworkers. First, they realized that the early practice of coining new specific names for magnetic intervals would soon clutter the stratigraphical nomenclature with terms of unclear linkage (Irving,1971). Linkage of such intervals to the existing timescale-nomenclature was judged preferable. The second problem related to correlation in time of the "Paterson Reversal" as the base of the "Kiaman" in eastern Australia, with observations on the base of the "Kiaman" in North America, South America and Eurasia (Irving and Pullaiah,1976). It appeared to them that the "Paterson Reversal" might well represent a short normal polarity event within the "Kiaman" and could not be used, therefore, to define its base. For these reasons Irving (1971) withdrew the term "Kiaman" and suggested "Late Palaeozoic Reversed Interval" as a more identifiable term. The term "Permo-Carboniferous Quiet Interval" or "PCR" was introduced subsequently (Irving and Pullaiah,1976).

Terminology for the "Kiaman" has evolved since then, unfortunately without arriving at a single commonly agreed-upon identifier. So different workers and groups use various terms such as: "Kiaman Hyperzone (R)" (Khramov and Rodionov,1981; Khramov,1987; Haag and Heller,1991; DiVenere and Opdyke,1991a), "Kiaman Superchron" (Molina-Garza *et al.*,1989; Magnus and Opdyke,1991), "Kiaman Reversed Superchron" (Ma *et al.*,1993)," Permo-Carboniferous Reversed Polarity Superchron" (McFadden *et al.*, 1988), Permo-Carboniferous Reversed Superchron (PCRS) (Magnus and Opdyke,1991; DiVenere and Opdyke,1991a; Opdyke *et al.*,1993) or "PC-R Superchron" (Cox in Harland *et al.*,1990). The International Subcommission on Stratigraphic Classification (Anonymous,1979) recommended the term Permo-Carboniferous Reversed Superchron (PCRS). This recommendation is followed herein, albeit slightly adapted to Permo-Carboniferous **Reverse** Superchron.

Devonian to Early Carboniferous constraints

The magnetostratigraphy of the Devonain and Lower Carboniferous has not been studied systematically, other than in Russian studies that are mostly of some vintage. Results from only a few modern studies of limited stratigraphic coverage have been reported:

- Studies on the uppermost Mississipian Mauch Chunk Formation in Pennsylvania, North America (DiVenere and Opdyke,1991b) show mixed polarities. The upper part of the sequence is tentatively correlated with the basal part of the polarity sequence in the Maringouin Formation. (Fig.9).

- Hurley and Van der Voo (1987,1990) have interpreted a series of five polarity intervals within a thin *Fruxites* stromatolite bed from the Virgin Hills Formation of the Canning Basin, Australia. The authors followed Druce (1976) in locating the *Fruxites* beds entirely within the *Palmatolepsis* *triangularis* conodont subzone and dated the beds accordingly as Frasnian-Famennian in age. A detailed study by Nicoll and Playford (1993) has now located the *Fruxites* beds within the Early *Palmatolepsis crepida* Zone of early Famennian age.

Smethurst and Khramov (1992) studied middle Palaeozoic successions from the Russian platform in the Ukraine and observed very pervasive "Kiaman"-type reverse polarity overprinting which put doubt on the interpretation of the earlier Russian results. Primary magnetization results were established in Lower Devonian successions for which unfortunatedly only limited stratigraphic detail is available. This showed the occurrence of reverse polarity in Gedinnian-Pridolian sections, normal polarity for the Gedinnian, and reverse polarity for the Gedinnian-Siegenian, in apparent contrast with the established Russian late Palaeozoic magnetic polarity scale (Fig.10).

Given the absence of recent detailed magnetostratigraphy studies on Devonian and Lower Carboniferous successions, use of the polarity timescale compiled from earlier Russian studies (Khramov and Rodionov,1981; Khramov,1987; Fig.10) is still appropriate. The recent study by Smethurst and Khramov (1992) demonstrates that care must be taken, however, with its interpretation as the polarity timescale was compiled prior to the realisation of widespread "Kiaman"-type overprinting within late Palaeozoic fold belts and adjacent cratonic basins.

As an adjunct to the Russian polarity timescale (Fig.10) the Global Palaeomagnetic Database (Lock and McElhinny,1991; McElhinny and Lock,1993) was interrogated for temporal predominance of polarity during the Devonian and Early Carboniferous. Such a search can provide no more than an indication of the polarity structure, because such compilations are fraught with problems related to imprecisions in the age of the rocks and uncertainties about the primary origin of the magnetizations. The search criterion was for directional results from rocks dated within an Epoch or occasionally Stage, and used age limits according to the Harland *et al.* (1990) timescale adopted by the database. The directional results were interpreted subsequently for polarity and the likelihood of the magnetization being primary. The information that passed this filtering process is presented in Figure 11 as a profile of the proportion of normal and reverse results at the Stage or substage level, and is not to be interpreted as a magnetostratigraphic profile. Comparison of this predominant polarity profile (Fig.11) with the Russian polarity timescale (Fig.10) underscores the warning sounded in the last paragraph, with for instance conflicting interpretations for the Tournaisian and Visean, but comparable interpretations for the Eifelian and Bashkirian.

Middle Carboniferous magnetostratigraphy and base of the PCRS

Determination of the base of the PCRS has come a long way since the original definition of the base of the "Kiaman" (Irving and Parry,1963; Irving,1966) between the "Paterson Toscanite" (Paterson Volcanics) of normal polarity and the overlying "Main Glacial Stage" (Seaham Formation) for which reverse polarity was observed. Recent U-Pb (SHRIMP) dating of zircons (Roberts *et al.*,1991,1994a) has shown a much older age for the Paterson Volcanics (328 ± 1.7 Ma; Late Visean) than originally envisaged, while preliminary findings of an ongoing magnetostratigraphic study (Théveniaut *et al.*,in preparation) to locate the base of the PCRS in the Hunter Valley have shown the presence of mixed polarities above the Paterson Volcanics, up to at least the Mirannie Volcanics which are dated at 321 ± 4.4 Ma (Roberts *et al.*,1994b).

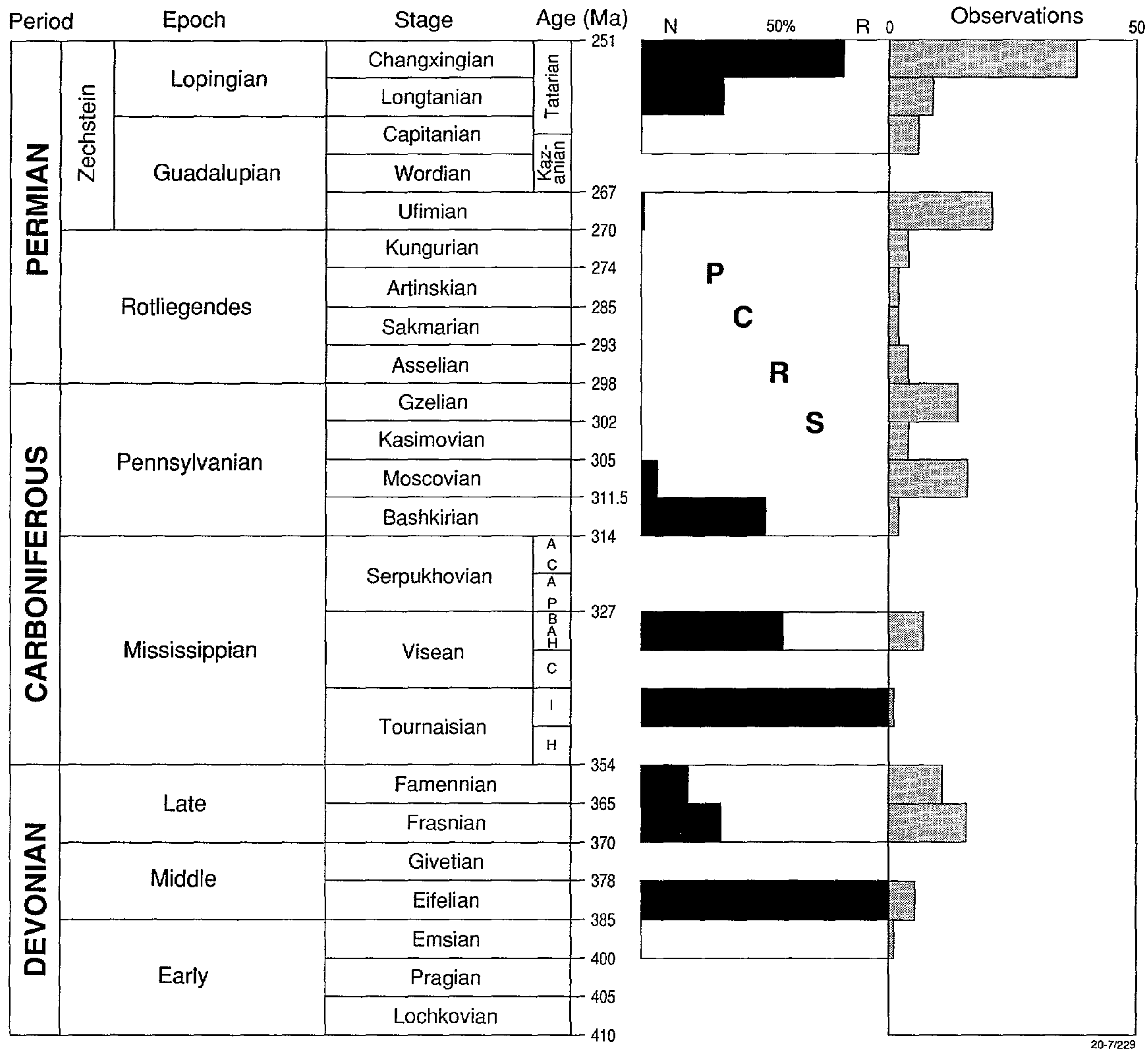


Fig.11 Predominant polarity sequence for the late Palaeozoic, based on the frequency of normal and reverse polarity results at stage or substage level, as obtained from interrogation of the global palaeomagnetic database (version 2.2). The database was interrogated using ages according to Harland et al. (1990), corresponding ages according to the Timescales Project (Young and Laurie,1994) are shown.

Attempts to compile constraints on the base of the PCRS (e.g. Palmer *et al.*,1985) have not always been successful due to biassing of the polarity record by "Kiaman" overprinting The most detailed control available at the moment comes from North American studies, i.e. the earlier work of Jean Roy and coworkers (Roy,1977; Roy and Morris,1983) in Nova Scotia and the more recent work of Opdyke and coworkers in Nova Scotia-New Brunswick (DiVenere and Opdyke,1988,1990,1991a), Pennsylvania (DiVenere and Opdyke,1991b), and Colorado (Miller and Opdyke,1985; Opdyke,1986; Magnus and Opdyke,1991). Roy's (1977) study of Minudie Point located the base of the PCRS in the top of Riversdale

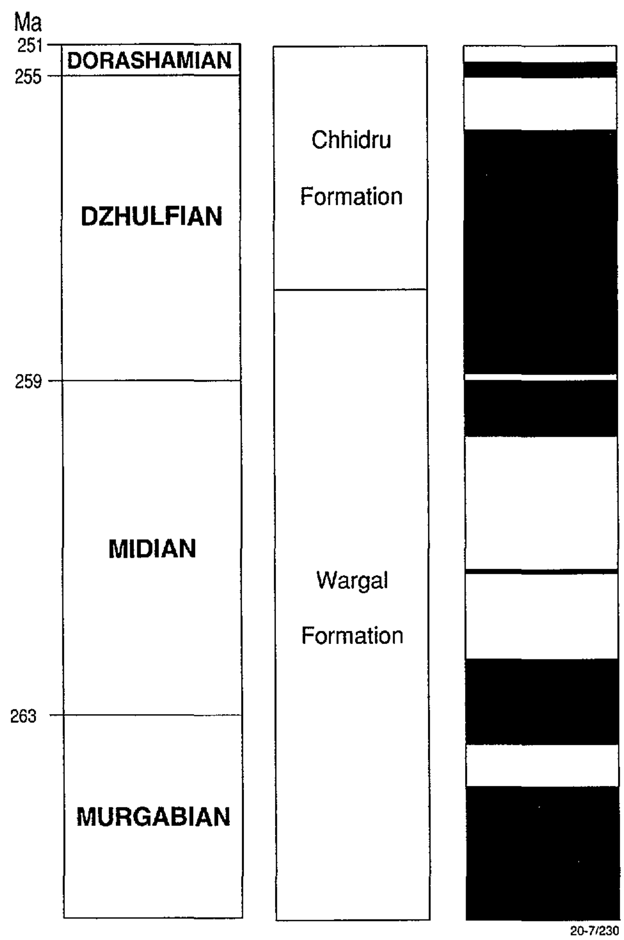


Fig.12 Magnetostratigraphic polarity profile for the Upper Permian of the Nammal Gorge, Salt Range, Pakistan, redrawn after Haag and Heller (1991, fig.8).

Group directly below the Pictou Group, corresponding with the upper Westphalian A. Subsequent work by DiVenere and Opdyke (1988,1990,1991a) of nearby and correlatable sequences on the Maringouin Peninsula of New Brunswick provided a detailed series of polarity reversals (Fig.9) in the Maringouin Formation, Shepody Formation, Claremont Formation and in the base of the Boss Point Formation, with more isolated observations of exclusively reverse polarity in the remainder of the Boss Point Formation and the overlying Joggins Formation. These observations locate the base of the PCRS somewhere within the Westphalian A, although the biostratigraphic control for such an age can be questioned (P. Jones, pers. comm.,1993,1994) from re-evaluation of the original studies (Belt,1965; Hacquebard,1972). Additional age control on the base of the PCRS comes from studies of the Minturn Formation in Colorado (Miller and Opdyke,1985; Magnus and Opdyke,1991), which showed exclusively reverse polarity. This further constrains the base of the PCRS to below the Minturn Formation of Atokan-Desmoinesian age, and thus to an early Atokan (Westphalian B) or older age.

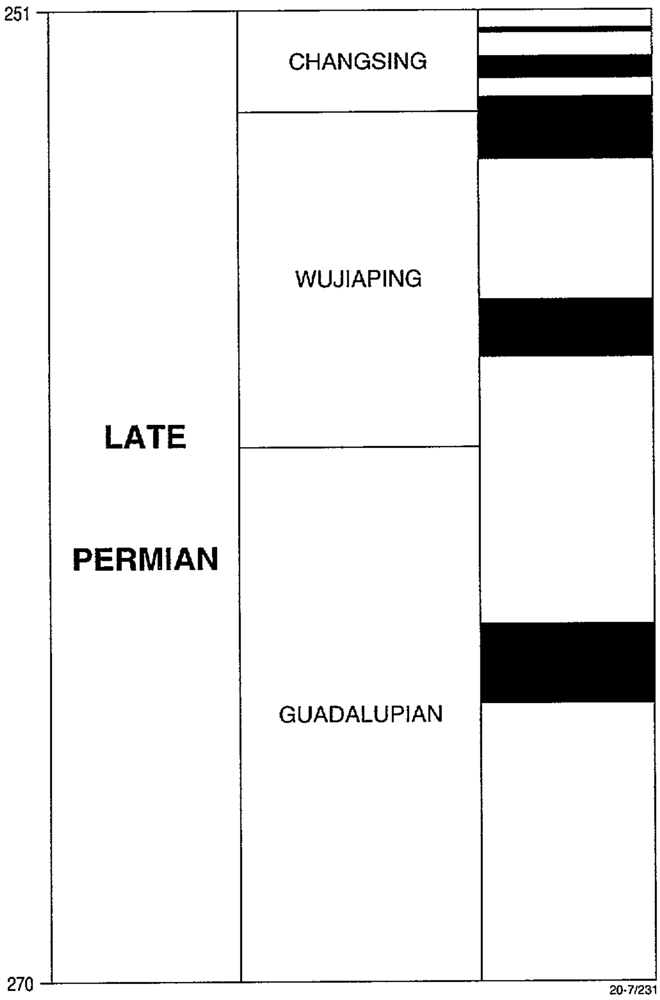


Fig.13 Late Permian magnetic polarity sequence from Sichuan, China, after Steiner et al. (1989, fig.13).

Early Russian studies (for compilation see Khramov and Rodionov,1981; Khramov,1987) identified the base of the PCRS from the occurrence of a single normal polarity subzone in the uppermost Moscovian (Fig.10). This interpretation disagrees with the positive findings by Opdyke and coworkers and Roy and coworkers in Nova Scotia-New Brunswick for an older upper Westphalian A age for the base of the PCRS. Location of the base of the PCRS at the normal polarity subzone in the Middle Bashkirian (Fig.10) seems a far more reasonable proposition. Opdyke *et al.* (1993) claim on the basis of preliminary, and as yet undocumented, results from magnetostratigraphic studies on sections in the Russian Donets Basin, taken as time equivalent to the Early and Middle Morrowan, that they have not been able to verify earlier Russian studies of the basin. If substantiated, this finding would put doubt on the previously determined base of the PCRS in the uppermost Moscovian.

Permo-Carboniferous Reverse Superchron (PCRS)

The extent of the PCRS is mainly determined from compilation studies (Pullaiah and Irving,1976;

Khramov and Rodionov,1981; Khramov,1987; Molostovskiy,1992; Solodukho *et al.*,1993). Only a few earlier studies have attempted to establish the full extent of the superchron (e.g. McMahon and Strangway,1968). Naturally, there has been some emphasis on the establishment of possible normal polarity subchrons within the superchron as global correlation datums. A few claims for their existence have been made, but none has been corroborated by independent studies using modern reliability standards. The "Quebrada del Pimiento event" (Valencio and Mitchell,1972; Valencio and Vilas,1972; Valencio *et al.*,1977), with a K-Ar age of 263$\pm$5 Ma (old decay constants), may postdate the PCRS and form part of the succeeding Illawarra Superchron. Normal polarity observations in middle Leonardian (late Early Permian) formations of southwestern North America (Peterson and Nairn,1971) are based upon thermal cleaning procedures that are less detailed than current standards would require. The observations have not been confirmed. Russian compilations (McElhinny,1969; Khramov and Rodionov,1981; Khramov,1987; Molostovskiy,1992; Solodukho *et al.*,1993) show a normal polarity subchron in the earliest Asselian (Fig.10), directly above the Permo-Carboniferous boundary. This magnetic subzone apparently has been observed in two different sections. It is, therefore, to be given some credence despite the lack of positive identification elsewhere. A suggested correlation (McElhinny,1969; Burek,1970; McElhinny and Burek,1971) with two observations of normal polarity in beds near to the Permo-Carboniferous boundary - the Supai Formation at Oak Creek Canyon of Arizona (Graham,1955) and the Dunkard Series in the Appalachians of West Viginia (Helsley,1965) - is tenuous because these observations were based on results that had not been cleaned magnetically. In any case, coining of the term "Oak Creek Event" (McElhinny,1969; McElhinny and Burek,1971) or its alias "Graham Event" (Burek,1970), may not properly reflect the more creditable observations of this event within the Permian stratotype sections.

Late Permian magnetostratigraphy and top of the PCRS

Major defining studies

A detailed magnetostratigraphic study on the Permo-Triassic boundary succession at the Nammal Gorge in the Salt Range, Pakistan (Haag and Heller,1991) has documented various normal and reverse polarity intervals in the uppermost Permian Chhidru and Wargal Formations. Thus the mixed polarity regime of the Illawarra Superchron had already been established in the Murgabian (possibly Midian according to Leven,1993, and Mac Dickins, pers. comm.,1994) of the central Tethys (Fig.12), which may be equated with the Guadalupian of North America and the Kazanian of the International Scale. The end of the PCRS thus predates the Tatarian, taken by most earlier workers, Russian in particular (Fig.11), to contain the changeover from the PCRS to the Illawarra Superchron. Magnetostratigraphic studies on Permo-Triassic boundary successions in the Sichuan province of southcentral China (Heller *et al.*,1988; Steiner *et al.*,1989) do not provide the same level of detail as the Nammal Gorge study (Haag and Heller,1991). The latter supersedes the compilation (Fig.13) of Permo-Triassic data available to Steiner *et al.* (1989).

Russian studies on Permian stratotype sections of Russia and Tatarstan (Khramov and Rodionov,1981; Khramov,1987; Molostovskiy,1992; Solodukho *et al.*,1993) have located the PCRS-Illawarra Superchron changeover at the boundary between the Lower and Upper Tatarian (Fig.10). This is in conflict with the finding of Haag and Heller (1991) for a Murgabian or earlier ending of the PCRS.

Facer (1981) in a cursory study of the magnetostratigraphy of drillcores from the Illawarra Coal Measures of the southern Sydney Basin, claimed the location of the PCRS-Illawarra Superchron boundary to be

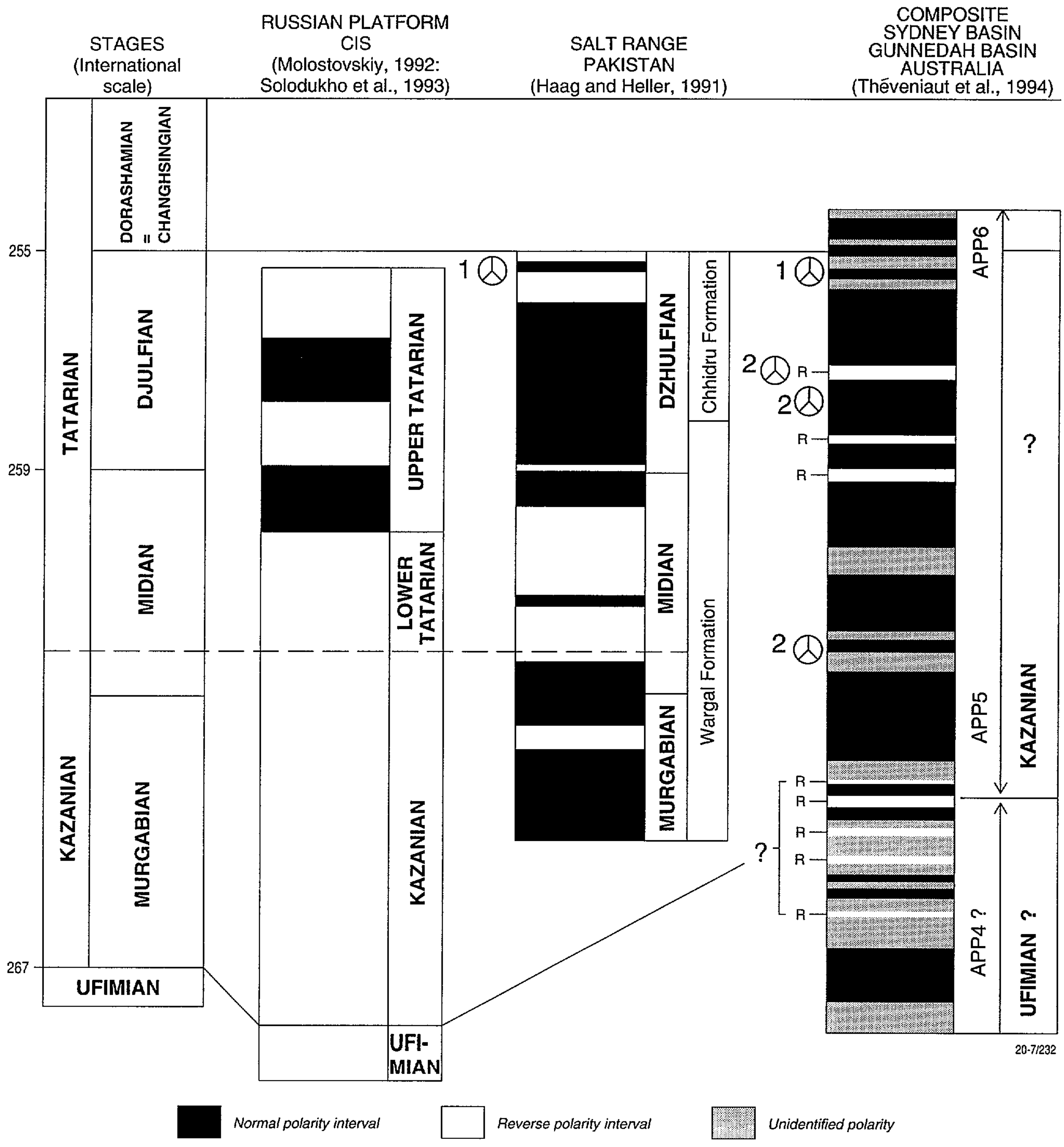


Fig.14 Tentative global correlation of Late Permian magnetostratigraphic profiles. 1 = Protohaploxypinus microcorpus Zone, 2 = Dulhuntyispora parvithola Zone (= AAP5). Reference timescale after Archbold & Dickins (1991), Kapoor (1992) and Kozur (1992). Salt Range timescale adapted after Pakistani-Japanese Research Group (1985).

in the lower part of the coal measures, near the Appin Formation and Tongarra coal seam. Limited thermal cleaning, however, may not have been fully successful in separating the primary polarity record from a pervasive normal polarity overprint of mid-Cretaceous origin that is well-developed along the Tasman seaboard. Pending further substantiation of Facer's claim, this has left the stratigraphic location of the "Illawarra Reversal" in its type region no better established than between the top of the Gerringong Volcanics (Irving and Parry,1963) and the base of the Narrabeen Group (Embleton and McDonnell,1980). A study in progress of drillcores through the coal measures of the Sydney Basin (Illawarra Coal Measures, Newcastle Coal Measures, Wittingham Coal Measures) and Gunnedah Basin, backed-up with outcrop samples from tuffs in the Newcastle Coal Measures and volcanics and sediments from the Gerringong Volcanics (Théveniaut *et al.*,1994), indicates that the top of the PCRS has apparently not yet been reached in any of the cores. This locates the upper boundary of the PCRS somewhere between the top of the Gerringong Volcanic Facies and the studied lower part of the Wittingham Formation from the northwestern Sydney Basin (Fig.14). Palynological control of the Wittingham Formation (C. Foster, pers. comm.,1994) indicates an Early Kazanian to possibly Ufimian age for the studied lower part with mixed polarity. A younger, possibly, Early Kazanian age (Mac Dickins, pers. comm.,1994) is indicated, however, by comparison of foraminiferal control and SHRIMP U-Pb dates for the underlying marine Mulbring Siltstone with the Ingelara Formation of the Bowen Basin. If sustained by further work, such observations date the end of the PCRS as no younger than Early Kazanian.The early end of the PCRS indicated by the preliminary findings of the "Illawarra Reversal" study appears to be supported by the well-established normal polarity observations of Murgabian age in the basal part of the Nammal Gorge magnetostratigraphic profile (Fig.14). These results highlight an emerging contradiction concerning the age of the younger end of the PCRS. On the one hand we now have evidence for an Early Kazanian to Ufimian age from the sections of the continental eastern Australian coal measures and a Murgabian or older age from the marine Nammal Gorge section of the Salt Range. On the other hand, a younger Early to Late Tatarian age is concluded for the younger boundary of the PCRS from the Upper Permian stratotypes in Tatarstan and Russia (Fig.14). Palaeontological control on the base of the Tatarian is reasonably well-established, and a correlation with Australia through the marine Permian of Greenland, Austria and the Salt Range of Pakistan has been made (see Théveniaut *et al.*,1994). This correlation is not likely to be a source of discrepancy with regard to the age of the younger boundary of the PCRS. We cannot with confidence exclude the possibility that conflict may arise from unrecognized normal polarity overprints of Late Cretaceous age in the Australian data, whose effect would be to make an otherwise reverse polarity interval appear mixed. Such overprints are pervasive in rocks along the Tasman seaboard, but their effect is less severe inland. The mutually supportive interpretations for an older age from both continental sections (Sydney and Gunnedah Basins) and a marine section (Nammal Gorge, Salt Range) make it more likely that the cause of the discrepancy may have to be sought in the interpretation of palaeomagnetic results from the Late Permian stratotypes of Tatarstan and Russia, particularly in regard to possible hiatuses in the sedimentary succession and the preoccupation of the palaeomagnetic studies with red beds at the exclusion of other lithologies with lower magnetic intensity.

Supporting data

A magnetostratigraphic study of a Permo-Triassic type section at Biyulopaokutze in the northern Tarim Basin of NW China (McFadden *et al.*,1988, fig.7) claims location of the top of the PCRS within level 35 of the sequence. However, no stratigraphic detail is presented other than locating the Permo-Triassic boundary at the overlying level 41. The observed polarity reversal could represent the "Illawarra Reversal", but the correctness of the claim remains to be tested pending provision of further stratigraphic detail. Mixed polarities observed in the Dewey Lake Formation, Texas, of Kazanian to Tatarian (Ochoan) age (Molina-Garza *et al.*,1989) likewise represent the Illawarra Superchron. The lowermost observed reverse polarity zone has been suggested to represent the top of the PCRS, but this remains to be tested through magnetostratigraphic study of the underlying formations.

Some older observations of normal polarity magnetozones may provide additional constraints on occurrence of the PCRS-Illawarra Superchron changeover. Peterson and Nairn (1971) observed normal polarities in red beds from southwestern North America of late Guadalupian and middle to late Ochoan age. Although a primary origin has not been established beyond doubt, these normal polarity results have generally been interpreted in terms of possible normal polarity magnetozones within the PCRS. Following Haag and Heller's (1991) findings for a Murgabian or earlier onset of the Illawarra Superchron, they could possibly represent the latter. Valencio and Vilas (1972) have documented normal polarity results for igneous rocks of the Quebrada del Pimiento Formation in the Paganzo Group of Argentina with a K-Ar date of 263 ± 5 Ma (old decay constants) (Valencio and Mitchell,1972; Valencio *et al.*,1977; Valencio,1981). This observation has generally been interpreted as a normal polarity magnetozone within the PCRS. Haag and Heller's (1991) results suggest that this normal polarity magnetozone could postdate the PCRS and would thus constrain its upper boundary.

Extensive magnetostratigraphic studies have been carried out on Permo-Triassic successions within the Germanic facies realm (Burek,1970; Dachroth,1976,1988; Mauritsch and Rother,1983; Beres and Soffel,1985; Menning,1986; Menning *et al.*,1988; Turner *et al.*,1989). These studies generally have no detailed biostratigraphic control and to be of use in regional correlation they will have to rely on external studies for calibration and the proper stratigraphic location of the PCRS-Illawarra Superchron boundary.

A magnetostratigraphic study on drillcore and outcrop material of the Upper Permian Bellerophon Formation and the Lower Triassic Werfen Formation of the Carnian Alps (Zeissl and Mauritsch,1991) showed mixed polarities throughout the studied succession. The authors, however, do not judge the record to be a reliable reflection of Permo-Triassic magnetostratigraphy, as it is beset with pervasive overprints acquired during the Cretaceous Normal Polarity Superchron and of Recent origin.

TRIASSIC TO MIDDLE JURASSIC MAGNETOSTRATIGRAPHY (Hervé Théveniaut)

General remarks

The establishment of a detailed magnetostratigraphy for the Triassic to Middle Jurassic has made good progress over the past decade. Handschumacher *et al.* (1988) identified the M25-M38 polarity sequence from magnetic lineations of the Northwest Pacific and dated the oldest magnetic anomalies as Callovian-Bathonian in age. This sequence of frequent reversals contradicts the existence of a Jurassic "Quiet Zone" as suggested in earlier analyses of the M-sequence of magnetic anomalies (Larson and Hilde,1975; Cande *et al.*,1978; Vogt and Einwich,1979). The interpretation of the M25-38 sequence is supported by magnetostratigraphic studies of Middle and Late Jurassic successions in northern Spain (Steiner *et al.*,1986), northern Italy (Channel *et al.*,1990) and Poland (Ogg *et al.*,1991) indicating frequent magnetic reversals comparable to the Pacific marine magnetic anomaly profiles, although not directly correlatable. The M25-38 sequence represents the oldest marine anomaly record currently identified, thus for times prior to the Callovian-Bathonian time boundary the magnetic polarity sequence has to be defined from stratigraphic profiles. In order to provide adequate biostratigraphic control, such studies have generally been undertaken on marine sedimentary successions with well-defined ammonite or conodont zonations.

Good polarity control can be obtained from land sections, but there are several pitfalls that have to be considered in order to arrive at a reliable magnetostratigraphy:

- Many studies show polarity zones that are based on no more than a single sample. These are generally taken as indicative for the polarity pattern, even though such observations are not statistically significant.

- The magnetostratigraphic detail that can be extracted from a section is, in part, a function of the sedimentation rate. Variations in sedimentation rate may lead to apparent fluctuations in reversal rate or to erroneous correlations between successions of equivalent age, particularly for periods of medium to high reversal frequency.

- Biostratigraphic control for continental sedimentary successions is generally far less detailed than for marine sediments. Thus hiatuses may not be identified and sampling densities may be inadequate for proper resolution of magnetostratigraphic detail.

Selected Early Triassic to Bathonian magnetostratigraphic profiles are presented in Figures 15-18. Their applicability as reference profiles is discussed below with respect to precision of results, accuracy of biostratigraphic control, and completeness of coverage per stage, period or biozonation.

Triassic

Many Triassic magnetostratigraphic studies have been carried out on continental successions in fluvial or lacustrine environments (e.g. Helsley,1969; Reeve and Helsley,1972; Baag and Helsley,1974a,b; Helsley and Steiner,1974; Steiner and Helsley,1974; Larson *et al.*,1982; Shive *et al.*,1984; McIntosh *et al.*,1985; Molina Garza *et al.*,1991; Witte *et al.*,1991; Steiner *et al.*,1993). Most of these studies were undertaken on rocks from the Colorado Plateau primarily for correlation purposes and to add magnetostratigraphic control to meagre biostratigraphic control. However, recent magnetostratigraphic studies of marine sediments from widely separated regions in Canada, China, Austria and Turkey have provided magnetically precise results with more accurate biostratigraphic control. These marine sections are more promising for the establishment of a magnetostratigraphic time scale, despite current problems with incomplete records, absence of stability tests, and sometimes considerable dispersion within the data.

Early Triassic

Magnetostratigraphic data for the Early Triassic have been obtained mostly as part of wider studies on the Permo-Triassic boundary (Heller *et al.*,1988; Steiner *et al.*,1989; Haag and Heller,1991). Various studies show the occurrence of a normal polarity interval during the earliest Triassic, but data gaps in all current studies prevent identification of the magnetic polarity at the Permo-Triassic boundary. Recently, however, a nearly complete magnetic polarity pattern (Fig.15) was obtained from a continuous Lower Triassic succession in the Canadian Arctic (Ogg and Steiner,1991). The magnetostratigraphy

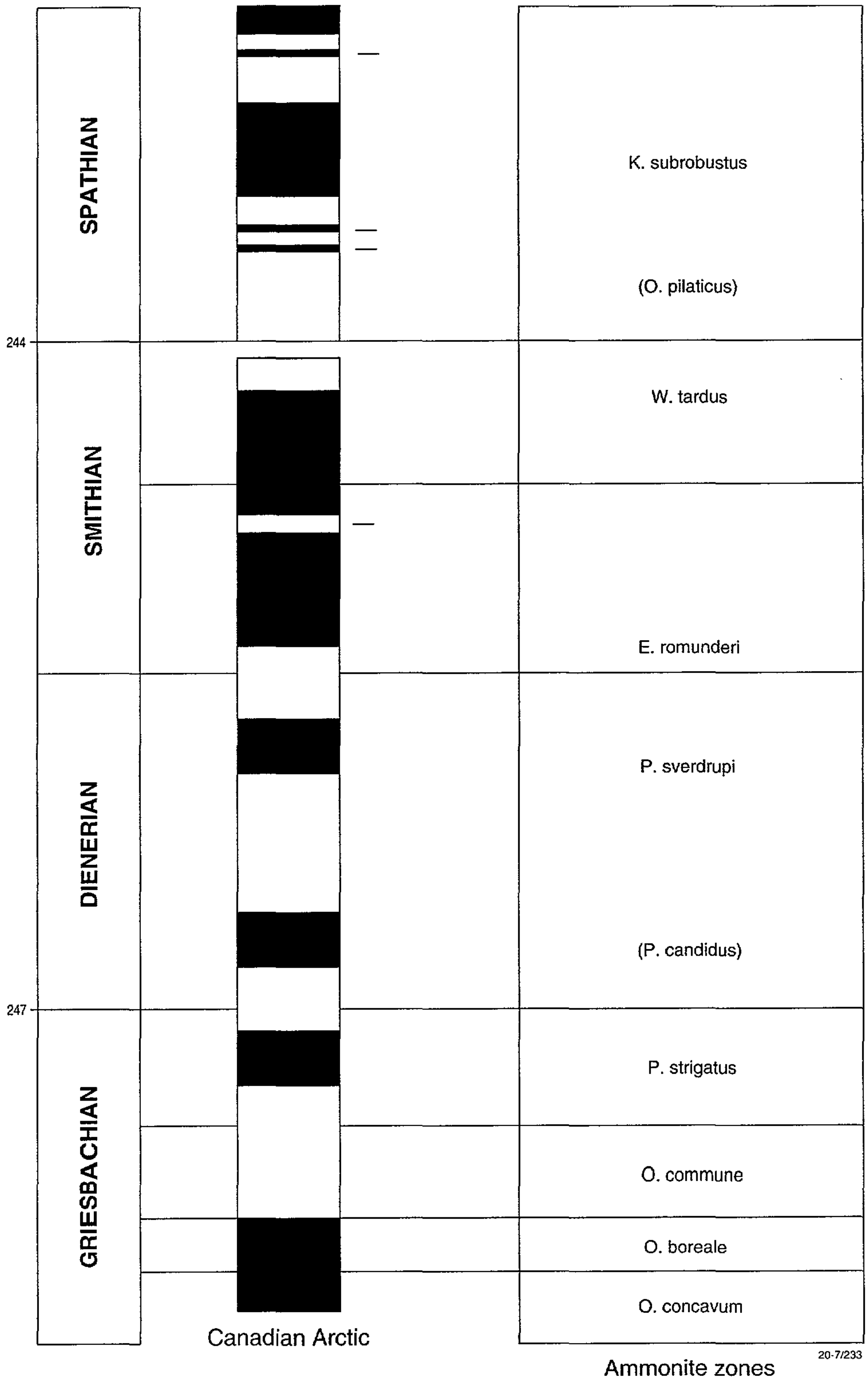


Fig.15 Early Triassic magnetostratigraphy obtained from the Canadian Arctic Archipelago (Ogg and Steiner,1991). Figure redrawn from the original composite diagram with stages taken to be of uniform duration.

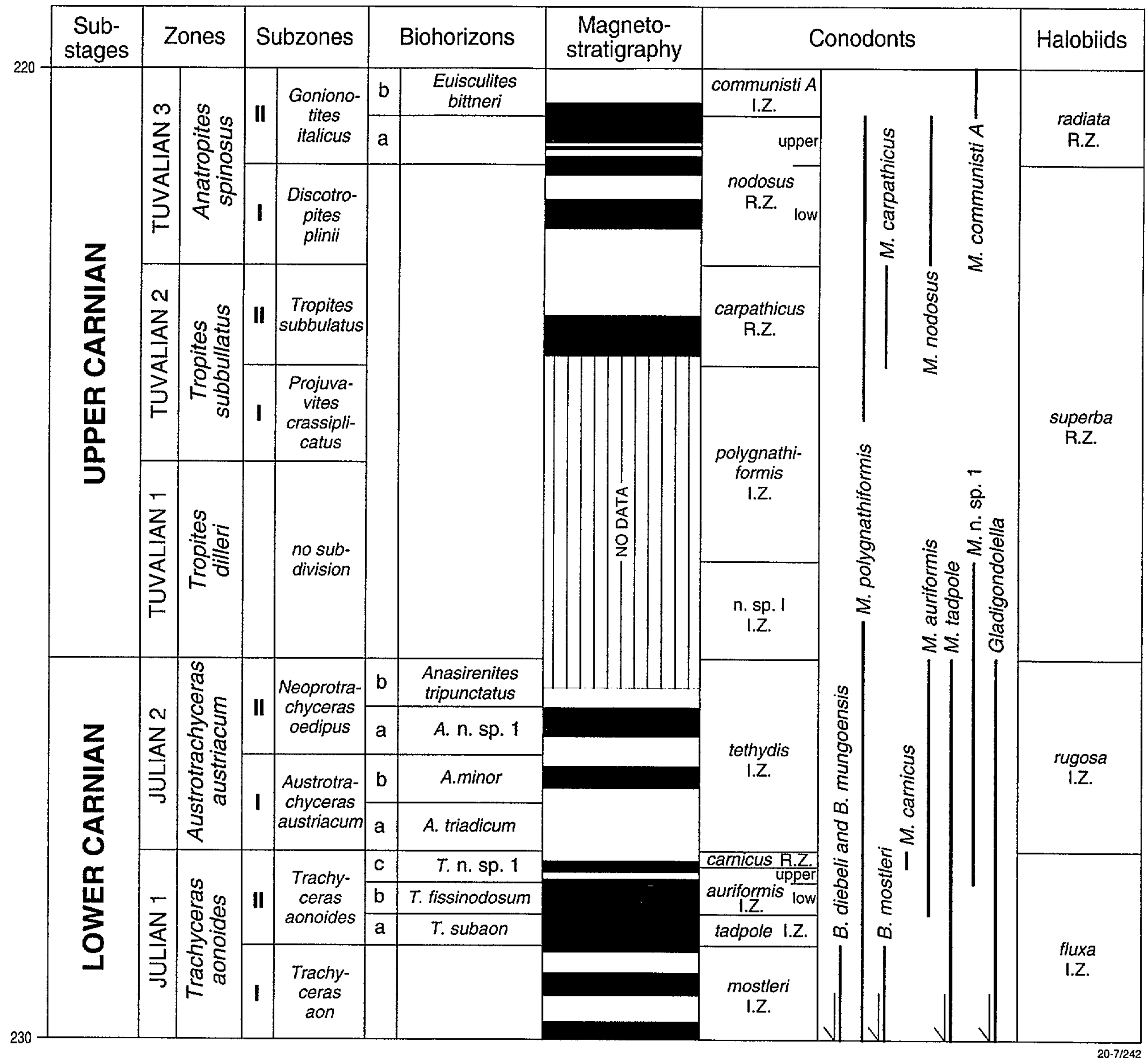


Fig.16 Carnian composite magnetostratigraphy obtained from southwestern Turkey and Austria (Gallet et al.,1992,1994).

could be tied in with ammonite zonations from stratotype sections. Magnetostratigraphic studies undertaken on Lower Triassic sections in China (Heller *et al.*,1988; Steiner *et al.*,1989) are hampered by the absence of well-defined stage boundaries. For instance, the Feixianguan Formation has a Griesbachian succession that is well-calibrated in time but is considerably condensed, and a Dienerian succession cannot be clearly identified. The Smithian and Spathian stages are evident in the Jialingjiang Formation from conodont zonations, but without precision on their timespan.

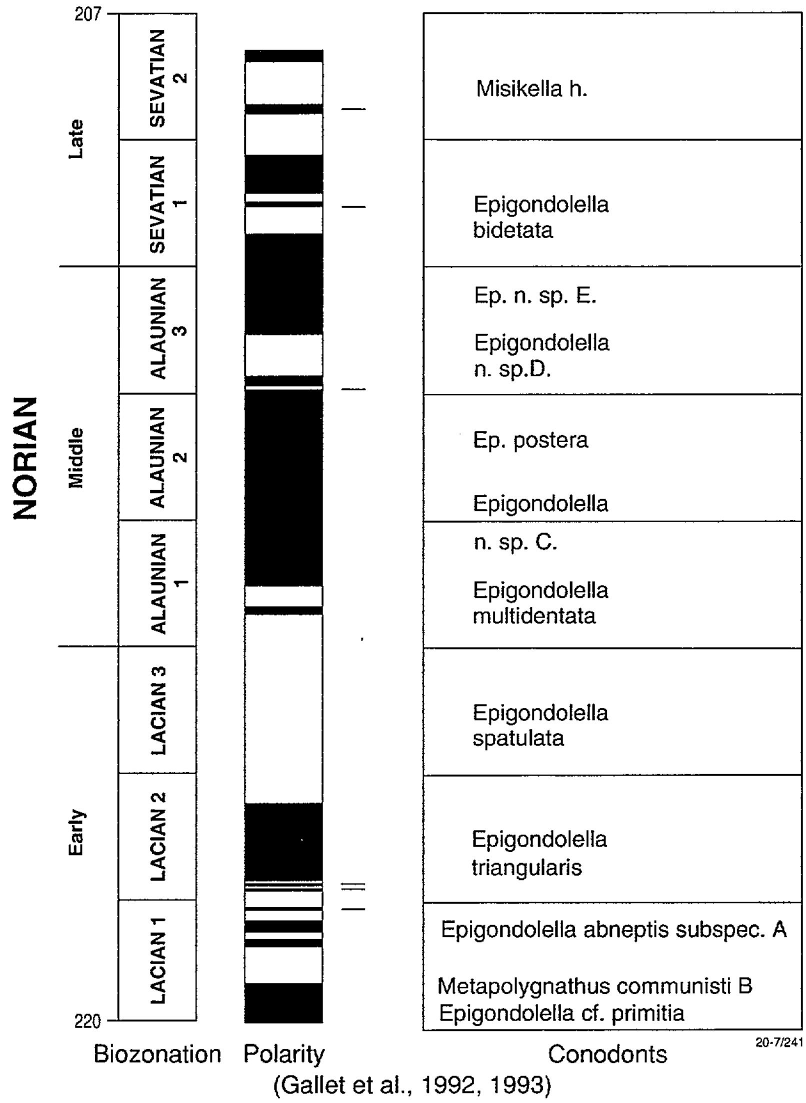


Fig.17 Norian composite magnetostratigraphy obtained from southwestern Turkey (Gallet et al.,1992,1993). Figure redrawn from the original papers, with ammonite zones taken to be of uniform duration.

The stratotype succession of the Canadian Arctic could be taken as the reference magnetostratigraphic succession for the Early Triassic (Fig.15). Ogg and Steiner's (1991) results for this succession appear similar to the composite magnetostratigraphy compiled by Steiner *et al.* (1989) from worldwide data, with more accurate biostratigraphic control, and with a more adequate time resolution of around 0.04 myr/sample.

Middle Triassic

Detailed magnetostratigraphic results are not available for the Middle Triassic. Occurrence of normal polarity has been suggested for the earliest Anisian and the latest Ladinian (Ogg and Steiner,1991; Gallet *et al.*,1992). Interrogation of the Global Palaeomagnetic Database (McElhinny and Lock,1990,1993; Lock and McElhinny,1991) shows a mixed polarity record for the Middle Triassic.

Late Triassic

Three recent studies by Gallet *et al.* (1992,1993,1994) give detailed magnetostratigraphic results for the Late Triassic. The results come from pelagic carbonates of South Tethyan successions in the Antalya region of southern Turkey and the northern Calcareous Alps of Austria. The three studied sections have precise biostratigraphic control from ammonites and conodonts and define a detailed magnetostratigraphic succession that covers the main part of the Carnian (Fig.16), apart from three biostratigraphic zonations in the mid-Carnian, and the whole of the Norian (Fig.17). The incomplete magnetic polarity time scale for the Carnian is established from 220 samples from three sections, details 24 polarity intervals, and has a time resolution of about 0.025 myr/sample for the Austrian section and between 0.05 and 0.1 myr/sample for the section in Turkey. The Norian time scale is established from 315 samples from two sections in southwestern Turkey, shows 30 polarity intervals, and has an average time resolution of 0.04 myr/sample. The three studies detail a total of 54 polarity intervals for the Late Triassic. This large number of reversals initially was perceived to conflict with magnetostratigraphic results obtained by Witte *et al.* (1991) from sequences in the Newark Basin of North America, which detail a lesser number of reversals. Problems with resolution through time and biostratigraphic control of the latter study were invoked by Gallet *et al.* (1993) in an attempt to explain these apparent discrepancies. Recently, however, Kent *et al.* (1993) reported the presence of 43 polarity intervals in the Late Triassic succession of the Newark Rift Basin. Although they lack biostratigraphic control, the large number of reversals for this period is confirmed by this study. The magnetostratigraphic results from Gallet *et al.* (1992,1993,1994) are supported further, in terms of the number of polarity intervals, by ODP Leg 122 results (Galbrun,1992; Galbrun *et al.*,1992) from the Wombat Plateau off northwestern Australia following biostratigraphic revision (Nicoll and Foster, 1994). Currently the Turkish and Austrian results represent the most complete and precise magnetostratigraphic record for the Late Triassic.

Jurassic

Early Jurassic

The magnetostratigraphy of the lowermost stage in the Jurassic, the Hettangian, is presently undefined.

The Sinemurian is poorly defined from two sections in the Umbrian Apennines, studied by Channel *et al.* (1984). Six polarity intervals were identified in the Fonte Avellana section and four intervals in the Cingoli section. There is no biostratigraphic control available for these two sections. A magnetostratigraphic correlation between the two sections is, therefore, tentative at best and the sections certainly do not qualify as reference sections.

The Pliensbachian is almost complete in the Breggia Gorge section (Fig.18) in the Southern Alps, only its very base is missing. The overlying Toarcian succession is less well-developed. Horner and Heller's (1983) study of the section provided a continuous magnetostratigraphic record. Results from the upper part of the section show a positive correlation with an uppermost Pliensbachian section from the Alpe Turati in the Italian Southern Alps, also detailed in the same study. Results from other Pliensbachian sections, i.e. the Fonte Avellana and Cingoli sections in the Umbrian Apennines (Channel *et al.*,1984) and the Baconycsernye section from the Transdanubian Central Mountains in Hungary (Marton *et al.*,1980), cannot be reliably correlated with the Breggia Gorge section. This is probably due to the condensed nature of the former sections, resulting in incomplete and less precisely defined reversal patterns.

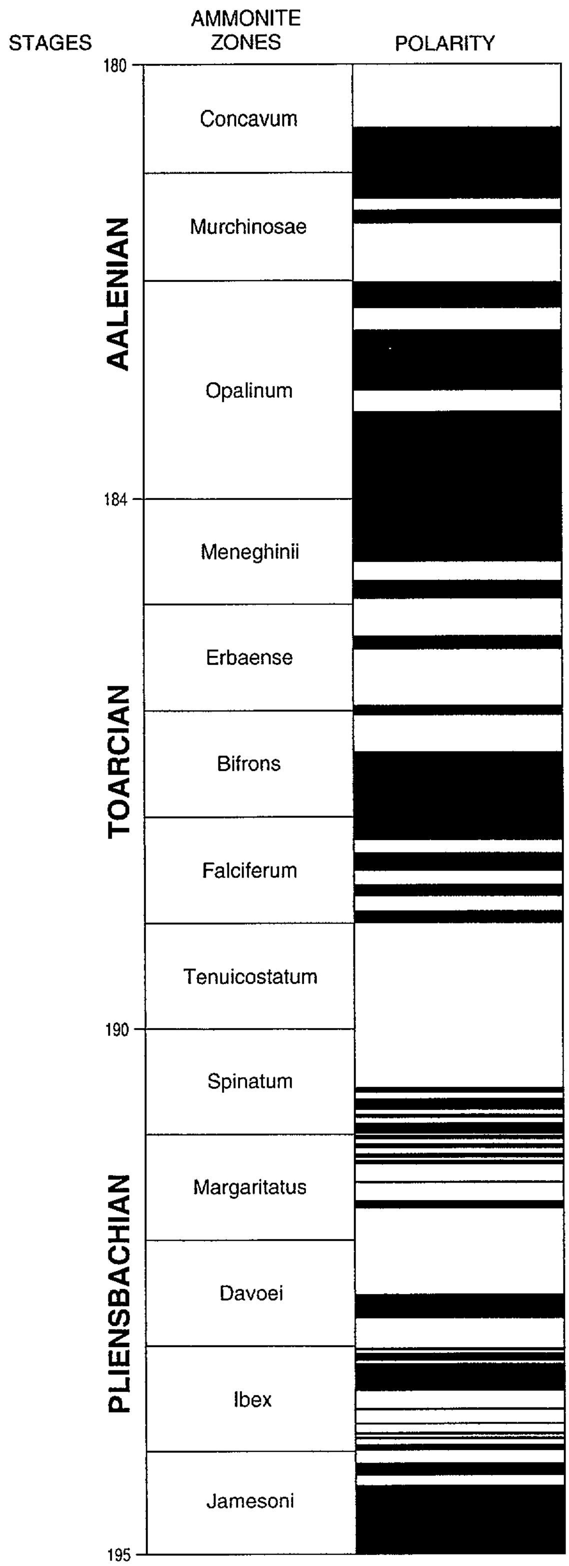
The various studies that have been carried out on Toarcian successions exemplify the problems confronting definition of a magnetostratigraphy. Study of Toarcian type sections at Thouars and Airvault in western France by Galbrun *et al.* (1988) showed an incomplete, although biostratigraphically precisely controlled, magnetostratigraphy, reflecting the condensed nature of the sections. Channel *et al.* (1984) interpreted fifteen polarity intervals from their study of the middle and upper part of the Toarcian section in the Valdorbia section of the central Appennines, but a third of the polarity intervals appear poorly-defined magnetically. Galbrun *et al.*'s (1990) study of the Iznalloz section in the Betic Cordillera of Spain showed a total of 28 polarity intervals for the entire Toarcian succession. The polarity intervals are, however, poorly-defined and sampling is not continuous. This section has potential as a reference section, should higher quality and more detailed results become available. The best defined magnetostratigraphic results for the Toarcian available so far come from Horner and Heller's (1983) study of the Breggia Gorge section in the southern Alps. The section was sampled in detail with an average time resolution of 0.07 myr/sample, has precise biostratigraphic control, and shows well-defined polarity intervals. This study may well be used as the best established polarity sequence for this stage (Fig.18), although a few reversals may have been missed because of the low sedimentation rate.

Middle Jurassic

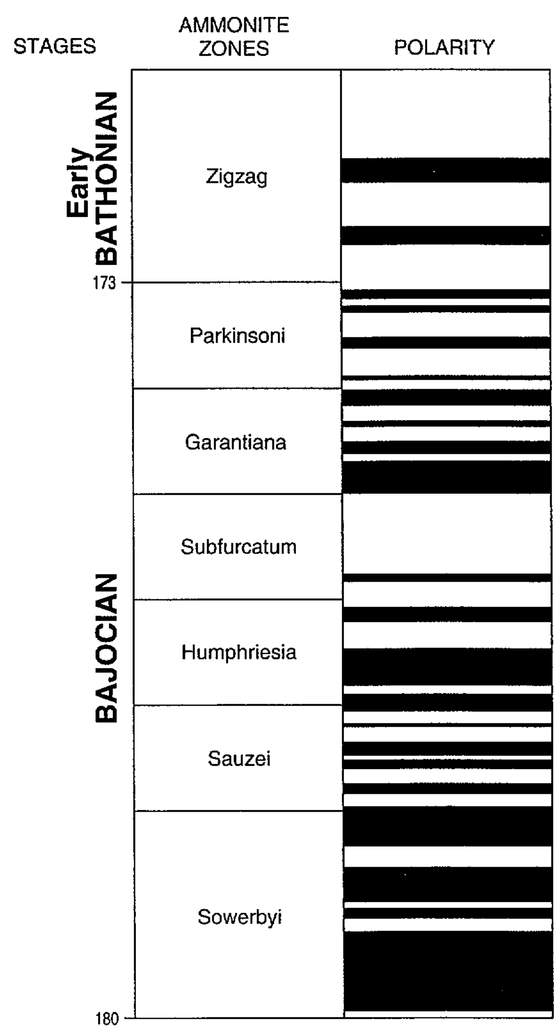
Steiner *et al.*'s (1987) study of the Carcabuey section from the Subbetic Cordillera in southern Spain represents the most complete study of the Bajocian currently available. Biostratigraphic control is good and sample density is high. Nevertheless, about half of the interpreted polarity intervals are based on single sample results only and need further confirmation.

The lowest ammonite zonation of the Bajocian (*Sowerbyi*) has also been documented from the Breggia Gorge section in the southern Alps (Horner and Heller,1983). The Breggia and Carcabuey sections show good correlation for the basal part of the *Sowerbyi* zone, which is characterized by the end of a reverse polarity interval followed by an interval of normal polarity. The magnetostratigraphy for the underlying Aalenian is also documented in the studies of Steiner *et al.* (1987) and Horner and Heller (1983), as well. The good correlation that was observed between the two studies for the lowermost Bajocian succession holds also for the uppermost Aalenian succession. Whereas the magnetostratigraphy and biostratigraphy for the whole of the Aalenian was established in the Breggia Gorge section (Horner and Heller,1983), biostratigraphic control is only available for the lower part of the Aalenian succession in the Valdorbia section (Channel *et al.*,1984). Despite the fact that only about half of the polarity intervals defined in the Breggia Gorge section are identified in the Valdorbia section, correlation of the base of the Aalenian stage is nevertheless possible between the two sections.

Fig.18 Early to Middle Jurassic magnetostratigraphy after Steiner et al. (1987) for the Early Bathonian and the Bajocian, and after Horner and Heller (1983) for the Aalenian to Pliensbachian. Results are redrawn from original papers with transformation of the original depthscale to a linear timescale following Burger (1990, Burger in Young and Laurie,1994).



Breggia Gorge
(Horner and Heller, 1983)



Composite Subbetic Cordillera
(Steiner et al., 1987) 20-7/235

Magnetostratigraphic data for the Bathonian are available from the Subbetic Cordillera in southern Spain. Although the whole of the Bathonian is represented, the three sections that were studied by Steiner *et al.* (1987) appear generally too condensed to provide a detailed and reliable reference magnetostratigraphy for the whole of this period. Only that part of the section containing the lowermost ammonite zonation (*Zigzag*) has provided a well defined reference magnetostratigraphy.

With the above limitations in mind, the magnetostratigraphy for the Aalenian zonations of the Breggia Gorge of the southern Alps (Horner and Heller,1983) and for Bajocian and the Early Bathonian ammonite zonations in the Betic Cordillera (Steiner *et al.*,1987) are the most complete and precise reference magnetostratigraphies currently available (Fig.18). Their time resolution is around 0.04 to 0.06 myr/sample.

MIDDLE JURASSIC TO RECENT MAGNETOSTRATIGRAPHY (Mart Idnurm)

General remarks

Except for the past 5 myr, for which abundant data are available from continental sources, the reversal time scale for the Middle Jurassic to Recent is based on marine magnetic anomalies. As new seafloor is extruded at the mid-ocean ridges it becomes magnetised and adds the latest feature to the continuously evolving pattern of normal and reverse polarity lineations. If, as seems likely, the generation and outward spreading of the seafloor have been continuous, the lineations would represent a complete record of geomagnetic reversals. In addition, if the changes in the rate of spreading have been gradual, linear interpolation between a few well-dated reversals would provide ages for the other reversals. Combined with a briefness that is well beyond the resolution of isotopic methods, and their global synchroneity, the reversals potentially provide a very precise time-correlation scale.

The main task in establishing the reversal time scale has been its absolute time calibration. The first calibration for the entire Cenozoic reversal sequence was obtained from South Atlantic seafloor anomalies by Heirtzler *et al.* (1968) who assumed in the calculation that the rate of seafloor spreading had been constant. This rate was estimated from a single lineation dated at 3.4 Ma. Since the initial calibration, the number and quality of age controls have improved greatly, giving better estimates for seafloor spreading rates. Nevertheless, the present calibration remains still based on only few data, especially for the Jurassic and Early Cretaceous.

The most direct method of calibration would be by dating of the basalts that cause the oceanic magnetic anomalies. Although developments in the ^{40}Ar-^{39}Ar technique appear promising (McWilliams,1993), the K-Ar ages of oceanic basalts are at present not considered sufficiently reliable. The volcanics are usually altered and have therefore lost or gained radiogenic argon and, because of the hydrostatic pressures at the ocean floor, it is not certain whether the K-Ar system is reset during solidification of the magma by removal of all argon (McDougall,1974), as required for the age calculations. Therefore indirect methods are used. Currently these are based on sedimentary reference sections (marine or continental) in which a dated biozone or stage boundary has been located in a specific part of the reversal pattern. Correlation of the pattern with seafloor lineations provides the calibration point. For example, Cande and Kent (1992a) obtain one of their calibration points from a deep-sea drillcore where the lower boundary

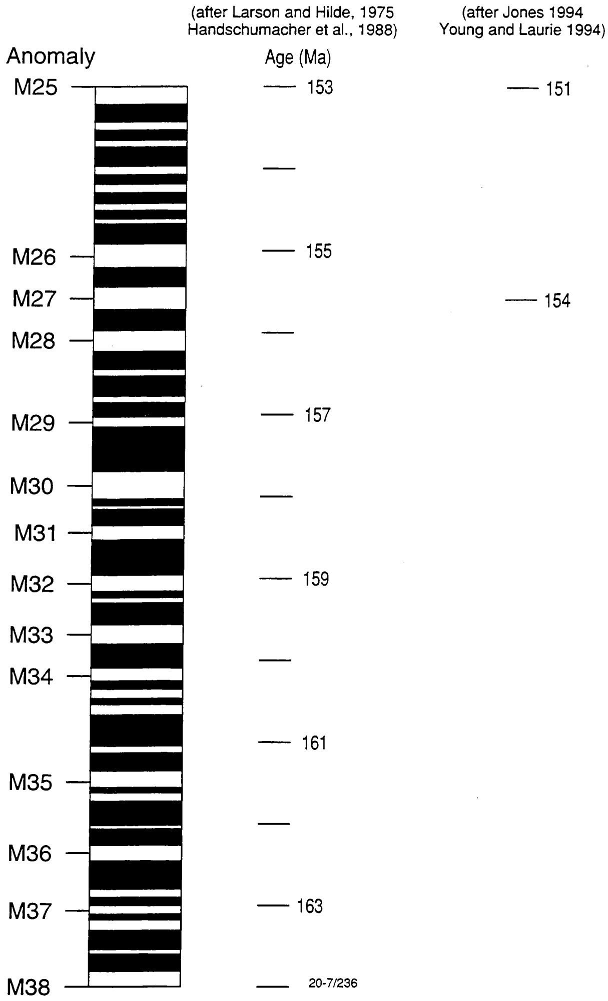
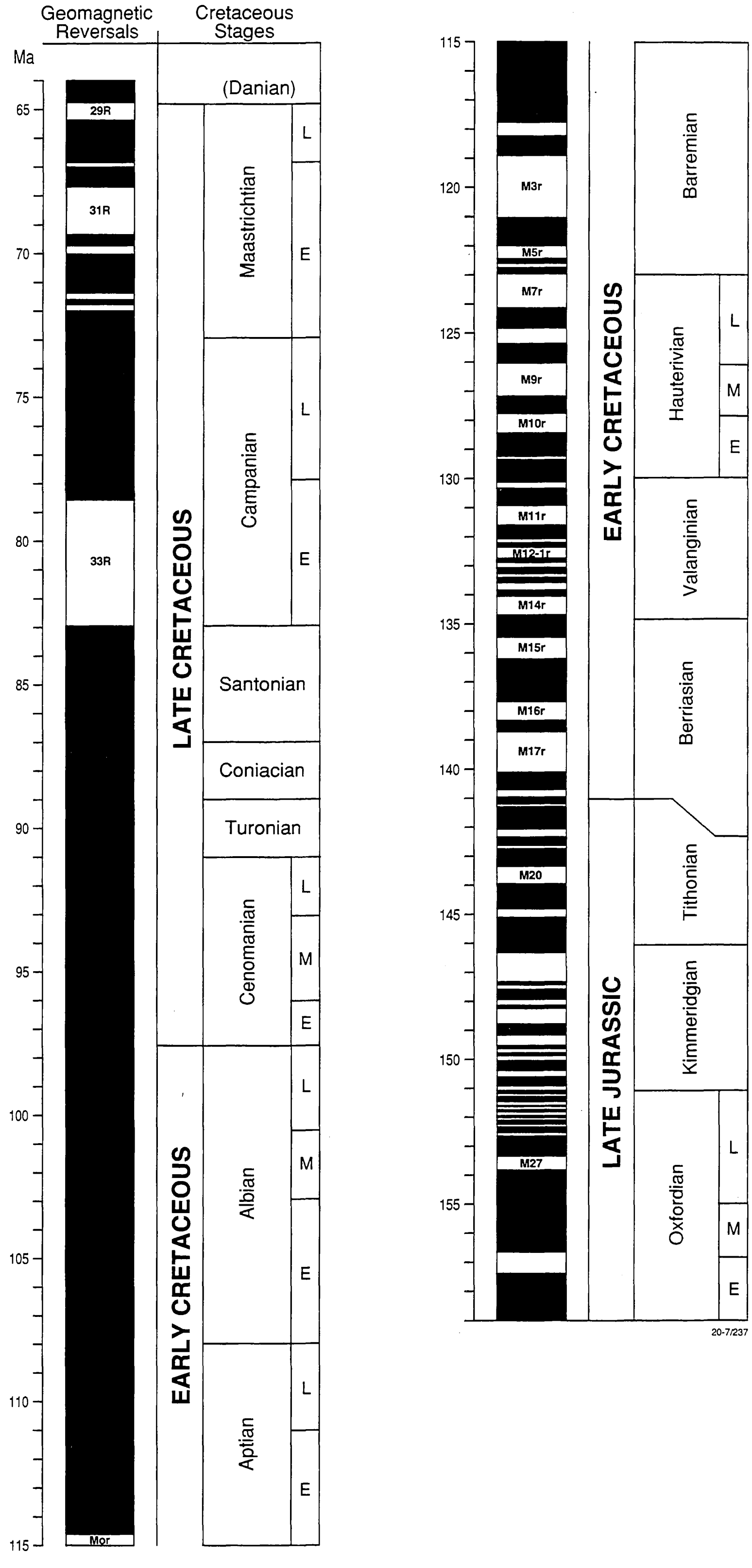


Fig.19 Older part of the Jurassic marine anomaly record, (after Handschumacher et al.,1988). Anomalies M30-M38 from the western Pacific Ocean have been tentatively interpreted by Handschumacher et al. as reverse polarity magnetisations. The left-hand timescale is based for anomalies M29-M25 on Larson and Hilde (1975), and for anomalies M38-M30 on extrapolation beyond 157 Ma of Larson and Hilde's time scale on the assumption that the seafloor spreading rate had been constant. The right-hand timescale shows some corresponding ages according to Jones (1994) and Young and Laurie (1994).

of the N9/N10 planktonic foraminiferal zone is linked to the younger part of chron C5Bn (Miller et al.,1985). This boundary had been dated elsewhere by ^{40}Ar-^{39}Ar as 14.8 Ma (Tsuchi *et al.*,1981; Andreieff *et al.*,1976), giving the calibration point. This, together with dates of several other magnetic lineations, defines an age-distance plot for the seafloor, from which the ages of the remaining lineations can be obtained by interpolation along the best fit to the plot.

The above procedure contains several uncertainties. First, the stratigraphic boundaries may not have been located accurately within the reference section. Second, the biozones may be time-transgressive


Geomagnetic Reversals
Cretaceous Stages
Ma
(Danian)
29R
31R
33R
Mor
LATE CRETACEOUS
EARLY CRETACEOUS
Maastrichtian
Campanian
Santonian
Coniacian
Turonian
Cenomanian
Albian
Aptian
M3r
M5r
M7r
M9r
M10r
M11r
M12-1r
M14r
M15r
M16r
M17r
M20
M27
LATE JURASSIC
Barremian
Hauterivian
Valanginian
Berriasian
Tithonian
Kimmeridgian
Oxfordian
20-7/237

over long distances. Third, the isotopic ages may not be secure, as seen for example in the recent revision of the Brunhes-Matuyama boundary from 0.73 to 0.78 Ma (Baksi *et al.*,1992; Spell and McDougall,1992) or of the Oligocene-Eocene boundary from 36.4 Ma (Harland *et al.*, 1990) to 33.7 Ma (Odin *et al.*,1991). Fourth, and probably the largest uncertainty, is in the assignment of stage boundary ages by date bracketing (e.g., the chronogram technique). Therefore further significant revisions are likely. The following summarises briefly the current state of work on the Middle Jurassic to Recent reversal sequence (Figs 19-21).

Middle Jurassic to Early Cretaceous

The magnetostratigraphic time scales of Kent and Gradstein (1985) and Harland *et al.* (1990) extend to the Callovian/Oxfordian boundary, into what had been regarded as the younger part of the Jurassic Quiet Zone. Handschumacher *et al.* (1988) have identified from aeromagnetic data of the East Mariana Basin still older, low-amplitude anomalies (M30-M38) which they estimate to extend the time scale back by another 8 myr, i.e. to the Bathonian/Callovian boundary, (Fig.19). It is not completely certain that these anomalies represent reversals rather than, for example, variations in the geomagnetic field strength (Cande and Kent 1992b). However, at least the existence of reversals in the 'Jurassic Quiet Zone' has now been confirmed in Polish sequences (Ogg *et al.*,1991).

The time scale from Oxfordian to Barremian (Kent and Gradstein,1985; Harland *et al.*,1990) is based on the Hawaiian M (Mesozoic) lineations, which span chrons M29 to M0 (Fig.20). The Hawaiian set has been selected because of its completeness and relatively high resolution, especially in comparison with the Keathley set of the North Atlantic, where low spreading rates give a poorer resolution. However, some of the younger lineations in the Hawaiian set have not been identified in the Keathley set. This has raised the possibility that parts of the Hawaiian set may be duplicates due to faulting (Channell *et al.*,1987; Harland *et al.*,1990). Recent support for the Hawaiian set comes from measurements on sedimentary successions in the Umbrian Apennines of Italy (Channell and Erba,1992).

For time calibration, absolute age estimates have been obtained by interpolation for all Oxfordian to Barremian stage boundaries; however, only the estimates at each end of this period are considered reasonably well-determined (Kent and Gradstein,1985). Nevertheless, the latest calibration by Harland *et al.* (1990) uses the ages of all stage boundaries within this period irrespective of reliability and assumes that the rate of seafloor spreading has been constant throughout. Support for a constant rate has since come from Early Cretaceous sequences in the Umbrian Apennines (Channell and Erba, 1992). If the intermediate stage boundaries with poorly defined chronogram ages are excluded, as by Kent and Gradstein (1985), the calibration points change by up to 8 myr. Bralower *et al.* (1990) have subsequently obtained tight age estimates for the Jurassic-Cretaceous and Berriasian-Valanginian boundaries. Although consolidation of the Late Jurassic to Early Cretaceous time scale requires additional dates, few have been reported in recent years. Instead, most recent advances have been in linking the reversals to biostratigraphy. The latter studies have been principally on uplifted pelagic sequences in southern Europe, especially Italy. The reversals have been correlated with ammonite zonations in the Jurassic and Cretaceous, and with calpionellid, nannofossil and planktic foraminiferal zones in younger sequences. References to the various studies are listed in Channell and Erba (1992) and Ogg *et al.* (1991).

Fig.20 Late Jurassic and Cretaceous magnetostratigraphy after Burger in Young and Laurie (1994).

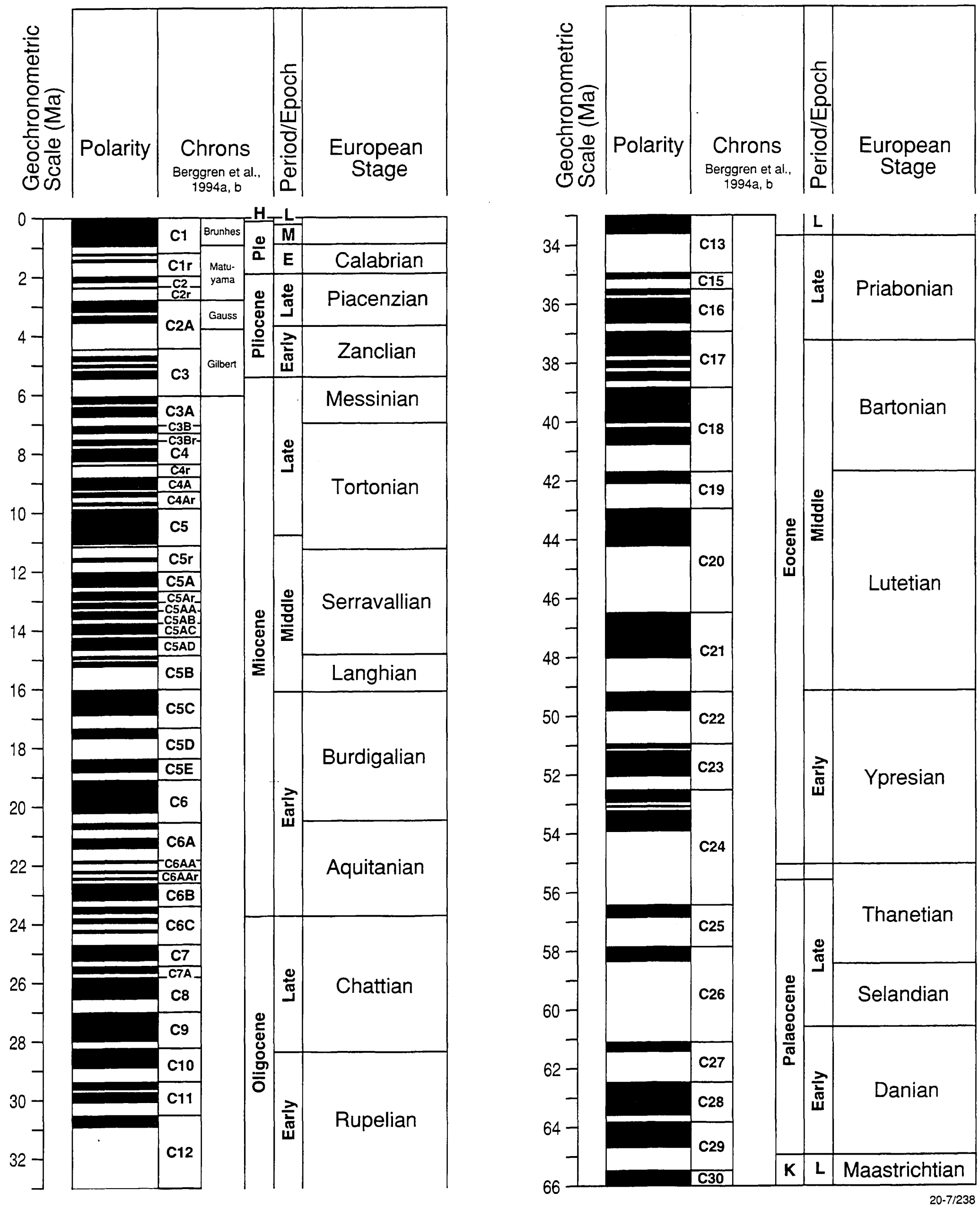


Fig.21 Cenozoic magnetostratigraphy after Truswell et al. (1991) and Chaproniere et al. (1994).

Cretaceous Normal Polarity Superchron

Only a few, brief intervals of reverse polarity have been reported within an ~45 myr period (chron 34N) that extends from the Aptian/Barremian to the Santonian/Campanian boundary (Fig.20) (e.g., within the Globigerinelloides algerianus Zone of late Aptian age: Van den Berg *et al.*,1978; Tarduno,1990). Magnetostratigraphy seems therefore not generally applicable to this period. However, a mixed polarity interval has been found in an Albian succession from the Umbrian Apennines, Italy (Tarduno *et* *al.*,1992).The reality of such short-lived reverse subchrons within the Cretaceous Normal Polarity Superchron can be questioned on theoretical grounds (P. McFadden, pers. comm.,1994; Merrill and McFadden,1994). Should these intervals prove to be genuine reversals, rather than an artefact of remagnetization, this would considerably extend the applicable time-range of magnetostratigraphy in the middle Cretaceous.

Late Cretaceous to Recent

For this period (chrons 34-1) the most recent time scale revision is by Cande and Kent (1992a). This timescale, with Cenozoic stage boundaries of Berggren *et al.* (1994), is shown in Figure 21. It is based on the South Atlantic and involves a revision of the relative spacing of the lineations. Cande and Kent's time scale differs from the preceding versions (Berggren *et al.*,1985; Harland *et al.*,1990) principally for the Palaeogene, where the revision reduces the chron ages by up to 3 myr. This difference is mainly due to a reassessment of the stage boundaries by Berggren *et al.* (1992) in response to mounting evidence for younger ages (e.g. Glass *et al.*,1986; Odin *et al.*,1991).

The Cande and Kent calibration uses the dates of nine stage boundaries selected at roughly equal intervals, and assumes that the rate of seafloor spreading varied smoothly. Not all of the available age constraints were used, and the inclusion of other ages could affect the calibration. While the main features of the reversal sequence appear to be reliably established, the existence of additional brief events remains uncertain. This is reflected in the omission by Cande and Kent (1992a) of some features in the oceanic magnetic profiles that had been interpreted in the earlier time scales as brief events.

Australian constraints

In Australia, magnetostratigraphic studies for the Jurassic to Recent period have been restricted to the latest Neogene and the Quarternary. These include both age dating and correlation, and have been carried out on beach ridges (Idnurm and Cook,1980), ephemeral and dry lakes (Singh *et al.*,1981; Chivas *et al.*,1986; An Zhisheng *et al.*,1986; McEwan Mason,1991; Cheng and Barton,1991) and vertebrate fossil sites (MacFadden *et al.*,1987; Whitelaw,1991a,b,1992). Notably lacking are attempts to link the reversal time scale to Australian biostratigraphy. Such links would show if the Australian biozones correspond to their inferred international equivalents, and would provide checks on possible time-transgressiveness of zonal boundaries.

HIGHLIGHTS OF PHANEROZOIC MAGNETOSTRATIGRAPHY

The magnetostratigraphic coverage of the Phanerozoic shows considerable variation in detail and quality. No more than a few dedicated magnetostratigraphic studies have been carried out on the lower and middle Palaeozoic, e.g. on the Precambrian-Cambrian boundary, the Cambro-Ordovician boundary and the Lower to Middle Ordovician. This interval, therefore, can only be described in terms of predominant polarity successions, not as magnetostratigraphic profiles. Some detailed magnetostratigraphic successions have been determined directly below the older boundary (Westphalian A?) and across the younger boundary (Tatarian-Kazanian?) of the PCRS. Its older boundary has not yet been determined. Its younger boundary has been determined at the Early to Late Tatarian boundary of the stratotype sections in Tatarstan and Russia, but global correlation with other continental and marine sections has not yet been established. The magnetostratigraphy of the Mesozoic and Cenozoic has been studied extensively. Considerable magnetostratigraphic detail is now available for the Triassic to Middle Jurassic

("Jurassic Quiet Zone") interval, although the coverage is not yet continuous with limited knowledge only for parts of the interval (e.g. earliest Jurassic). Continuous and detailed magnetostratigraphic control from both marine magnetic anomalies and continental sections is now available for the Middle Jurassic (post-"Jurassic Quiet Zone") to Recent interval with detailed biostratigraphic and good geochronologic control. Intervals of prolonged absence of reversals, such as the PCRS, the "Jurassic Quiet Zone" and the CNPS, restrict application of magnetostratigraphic correlation and dating to their boundaries, which represent very definite markers where properly defined.

ACKNOWLEDGEMENTS

We thank Zheng Xiang Li (University of Western Australia), Yves Gallet (Institut de Physique du Globe de Paris) and John Giddings (AGSO) for discussions on palaeomagnetic data. Contributors to the Phanerozoic Timescales Project were very generous with provision of biostratigraphic and chronostratigraphic constraints. We thank Dennis Burger, George Chaproniere, Mac Dickins, Clinton Foster, Peter Jones, John Laurie, Bob Nicoll, John Shergold and Gavin Young (AGSO) in particular. Figures were drafted by Rex Bates in his usual dependable and cheerful way. Phil McFadden, David Denham and John Giddings (AGSO) reviewed the manuscript and provided very thoughtful editorial comments.

REFERENCES

Andreieff, P., Bellon, H. and Westercamp, D., 1976. Chronométrie et stratigraphie comparée des édifices volcaniques et formations sédimentaires de la Martinique (Antilles françaises). Bulletin Bureau de Recherches Géologiques et Minières, 4: 335-346.

Anonymous,1979, Magnetostratigraphic polarity units, a supplementary chapter of the International Subcommission on Stratigraphic Classification, International Stratigraphic Guide. Geology, 7: 578-583.

An Zhisheng, Bowler, J.M. Opdyke, N.D. Macumber, P.G., and Firman, J.B., 1986. Palaeomagnetic stratigraphy of Lake Bungunnia: Plio-Pleistocene precursor of aridity in the Murray Basin, southeastern Australia. Palaeogeography, Palaeoclimatology, Palaeoecology, 54: 219-239.

Archbold, N.W. & Dickins, J.M., 1991. Australian Phanerozoic Timescales: 6. A standard for the Permian System in Australia. Bureau of Mineral Resources, Australia, Record 1989/36, pp17.

Baag, C. and Helsley, C.E., 1974a. Remanent magnetization of a 50m core from the Moenkopi formation, Western Colorado, Geophysical Journal Royal Astronomical Society, 37: 245-262.

Baag, C. and Helsley, C.E., 1974b. Evidence for penecontemporaneous magnetization of the Moenkopi Formation, Journal of Geophysical Research, 79: 3308-3320.

Baksi, A.K., Hsu, V., McWilliams, M.O. and Farrar, E., 1992. $^{40}Ar/^{39}Ar$ dating of the Brunhes-Matuyama geomagnetic field reversal. Science, 256: 356-357.

Belt, E.S., 1965. Stratigraphy and paleogeography of Mabou Group and related Middle Carboniferous facies, Nova Scotia, Canada. Geological Society of America Bulletin, 76: 777-802.

Beres, J. and Soffel, H., 1985. Magnetostratigraphie und Anisotropie der magnetischen Suszeptibilität von Proben aus der Forschungsbohrung Obernsees zwischen Bohrmeter 1341,15 und 1170,40 (Perm-Trias Übergang). Geologica Bavarica, 88: 153-161.

Berggren, W.A., Kent, D.V., Flynn, J.J. and Van Couvering, J.A., 1985. Cenozoic geochronology. Geological Society of America Bulletin, 96: 1407-1418.

Berggren, W.A., Kent, D.V., Obradovich, J.D. and Swisher III, C.C., 1992. Towards a revised Paleogene geochronology. In: D.R. Prothero and W.A. Berggren (Editors) Eocene-Oligocene Climatic and Biotic Evolution pp 29-45. Princeton University Press, Princeton, N.J.

Berggren, W.A., Kent, D.V., Swisher III, C.C. and Aubry, M.-P., 1994. A revised Cenozoic geochronology and chronostratigraphy. In: Berggren, W.A., Kent, D.V. and Hardenbol, J. (Eds.), Geochronology, timescales and global stratigraphic correlations: a unified temporal framework for an historical geology. Society of Economic Paleontologists and Mineralogists Special Publication, in press.

Bralower, T.J., Ludwig, K.R., Obradovich, J.D. and Jones, D.L., 1990. Berriasian (Early Cretaceous) radiometric ages from the Grindstone Creek Section, Sacramento Valley, California. Earth and Planetary Science Letters, 98: 62-73.

Bowring, S.A., Grotzinger, J.P., Isachsen, C.E., Knoll, A.H., Pelechaty, S.M. and Kolosov, P., 1993. Calibrating rates of Early Cambrian evolution. Science, 261: 1293-1298.

Briden, J.C. and 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.

Buchan, K.L. and Hodych, J.P., 1989. Early Silurian palaeopole for redbeds and volcanics of the King George IV Lake area, Newfoundland. Canadian Journal of E Sciences, 26: 1904-1917.

Burek, P.J., 1970. Magnetic reversals: their appl to stratigraphic problems. American Association of Petroleum Geologists Bulletin, 54: 1120-1139.

Burger, D., 1990. Australian Phanerozoic Timescales: 8. Jurassic Biostratigraphic Chart and Explanatory Notes. Bureau of Mineral Resources, Australia, Record 1989/38, pp32.

Cande, S.C., Larson, R.L. and Labrecque, J.L., 1978. Magnetic lineations in the Pacific Jurassic Quiet Zone. Earth and Planetary Science Letters, 41: 434-440.

Cande, S.C. and Kent, D.V., 1992a. A new geomagnetic polarity time scale for the Late Cretaceous and Cenozoic. Journal of Geophysical Research, 97: 13917-13951.

Cande, S.C. and Kent, D.V., 1992b. Ultrahigh resolution marine magnetic anomaly profiles: a record of continuous paleointensity variations. Journal of Geophysical Research, 97: 15075-15083.

Channell, J.E.T., Lowrie, W., Pialli, P. and Venturi, F., 1984. Jurassic magnetic stratigraphy from Umbrian (Italian) land sections. Earth and Planetary Science Letters, 68: 309-325.

Channell, J.E.T., Bralower, T.J. and Grandesso, P., 1987. Biostratigraphic correlation of Mesozoic polarity chrons CM1 to CM23 at Capriolo and Xausa (Southern Alps, Italy). Earth and Planetary Science Letters, 85: 203-221.

Channell, J.E.T., Massari, F., Benetti, A. and Pezzoni, N., 1990. Magnetostratigraphy and biostratigraphy of Callovian-Oxfordian limestones from the Trento Plateau (Monti Lessini, northern Italy). Palaeography, Paleoclimatology, Paleoecology, 79: 289-303.

Channell, J.E.T. and Erba, E., 1992. Early Cretaceous polarity chrons CM0 to CM11 recorded in northern Italian land sections near Brescia. Earth and Planetary Science Letters, 108: 161-179.

Chaproniere, G.C.H., Shafik, S., Truswell, E.M., MacPhail, M.K. and Partridge, A.D., 1994. Phanerozoic Timescales: Cainozoic biostratigraphic chart of Australia. Australian Geological Survey Organisation, Record, in preparation.

Cheng, X.Y. and Barton, C.E., 1991. Onset of aridity and dune-building in central Australia: sedimentological and magnetostratigraphic evidence from Lake Amadeus. Palaeogeography, Palaeoclimatology, Palaeoecology, 84: 55-73.

Chivas, A.R., De Deckker, P., Nind, M., Thiriet, D. and Watson, G., 1986. The Pleistocene palaeoenvironmental record of Lake Buchanan: an atypical Australian playa. Palaeogeography, Palaeoclimatology, Palaeoecology, 54: 131-152.

Claesson, K.C., 1979. Early Palaeozoic geomagnetism of Gotland. Geologiska Föreningens i Stockholm Förhandlingar, 101: 149-155.

Dachroth, W., 1976. Gesteinsmagnetische Marken im Perm Mitteleuropas. Geologisches Jahrbuch, E 10: 3-63.

Dachroth, W., 1988. Gesteinsmagnetischer Vergleich Permischer Schichtenfolgen in Mitteleuropa. Zeitschrift für Geologischen Wissenschaften, 16: 959-968.

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. and Valencio, D.A. (eds) Global Reconstruction and the Geomagnetic Field during the Palaeozoic. Journal of Geomagnetism and Geoelectricity, Supplement III, 32: 77-98.

Deutsch, E.R. and Somayajulu, C., 1973. Palaeomagnetism of Ordovician ignimbrites from Killary Harbour, Eire. Earth and Planetary Science Letters, 7: 337-345.

DiVenere, V.J. and Opdyke, N.D., 1988. A Mississippian magnetic stratigraphy: Maringouin Peninsula, New Brunswick. EOS (Transactions American Geophysical Union), 69: 340.

DiVenere, V.J. and Opdyke, N.D., 1990., Paleomagnetism of the Maringouin and Shepody Formations, New Brunswick: a Namurian magnetic stratigraphy. Canadian Journal of Earth Sciences, 27: 803-810.

DiVenere, V.J. and Opdyke, N.D., 1991a. Magnetic polarity stratigraphy and Carboniferous paleopole positions from the Joggins section, Cumberland Structural basin, Nova Scotia. Journal of Geophysical Research, 96: 4051-4064.

DiVenere, V.J. and Opdyke, N.D., 1991b. Magnetic polarity stratigraphy in the uppermost Mississipian Mauch Chunk Formation, Pottsville, Pennsylvania. Geology, 19: 127-130.

Douglass, D.N., 1988. Palaeomagnetics of Ringerike Old Red Sandstone and related rocks, southern Norway: implications for Pre-Carboniferous separtion of Baltica and British terranes. Tectonophysics, 148: 11-27.

Druce, E.C., 1976. Conodont biostratigraphy of the Upper Devonian reef complexes of the Canning Basin, Western Australia. Bureau of Mineral Resources Australia Bulletin, 158, pp303.

Embleton, B.J.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.

Embleton, B.J.J. and McDonnell, K.L., 1980. Magnetostratigraphy in the Sydney Basin, Southeastern Australia. Journal of Geomagnetism and Geoelectricity, 32: Suppl. III: SIII 1- SIII 10.

Facer, R.A., 1981. Palaeomagnetic data for Permian and Triassic rocks from drill holes in the southern Sydney Basin, New South Wales. Tectonophysics, 74: 305-321.

Faller, A.M., Briden, J.C. and 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.R., Van der Voo, R. and Liang, Q., 1990. Ordovician palaeomagnetism of Eastern Yunnan, China. Geophysical Research Letters, 17: 953-956.

Farr, M.A., Sprowl, D.R. and Johnson,J., 1993. Identification and initial correlation of magnetic reversals in the Lower to Middle Ordovician of northern Arkansas. In: Aïssaoui, D.M., McNeill, D.F., Hurley, N.F. and Lidz, B.H., (Eds.), Application of Paleomagnetism to Sedimentary Geology. SEPM (Society for Sedimentary Geology) Special Publication, 49: 83-93.

Fortey, R.A. and Owens, R.M., 1987, The Arenig in South Wales. Bulletin of the British Museum of Natural History, 36: 69-307.

French, R.B. and Van der Voo, R., 1977. Remagnetisation problems with the palaeomagnetism of the Middle Silurian Rose Hill Formation of the central Appalachians. Journal of Geophysical Research, 82: 5803-5806.

French, A.N. and Van der Voo, R., 1979. The magnetization of the Rose Hill Formation at the classical site of Graham's fold test. Journal of Geophysical Research, 84: 7688-7696.

Galbrun, B., 1992. Triassic (Upper Carnian-Lower Rhaetian) magnetostratigraphy of Leg 122 sediments, Wombat Plateau, northwest Australia. In: von Rad, U., Haq, B.U., et al., 1992. Proc. ODP, Sci. Results, 122: College Station, TX (Ocean Drilling Program): 685-693.

Galbrun, B., Gabilly, J. and Rasplus, L., 1988. Magnetostratigraphy of the Toarcian stratotype sections at Thouars and Airvault (Deux Sèvres, France). Earth and Planetary Science Letters, 87: 453-462.

Galbrun, B., Crasquin-Soleau, S. and Jaugey, J.M., 1992. Magnétostratigraphie des sédiments Triasiques des sites 759 et 760, ODP Leg 122, Plateau de Wombat, Nord-Ouest de l'Australie. Marine Geology, 107: 293-298.

References

Gales, J.E., van der Pluijm, B.A. and Van der Voo, R., 1989. Palaeomagnetism of the Lawrenceton Formation, volcanic rocks, Silurian Botwood Group, Change Islands, Newfoundland. Canadian Journal of Earth Sciences, 26: 296-304.

Gallet, Y., Besse, J., Krystyn, L., Marcoux, J. and Théveniaut, H., 1992. Magnetostratigraphy of the late Triassic Bolücektasi Tepe section (southwestern Turkey): implications for changes in magnetic reversal frequency. Physics of the Earth and Planetary Interiors, 93: 273-282.

Gallet, Y., Besse, J., Krystyn, L., Théveniaut, H. and Marcoux, J., 1993. Magnetostratigraphy of the Kavur Tepe section (southwestern Turkey): A magnetic polarity time scale for the Norian. Earth and Planetary Science Letters, 117: 443-456.

Gallet, Y., Besse, J., Krystyn, L., Théveniaut, H. and Marcoux, J., 1994. Magnetostratigraphy of the Mayerling section (Austria) and Erenkolu Mezarlik (Turkey) section: Improvement of the Carnian (Late Triassic) magnetic polarity time scale. Earth and Planetary Science Letters, 125: 173-191.

Gao, E.F., Huang, H.L., Zhu, Z.W., Liu, H.S., Fan, Y.Q. and Qing, Z.J., 1993. The study of paleomagnetism in northeastern Sino-Korean Massif during pre-late Paleozoic (in Chinese). In: Contributions to Project of Plate Tectonics of Northern China, 1: 265-274. Geological Publishing House, Beijing.

Glass, B.P., Hall, C.M. and York, D., 1986. $^{40}Ar/^{39}Ar$ laser-probe dating of North American tektite fragments from Barbados and the age of the Eocene-Oligocene boundary. Chemical Geology (Isotope Science Section), 59: 181-186.

Graham, J.W., 1955. Evidence of polar shift since Triassic time. Journal of Geophysical Research, 60: 329-348.

Haag, M. and Heller, F., 1991. Late Permian to Early Triassic magnetostratigraphy. Earth and Planetary Science Letters, 107: 42-54.

Hacquebard, P.A., 1972. The Carboniferous of Eastern Canada. In: Josten, K.-H., (Ed.), Compte Rendu Septième Congrès International de Stratigraphie et de Géologie du Carbonifère, Krefeld 23-28 August 1971: 69-90.

Hailwood, E.A., 1989. Magnetostratigraphy. Geological Society Special Report, 19: 84pp.

Handschumacher, D.V., Sager, W.W., Hilde, T.W.C. and Bracey, D.R., 1988. Pre-Cretaceous tectonic evolution of the Pacific plate and extension of the geomagnetic polarity time scale with implications for the origin of the Jurassic 'Quiet Zone', Tectonophysics, 155: 365-380.

Harland, W.B., Cox, A.V., LLewellyn, P.G., Pickton, C.A.G., Smith, A.G. and Walters, R., 1982. A geologic time scale. Cambridge University Press, pp131.

Harland, W.B., Armstrong, R.L., Cox, A.V., Craig, L.E., Smith, A.G., Smith, D.G., 1990. A geologic time scale 1989. Cambridge University Press, pp263.

Heirtzler, J.R., Dickson, G.O., Herron, E.M., Pitman, W.C., III and Le Pichon, X., 1968. Marine magnetic anomalies, geomagnetic field reversals, and motions of the ocean floor and continent. Journal of Geophysical Research, 73: 2119-2136.

Heller, F., Lowrie, W., Huamei, L. and Junda, W., 1988. Magnetostratigraphy of the Permo-Triassic boundary section at Shangsi (Guangyuan, Sichuan Province, China). Earth and Planetary Science Letters, 88: 348-356.

Helsley, C.E., 1965. Paleomagnetic results from the Lower Permian Dunkard Series of West Virginia. Journal of Geophysical Research, 70: 413-424.

Helsley, C.E., 1969. Magnetic reversal stratigraphy of the Lower stratigraphy of the Lower Triassic Moenkopi Formation of Western Colorado, Geological Society of America Bulletin, 80: 2431-2450.

Helsley, C.E. and Steiner, M.B., 1974. Paleomagnetism of the Lower Triassic Moenkopi Formation of Western Colorado. Geological Society of America Bulletin, 85: 457-464.

Horner, F. and Heller, F., 1983. Lower Jurassic magnetostratigraphy at the Breggia Gorge (Ticino, Switzerland) and Alpe Turati (Como, Italy). Geophysical Journal of the Royal Astronomical Society, 73: 705-718.

Hurley, N.F. and Van der Voo, R., 1987. Paleomagnetism of Upper Devonian reefal limestones, Canning basin, Western Australia. Geological Society of America Bulletin, 98: 138-146.

Hurley, N.F. and Van der Voo, R., 1990. Magnetostratigraphy, Late Devonian iridium anomaly, and impact hypotheses. Geology, 18: 291-294.

Idnurm, M. and Cook, P.J., 1980. Palaeomagnetism of beach ridges in South Australia and the Milankovitch theory of ice ages. Nature, 287: 699-702.

Irving, E., 1963. Paleomagnetism of the Narrabeen Chocolate Shales and the Tasmanian Dolerite. Journal of Geophysical Research, 68: 2283-2287.

Irving, E., 1966. Paleomagnetism of some Carboniferous rocks from New South Wales and its relation to geological events. Journal of Geophysical Research, 71: 6025-6051.

Irving, E., 1971. Letter to the Editors, Nomenclature in Magnetic Stratigraphy. Geophysical Journal Royal Astronomical Society, 24: 529-531.

Irving, E. and Parry, L.G., 1963. The magnetism of some Permian rocks from New South Wales. Geophysical Journal Royal Astronomical Society, 7: 395-411.

Irving, E. and Pullaiah, G., 1976. Reversals of the geomagnetic field, magnetostratigraphy, and relative magnitude of palaeosecular variation in the Phanerozoic. Earth Science Reviews, 12: 35-64.

Johnson, R.J.E., van der Pluijm, B.A., and 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: 11689-11701.

Jones, P.J. (compiler), 1994. AGSO Phanerozoic Timescale 1994: a summary. AGSO Journal of Australian Geology and Geophysics, 15: in preparation.

Kapoor, H.M., 1992. Permo-Triassic boundary of the Indian subcontinent and its international correlation. In: Sweet, W.C., Yang Zunyi, Dickins, J.M. and Yin Hingfu, (Eds.), Permo-Triassic events in the Eastern Tethys, pp 21-36. Cambridge University Press, Cambridge.

Kent, D.V., 1988. Further palaeomagnetic evidence for oroclinal rotation in the central folded Appalachians from the Mauch Chunk Formation. Tectonics, 7: 749-759.

Kent, D.V. and Gradstein, F.M., 1985. A Cretaceous and Jurassic geochronology. Geological Society of America Bulletin, 96: 1419-1427.

Kent D.V., Witte, W.K. and Olsen, P.E., 1993. A complete Triassic Magnetostratigraphy From the Newark Basin, EOS Trans. AGU, supplement ,74: 109.

Khramov, A.N., Rodionov, V.P. and 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]. 'Nauka' Press, Moscow, 206-213.

References

Khramov, A.N., 1987. Paleomagnetology. Springer Verlag, Berlin, pp308.

Khramov, A.N. and Rodionov, V.P., 1981. The geomagnetic field during Palaeozoic time. In: McElhinny, M.W., Khramov, A.N., Ozima, M. and Valencio, D.A., (Eds.), Global reconstruction and the geomagnetic field during the Palaeozoic, Advances in Earth and Planetary Sciences, 10: 99-115, Reidel, Dordrecht.

Kirschvink, J.L., 1978a. The Precambrian-Cambrian boundary problem: Magnetostratigraphy of the Amadeus Basin, Central Australia. Geological Magazine, 115: 2-20.

Kirschvink, J.L., 1978b. The Precambrian-Cambrian boundary problem: Palaeomagnetic directions from the Amadeus Basin, Central Australia. Earth and Planetary Science Letters, 40: 91-100.

Kirschvink, J.L., 1992. A palaeogeographic model for Vendian and Cambrian time. In: Schopf, J.W., Klein, C., and Des Maris, D. (Eds.), The Proterozoic Biosphere: A Multidisciplinary study: 567-581, Cambridge University Press, Cambridge, England.

Kirschvink, J.L. and Rosanov, 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.

Kirschvink, J.L., Magaritz, M., Ripperdan, R.L., Zhuravlev, A.Yu., and Rosanov, A.Yu., 1991. The Precambrian/Cambrian Boundary: Magnetostratigraphy and carbon isotopes resolve correlation problems between Siberia, Morocco and South China. GSA Today, 1: 69-91.

Klootwijk, C.T., 1980. Early Palaeozoic Palaeomagnetism in Australia. Tectonophysics, 64: 249-332.

Kozur, H., 1992. Boundaries and stage subdivision of the mid-Permian (Guadalupian Series) in the light of new micropaleontological data. International Geological Review, 34: 907-932.

Landing, E., 1994. Precambrian-Cambrian boundary global stratotype ratified and a new perspective of Cambrian time. Geology, 22: 179-182.

Larson, R.L. and Hilde, T.W.C., 1975. A revised time scale of magnetic reversals for the Early Cretaceous and Late Jurassic. Journal of Geophysical Research, 80: 2586-2594.

Larson, E.E., Walker, T.R., Patterson, P.E., Hoblitt, R.P. and Rosenbaum, J.G., 1982. Paleomagnetism of the Moenkopi Formation, Colorado Plateau: Basis for a long term model of acquisition of chemical remanent magnetism in red beds. Journal of Geophysical Research, 87: 1081-1106.

Leven, E.Ya., 1993. Main events in Permian history of the Tethys and Fusulinids. Stratigraphy and Geological Correlation, 1: 59-75.

Lin, J.R., Fuller, M. and Zhang, W.Y., 1985. Paleogeography of the North and South China Blocks during the Cambrian. Journal of Geodynamics, 2: 91-114.

Lock, J. and McElhinny, M.W., 1991. The global palaeomagnetic database. Surveys in Geophysics, 12: 317-491.

Luck, G.R., 1973. Palaeomagnetic results from Palaeozoic rocks of south-east Australia. Geophysical Journal of the Royal Astronomical Society, 32: 35-52.

Ma, X., McElhinny, M.W., Embleton, B.J.J. and Zhang, Z., 1993. Permo-Triassic palaeomagnetism in the Emei Mountain region, Southwest China. Geophysical Journal International, 114: 293-303.

MacFadden, B.J., Whitelaw, M.J., McFadden, P., and Rich, T.H.V., 1987. Magnetic polarity stratigraphy of the Pleistocene section at Portland (Victoria), Australia. Quaternary Research, 28: 364-373.

Magnus, G. and Opdyke, N.D., 1991. A paleomagnetic investigation of the Minturn Formation, Colorado: a study in establishing the timing of remanence acquisition. Tectonophysics, 187: 181-189.

Marton, E., Marton, P. and Heller, F., 1980. Remanent magnetization of a Pliensbachian limestone sequence at Bakonycsernye (Hungary). Earth and Planetary Science Letters, 57: 182-190.

Mauritsch, H.J. and Rother, K., 1983. Paleomagnetic investigations in the Thüringer Forest (G.D.R.). Tectonophysics, 99: 63-72.

McCabe, C., Van der Voo, R., Wilkinson, B.H. and Devaney, K., 1985. A Middle/Late Silurian palaeomagnetic pole from limestone reefs of the Wabash Formation (Indiana, USA). Journal of Geophysical Research, 90: 2959-2965.

McCabe, C. and Channell, J.E.T., 1990. Palaeomagnetic results from volcanic rocks of the Shelve inlier, Wales: Evidence for a wide Late Ordovician lapetus Ocean in Britain. Earth and Planetary Science Letters, 96: 458-468.

McDougall, I., 1974. Potassium-argon ages on basaltic rocks recovered from DSDP Leg 22, Indian Ocean, 1974. In: A.C. Pimm (Ed.), Initial Reports of the Deep Sea Drilling Project, Washington (U.S. Government Printing Office), 22: 377-379.

McElhinny, M.W., 1969. The palaeomagnetism of the Permian of southeast Australia and its significance regarding the problem of intercontinental correlation. Special Publications Geological Society of Australia, 2: 61-67.

McElhinny, M.W. and Burek, P.J., 1971. Mesozoic palaeomagnetic stratigraphy. Nature, 232: 98-102.

McElhinny, M. W., and Lock, J., 1990. Global Palaeomagnetic Database Project, Physics of the Earth and Planetary Interiors, 63: 1-6.

McElhinny, M.W. and Lock, J., 1993. Global paleomagnetic database supplement number one: update to 1992. Surveys in Geophysics, 14: 303-329.

McEwan Mason, J.R.C., 1991. The late Cainozoic magnetostratigraphy and preliminary palynology of Lake George, New South Wales. In: M.A.J. Williams, P. De Deckker and A.P. Kershaw. The Cainozoic in Australia; a re-appraisal of the evidence. Geological Society of Australia Special Publication, 19: 195-209.

McFadden, P.L., Ma, X.H., McElhinny, M.W. and Zhang, Z.K., 1988. Permo-Triassic magnetostratigraphy in China: northern Tarim. Earth and Planetary Science Letters, 87: 152-160.

McIntosh, W.C., Hargraves, R.B. and West, C.L., 1985. Paleomagnetism and oxide mineralogy of Upper Triassic to Lower Jurassic red beds and basalts in the Newark basin, Geological Society of America Bulletin, 96: 463-480.

McKerrow, W.S., Scotese, C.R. and Brasier, M.D., 1992. Early Cambrian continental reconstructions. Journal of the Geological Society, London, 149: 599-606.

McMahon, B.E. and Strangway, D.W., 1968. Investigation of Kiaman Magnetic Division in Colorado Redbeds. Geophysical Journal of the Royal Astronomical Society, 5: 265-285.

McWilliams, M., 1993. On integrating palaeomagnetism and geochronology. In: C. Klootwijk (compiler) Paleomagnetism in Australasia: dating, tectonic and environmental applications. AGSO Record 1993/20: 9.

Menning, M., 1986. Zur Dauer des Zechsteins aus magnetostratigraphischer Sicht. Zeitschrift für Geologischen Wissenschaften, 14: 395-404.

Menning, M., Katzung, G. and Lützner, H., 1988. Magnetostratigraphic investigations in the Rotliegendes (300-252 Ma) of Central Europe. Zeitschrift für Geologischen Wissenschaften, 16: 1045-1063.

Merrill, R.T. and McFadden, P.L., 1994. Geomagnetic field stability: Reversal events and excursions. Earth and Planetary Science

Letters, 121: 57-69.

Miller, J.D. and Opdyke, N.D., 1985. Magnetostratigraphy of the Red Sandstone Creek section - Vail, Colorado. Geophysical Research Letters, 12: 133-136.

Miller, K.G., Aubry, M-P., Khan, M.J., Melillo, A.J., Kent, D.V. and Berggren, W.A., 1985. Oligocene-Miocene biostratigraphy, magnetostratigraphy, and isotopic statigraphy of the western North Atlantic. Geology, 13: 257-261.

Miller, J.D. and Kent, D.V., 1989. Palaeomagnetism of the Upper Ordovician Juniata Formation of the Central Appalachians revisited again. Journal of Geophysical Research, 94: 1843-1849.

Molina-Garza, R.S., Geissman, J.W. and Van der Voo, R., 1989. Paleomagnetism of the Dewey Lake Formation (Late Permian), northwest Texas: end of the Kiaman Superchron in North America. Journal of Geophysical Research, 94: 17881-17888.

Molina-Garza, R., Geissman, J., Van der Voo, R., Lucas, S. and Hayden, S., 1991. Paleomagnetism of the Moenkopi and Chinle formations in central New Mexico: implications for the North American apparent polar wander path and Triassic magnetostratigraphy, Journal of Geophysical Research, 96: 14 239-14262,.

Molostovskiy, E.A., 1992. Paleomagnetic stratigraphy of the Permian System. International Geological Review, 34: 1001-1007.

Moores, E.M., 1991. Southwest U.S. - East Antarctic (SWEAT) connection: a hypothesis. Geology 19: 425-428.

Morris, W.A., Briden, J.C., Piper, J.D.A. and 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.

Morrison, J. and Ellwood, B.B., 1986. Palaeomagnetism of Silurian-Ordovician sediments from the Valley and Ridge Province, Northwest Georgia. Geophysical Research Letters, 13: 189-192.

Nicoll, R.S. and Playford, P.E., 1993. Upper Devonian iridium anomalies, conodont zonation and the Frasnian-Famennian boundary in the Canning Basin, Western Australia. Palaeogeography, Palaeoclimatology, Palaeoecology, 104: 105-113.

Nicoll, R.S. and Foster, C.B., 1994. Late Triassic conodont and palynomorph biostratigraphy and conodont thermal maturation, North West Shelf, Australia. AGSO Journal of Australian Geology and Geophysics, 15: 101-118.

Odin, G.S., Montanari, A., Deino, A. Guise, P.G., Kreuzer, H. and Rex, D.C., 1991. Reliability of volcano-sedimentary biotite ages across the Eocene-Oligocene boundary (Apennines, Italy). Chemical Geology (Isotope Secience Section), 86: 203-224.

Ogg, J.G. and Steiner M. B., 1991. Early Triassic magnetic polarity time scale- integration of magnetostratigraphy, ammonite zonation and sequence stratigraphy from stratotype sections (Canadian Arctic Archipelago). Earth and Planetary Science Letters, 107: 69-89.

Ogg, J.G., Steiner, M.B., Wieczorek, J. and Hoffmann, M., 1991. Jurassic magnetostratigraphy, 4. Early Callovian through Middle Oxfordian of the Krakow Uplands (Poland). Earth and Planetary Science Letters, 104: 488-504.

Opdyke, N.D., 1986, The Kiaman Superchron in North America. EOS (Transactions American Geophysical Union), 67: 269.

Opdyke, N.D., Huang, K., Xu, G., Zhang, W.Y., and Kent, D.V., 1987. Palaeomagnetic results from the Silurian of the Yangtze paraplatform. Tectonophysics, 139: 123-132.

Opdyke, N.D., Khramov, A.N., Gurevitch, E., Iosifidi, A.G. and Makarov, I.A., 1993. A paleomagnetic study of the Middle Carboniferous of the Donets Basin, Ukraine. EOS (Transactions American Geophysical Union), 74 Spring Meeting

Supplement: 118.

Pakistani-Japanese Research Group, 1985. Permian and Triassic Systems in the Salt Range and Surghar Range, Pakistan. In Nakazawa, K. and Dickins, J.M., (Eds.), "THE TETHYS" Her paleogeography and paleobiogeography from Paleozoic to Mesozoic: 221-312. Tokai University Press,Tokyo.

Palmer, J.A., Perry, S.P.G. and Tarling, D.H., 1985. Carboniferous magnetostratigraphy. Journal of the Geological Society of London, 142: 945-955.

Perroud, H., Bonhommet, N. and Thebault, J.P., 1985. Palaeomagnetism of the Ordovician Moulin de Chateaupanne Formation, Vendée, western France. Geophysical Journal of the Royal Astronomical Society, 85: 573-582.

Peterson, D.N. and Nairn, A.E.M., 1971. Palaeomagnetism of Permian redbeds from the south-western United States. Geophysical Journal Royal Astronomical Society, 23: 191-205.

Piper, J.D.A., 1975. Palaeomagnetism of Silurian lavas of Somerset and Gloucestershire, England. Earth and Planetary Science Letters, 25: 355-360.

Piper, J.D.A., 1987. Palaeomagnetism and the continental crust. Open University Press, Milton Keynes, pp432.

Potts, S.S., van der Pluijm, B.A. and Van der Voo, R., 1993. Palaeomagnetism of the Ordovician Bluffer Pond Formation: Palaeogeographic implications for the Munsungun Terrane of northern Maine. Journal of Geophysical Research, 98: 7987-7996.

Reeve, S.C. and Helsley C.E., 1972. Magnetic reversal sequence in the upper portion of the Chinle Formation, Montoya, New Mexico, Geological Society of America Bulletin, 83: 3795-3812.

Ripperdan, R.L., 1990. Magnetostratigraphic investigations of the Lower Palaeozoic system boundaries, and associated palaeogeographic implications. Ph.D. Thesis, California Institute of Technology, pp195.

Ripperdan, R.L. and Kirschvink, J.L., 1992. Palaeomagnetic results from the Cambrian-Ordovician boundary section at Black Mountain, Georgina Basin, western Queensland, Australia. In: Webby, B.D., and Laurie, J.R. (Eds.), Global Perspectives on Ordovician Geology: 93-103, Rotterdam, Balkema.

Ripperdan, R.L., Magaritz, M., Nicoll, R.S. and Shergold, J.H., 1992. Simultaneous changes in carbon isotopes, sea level, and conodont biozones within the Cambrian-Ordovician boundary interval at Black Mountain, Australia. Geology, 20: 1039-1042.

Ripperdan, R.L., Magaritz, M. and Kirschvink, J.L., 1993. Carbon isotope and magnetic polarity evidence for non-depositional events within the Cambrian-Ordovician boundary section near Dayangcha, Jilin Province, China. Geological Magazine, 130: 443-452.

Roberts, J., Claoué-Long, J.C. and Jones, P.J., 1991. Calibration of the Carboniferous and Early Permian of the southern New England Orogen by SHRIMP ion microprobe zircon analyses. Twenty-fifth Newcastle Symposium: 38-43.

Roberts, J., Claoué-Long, J.C. and Jones, P.J., 1994a. Australian Early Carboniferous time. In: Berggren, W.A., Kent, D.V. and Hardenbol, J. (Eds.), Geochronology, timescales and global stratigraphic correlations: a unified temporal framework for an historical geology. Society of Economic Paleontologists and Mineralogists Special Publication, in press.

Roberts, J., Claoué-Long, J.C., Jones, P.J. and Foster, C.B., 1994b. SHRIMP zircon age control of Gondwanan sequences in Late Carboniferous Australia. In: Dunay, R. and Hailwood, E. (Eds.), Dating and correlation of biostratigraphic barren strata. Geological Society of London Special Publication, in press.

Rodionov, V.P., 1966. Dipole character of the geomagnetic field in the late Cambrian and Ordovician in the south of the Siberian

Platform. (Translated from) Geologiya i Geofizika, 1: 94-101.

Roy, J.L., 1977. La position stratigraphique déterminée paléomagnétiquement de sédiments Carbonifères de Minudie Point, Novelle Ecosse: à prôpos de l'horizon repère magnétique du Carbonifère. Canadian Journal of Earth Sciences, 14: 1116-1127.

Roy, J.L. and Morris, W.A., 1983. A review of paleomagnetic results from the Carboniferous of North America: the concept of Carboniferous geomagnetic field horizon markers. Earth and Planetary Science Letters, 65: 167-181.

Seguin, M.K. and 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.

Shergold, J.H., 1989. The Australian Cambrian Timescale. Bureau of Mineral Resources Record 1989/31, pp25.

Shergold, J.H., 1994. The Australian Cambrian Timescale Second Edition. Australian Geological Survey Organisation Record, in preparation.

Shive, P.N., Steiner, M.B. and Huycke, D.T., 1984. Magnetostratigraphy, paleomagnetism and remanence acquisition in the Triassic Chugwater Group of Wyoming, Journal of Geophysical Research, 89: 1801-1815.

Singh, G., Opdyke, N.D. and Bowler, J.M., 1981. Late Cainozoic stratigraphy, palaeomagnetic chronology and vegetational history from Lake George, N.S.W. Journal of the Geological Society of Australia, 28: 435-452.

Smethurst, M.A. and Briden, J.C., 1988. Palaeomagnetism of Silurian sediments in W Ireland: evidence for block rotation in the Caledonides. Geophysical Journal, 95: 327-346.

Smethurst, M.A. and Khramov, A.N., 1992. A new Devonian palaeomagnetic pole for the Russian Platform and Baltica, and related apparent polar wander. Geophysical Journal International, 108: 179-192.

Solodukho, M.G., Gusev, A.K., Ignatyev, V.I., Lukin, V.A., Boronin, V.P., Esaulova, N.K. Zharkov, I.Ya., Silantyev, V.V. and Bogov, A.V., 1993. Part 5-Volga Region. In: Chuvashov, B.I. and Nairn, A.E.M., (Eds.), Permian System: Guides to geological excursions in the Uralian type localities. Occasional Publications Earth Sciences and Resources Institute, University of South Carolina, New Series, 10: 269-303.

Spell, T.I. and McDougall, I., 1992. Revisions to the age of the Brunhes-Matuyama boundary and the Pleistocene geomagnetic polarity timescale. Geophysical Research Letters, 19: 1181-1184.

Steiner, M.B. and Helsley C.E., 1974. Magnetic polarity sequence of the Upper Triassic Kayenta Formation. Geology, 2: 191-198.

Steiner, M.B., Ogg, J.G., Melendez, G. and Sequeiros, L., 1986. Jurassic magnetostratigraphy, 2. Middle-Late Oxfordian of Aquilon, Iberian Cordillera, northern Spain. Earth and Planetary Science Letters, 76: 151-166.

Steiner, M.B., Ogg, J.G. and Sandoval,J., 1987. Jurassic magnetostratigraphy, 3. Bathonian-Bajocian of Carcabuey, Sierra Harana and Campillo de Arenas (Subbetic Cordillera, Southern Spain), Earth and Planetary Science Letters, 82: 357-372.

Steiner, M.B., Ogg, J.G., Zhang, Z. and Sun, S.,1989. The late Permian/early Triassic magnetic polarity time scale and plate motions of South China, Journal of Geophysical Research, 94: 7343-7363.

Tarduno, J.A., 1990. Brief reversed polarity interval during the Cretaceous Normal Polarity Superchron. Geology, 18: 683-686.

Tarduno, J.A., Lowrie, W., Sliter, W.V., Bralower, T.J. and Heller, F., 1992. Revised polarity characteristic magnetizations in the Albian Contessa section, Umbrian Apennines, Italy: implications for the existence of a mid-Cretaceous mixed polarity interval. Journal of Geophysical Research, 97: 241-271.

Théveniaut, H., Klootwijk, C., Foster, C. and Giddings, J., 1994. Magnetostratigraphy of the Late Permian coal measures of the Sydney and Gunnedah Basins: A regional and global correlation tool. Proceedings of the 28th Newcastle Symposium, Department of Geology, University of Newcastle, 17-30.

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

Torsvik, T.H. and Trench, A.,1991. Ordovician magnetostratigraphy: Llanvirn - Caradoc limestones of the Baltic Platform. Geophysical Journal International, 107: 171-184.

Torsvik, T.H., Trench, A., Svensson, I., and Walderhaug, H.J., 1993. Palaeogeographic significance of mid-Silurian palaeomagnetic results from southern Britain - major revision of the apparent polar wander path for Eastern Avalonia. Geophysical Journal International, 113: 651-668.

Trench, A. and Torsvik, T.H., 1991. The Lower Palaeozoic apparent polar wander path for Baltica: palaeomagnetic data from Silurian limestones of Gotland, Sweden. Geophysical Journal International, 107: 171-184.

Trench, A., Bluck, B.J. and 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.

Trench, A., McKerrow, W.S., and Torsvik, T.H., 1991. Ordovician magnetostratigraphy: a correlation of global data. Journal of the Geological Society, London, 148: 949-957.

Trench, A., Dentith, M.C., McKerrow, W.S. and Torsvik, T.H., 1992. The Ordovician magnetostratigraphic time scale: Reliability and correlation potential. In: Webby, B.D., and Laurie, J.R., (Eds.), Global Perspectives on Ordovician Geology: 69-77, Balkema, Rotterdam.

Trench, A., McKerrow, W.S., Torsvik, T.H., Li, Z.X., and McCracken, S.R., 1993. The polarity of the Silurian magnetic field: indications from a global data compilation. Journal of the Geological Society, 150: 823-831.

Truswell, E.M., Chaproniere, G.C.H. and Shafik, S., 1991. Australian Phanerozoic Timescales: 10. Cainozoic biostratigraphic chart and explanatory notes. Bureau of Mineral Resources, Record 1989/40, pp16.

Tsuchi, R., Takayanagi, Y. and Shibata, K., 1981. Neogene bio-events in the Japanese Islands. In: R. Tsuchi (Ed.), Neogene in Japan - Its Biostratigraphy and Chronology: 15-32,. Kurofune Printing Co., Shizuoka.

Turner, P., Turner, A., Ramos, A. and Sopeña, A., 1989. Palaeomagnetism of Permo-Triassic rocks in the Iberian Cordillera, Spain: acquisition of secondary and characteristic remanence. Journal of the Geological Society, London, 146: 61-76.

Valencio, D.A., 1981, Reversals and excursions of the geomagnetic field as defined by palaeomagnetic data from Upper Palaeozoic-Lower Mesozoic sediments and igneous rocks from Argentina. In: McElhinny, M.W., Khramov, A.N., Ozima, M. and Valencio, D.A., (Eds.), Global reconstruction and the geomagnetic field during the Palaeozoic. Advances in Earth and Planetary Sciences, 10: 137-142, Reidel, Dordrecht.

Valencio, D.A. and Mitchell, J., 1972. Palaeomagnetism and K-Ar ages of Permo-Triassic igneous rocks from Argentina and the international correlation of Upper Palaeozoic-Lower Mesozoic formations. 24th International Geological Congress, section 3: 189-195.

Valencio, D.A. and Vilas, J.F., 1972. Palaeomagnetism of late Palaeozoic and early Mesozoic rocks of South America. Earth and Planetary Science Letters, 15: 75-85.

Valencio, D.A., Vilas, J.F.A. and Mendia,J.E., 1977. Palaeomagnetism of a sequence of red beds of the middle and upper sections of Paganzo Group (Argentina) and the correlation of Upper Palaeozoic-Lower Mesozoic rocks. Geophysical Journal of the Royal Astronomical Society, 51: 59-74.

References

Van den Berg, J., Klootwijk, C.T. and Wonders, A.A.H., 1978. The Late Mesozoic and Cenozoic movements of the Umbrian Peninsula: Further paleomagnetic data from the Umbrian sequence. Geological Society of America Bulletin, 89: 133-155.

Van der Voo, R. and Johnson, R.J.E., 1985. Palaeomagnetism of the Dunn Point Formation (Nova Scotia): High palaeolatitudes for the Avalon terrane in the Late Ordovician. Geophysical Research Letters, 12: 337-340.

Vogt, P.R. and Einwich, A.M., 1979. Magnetic anomlaies and sea floor spreading in the western North Atlantic, and a revised calibration of the Keathley (M) geomagnetic reversal chronology. In: Tucholka, B.E., Vogt, P.R., et al., (Eds.), Initial Reports of the Deep Sea Drilling Project, Washington (U.S. Government Printing Office), 43: 857-876.

Whitelaw, M.J., 1991a. Magnetic polarity stratigraphy of the Fisherman's Cliff and Bone Gulch vertebrate fossil faunas from the Murray Basin, New South Wales, Australia. Earth and Planetary Science Letters 104: 417-423.

Whitelaw, M.J., 1991b. Magnetic polarity stratigraphy of Plio and Pleistocene fossil vertebrate localities in southeastern Australia. Geological Society of America Bulletin, 103: 1493-1503.

Whitelaw, M.J., 1992. Magnetic polarity stratigraphy of the Pliocene sections and inferences for the ages of vertebrate fossil sites near Bacchus Marsh, Victoria, Australia. Australian Journal of Earth Sciences, 39: 521-528.

Witte, W.K. Kent, D.V. and Olsen, P.E., 1991. Magnetostratigraphy and paleomagnetic poles from late Triassic-earliest Jurassic strata of the Newark basin, Geological Society of America Bulletin, 103: 1648-1662.

Young, G.C. and Laurie, J.R., (Eds.), 1994. AGSO Phanerozoic Timescale 1994. Australian Geological Survey Organisation, Record, in preparation.

Zeissl, W. and Mauritsch, H., 1991. The Permian-Triassic of the Gartnerkofel-1 Core (Carnic Alps, Austria): Magnetostratigraphy. In: Holser, W.T. and Schönlaub, H.P., (Eds.) The Permian-Triassic boundary in the Carnic Alps of Austria (Gartnerkofel Region). Abhandlungen Geologischen Bundesanstalt, Wien, 45: 193-207.

Zhao, X., Coe, R.S., Liu, C., and Zhou, Y., 1992. New Cambrian and Ordovician palaeomagnetic poles for the North China Block and their palaeogeographic implications. Journal of Geophysical Research, 97: 1767-1788.