

# Geomagnetic polarity bias patterns through the Phanerozoic

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**Abstract.** Phanerozoic geomagnetic polarity bias patterns have been reconstructed using polarity data from 278 stratigraphic formations of Cambrian-Jurassic age combined with data from an established geomagnetic polarity timescale for the Cretaceous-Recent. In addition to the well-known Cretaceous Normal Polarity Superchron and Kiaman Reversed Polarity Superchron, other first-order polarity features are recognized: (1) a Middle Cambrian-Middle Ordovician Burskan Reversed Polarity Bias Interval, (2) a Late Ordovician-Late Silurian Nepan Normal Polarity Bias Interval, (3) an Early Jurassic Normal Polarity Bias Interval, and, possibly, (4) a Middle Jurassic Normal Polarity Bias Interval. A combination of strong polarity bias and low reversal rates during the Ordovician may indicate the existence of a "dual-polarity superchron" containing a single major polarity transition, the Middle Ordovician Polarity Shift. Reconstruction of an accurate Phanerozoic polarity trend permits application of a "polarity bias test" to evaluate the primary character of magnetic remanences. A polarity bias test of British Siluro-Devonian remanences reveals that group "A" remanences ( $0^{\circ}$ - $20^{\circ}$  paleopole latitude; 30-100% normal polarity) exhibit polarity concordance with coeval non-British remanences, whereas group "B" remanences ( $25^{\circ}$ - $50^{\circ}$  paleopole latitude; 0-20% normal polarity) are strongly discordant, suggesting that the latter are largely of secondary origin. Analysis of groups of magnetic remanences also permits estimation of (1) characteristic timescales for formation polarity data and (2) evaluation of sources of age-dependent polarity-ratio variance. For the Cambrian-Jurassic polarity data set, formations exhibit a mean characteristic timescale of 1.0-1.5 m.y., and circa 50% of polarity-ratio variance is attributable to paleomagnetic sampling of a binomial variable (i.e., geomagnetic field polarity) and 50% to other factors (i.e., stochastic and systematic depositional and sampling biases, incorrect age estimates for stratigraphic formations and characteristic remanences, complex magnetizations, and low epochal reversal frequencies).

## Introduction

Long-term variations in geomagnetic field behavior are thought to reflect changes in conditions within the core and at the core-mantle boundary associated with generation of the Earth's magnetic dynamo [e.g., Merrill and McElhinny, 1983; Jacobs, 1994]. Such variations have been correlated with mantle plume activity [Loper and McCartney, 1986; Larson, 1991a; Larson and Olson, 1991; Loper, 1992], global climate change [Larson, 1991b], eustatic elevations [Gaffin, 1987; Marzocchi et al., 1992], extinction events [Courillot, 1990], and true polar wander [Courillot and Besse, 1987]. Most studies of long-term geomagnetic variation have focused on reversal frequency [e.g., McElhinny, 1971; Lowrie and Kent, 1983; Mazaud and Laj, 1991; Marzocchi and Mulargia, 1992; Johnson et al., 1995] or statistical differences between the normal and reversed polarity states [e.g., Merrill et al., 1979; McFadden and Merrill, 1984; McFadden et al., 1987] rather than on polarity bias. However, the lack of research on secular variation and controls on geomagnetic field polarity is unfortunate because (1) polarity bias patterns are subject to less uncertainty than reversal rates, which are strongly influenced by inclusion of short (circa <40 ka), poorly known magnetic events and excursions [e.g., LaBrecque et al., 1977; McFadden and Merrill, 1984; McFadden et al.,

1987], and (2) such patterns may provide important insights regarding geodynamo operation.

The last comprehensive study of Phanerozoic polarity bias patterns was that of Irving and Pullaiah [1976], and the advent of improved magnetic cleaning methods and publication of substantial amounts of paleomagnetic data in the intervening period warrant a reexamination of such patterns using an updated polarity data set. Therefore the goals of this study were (1) to assemble a polarity data set for the Cambrian-Jurassic derived largely from paleomagnetic studies published since 1975, (2) to evaluate sources of age-dependent variance among formation polarity ratios, and (3) to construct a polarity trend for the Phanerozoic. Important features of the present study include the following: (1) application of a set of rigorous criteria for acceptance of characteristic magnetic remanences as primary (i.e., approximately syndepositional), (2) determination of characteristic timescales associated with formation polarity ratios and polarity trends, and (3) use of a binomial probability model to analyze patterns of variance in polarity data and to identify and selectively remove unrepresentative polarity ratios. These procedures produced a data set that is smaller ( $n = 278$ ) but internally more consistent than that of Irving and Pullaiah [1976], allowing construction of a reliable polarity trend for the Phanerozoic.

## Definitions

"Polarity ratio," as used in this study, is the ratio of normal polarity to total polarity (i.e., normal plus reversed) relative to

a scale of choice [cf. *Irving and Pullaiah, 1976*]. Polarity ratios can be determined for either magnetostratigraphic or magneto-chronologic units and can be measured as a function of number of paleomagnetic sites or samples, as thicknesses of polarity zones, or as durations of polarity chrons of the geomagnetic polarity timescale (GPTS). In this study, polarity ratios will be given as percent normal polarity (%NP), such that 0%NP and 100%NP represent entirely reversed (*R*) and entirely normal (*N*) polarities, respectively, and 50%NP represents normal and reversed polarities in equal proportions. Polarity ratios convey no information regarding reversal frequency other than that ratios of 0%NP and 100%NP indicate a lack of reversals and any intermediate value indicates a minimum of one reversal. However, strong polarity bias generally correlates with low reversal frequency [*Cox, 1981*].

Magnetostratigraphic terminology recognizes the existence of polarity bias at several timescales. The International Union of Geological Sciences (IUGS) International Subcommittee on Stratigraphic Classification [*Geology, 1979*] recommended use of the terms "polarity subchron," "polarity chron," "polarity superchron," and "polarity hyperchron" for geochronologic intervals of  $10^4$ - $10^5$ ,  $10^5$ - $10^6$ ,  $10^6$ - $10^7$ , and  $10^7$ - $10^8$  year duration, respectively. In practice, "polarity superchron" has been applied only to two well-documented intervals of nearly uniform polarity of  $>10^7$  year duration, i.e., the Cretaceous Normal Polarity Superchron (CNPS) [*Sasajima and Shimada, 1966*] and the Kiaman Reversed Polarity Superchron (KRPS) [*Irving and Parry, 1963*]. In addition to these formal terms, "polarity bias interval" (PBI) will be employed in the present study to describe intervals longer than a chron that contain reversals but exhibit some degree of polarity bias [cf. *Irving and Pullaiah, 1976*]. Polarity bias intervals may be qualified as moderate (20-40%NP or 60-80%NP) or strong ( $<20\%$ NP or  $>80\%$ NP) in degree. Intervals exhibiting both *N* and *R* polarities in any proportion will be referred to as "mixed polarity intervals," and those containing *N* and *R* polarities in subequal proportions (40-60%NP) will be referred to as "balanced polarity intervals."

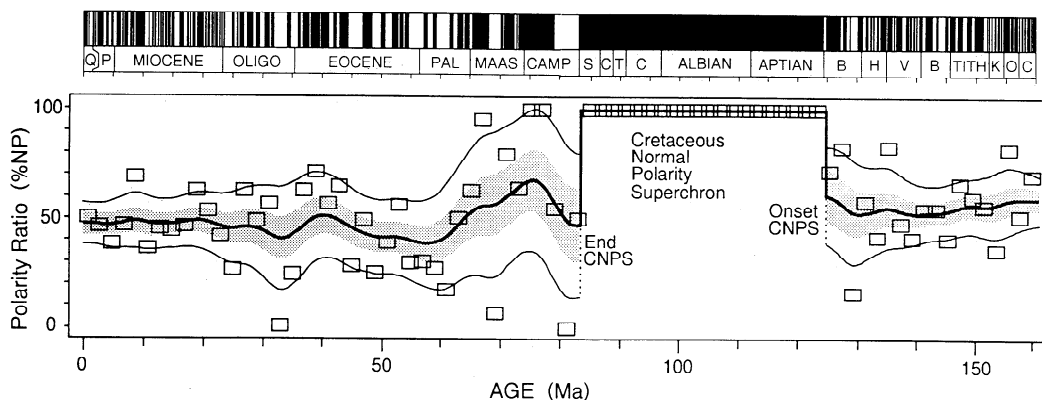
## Polarity Data Set

The polarity data set of the present study is derived from two sources: (1) the geomagnetic polarity timescale (GPTS) of

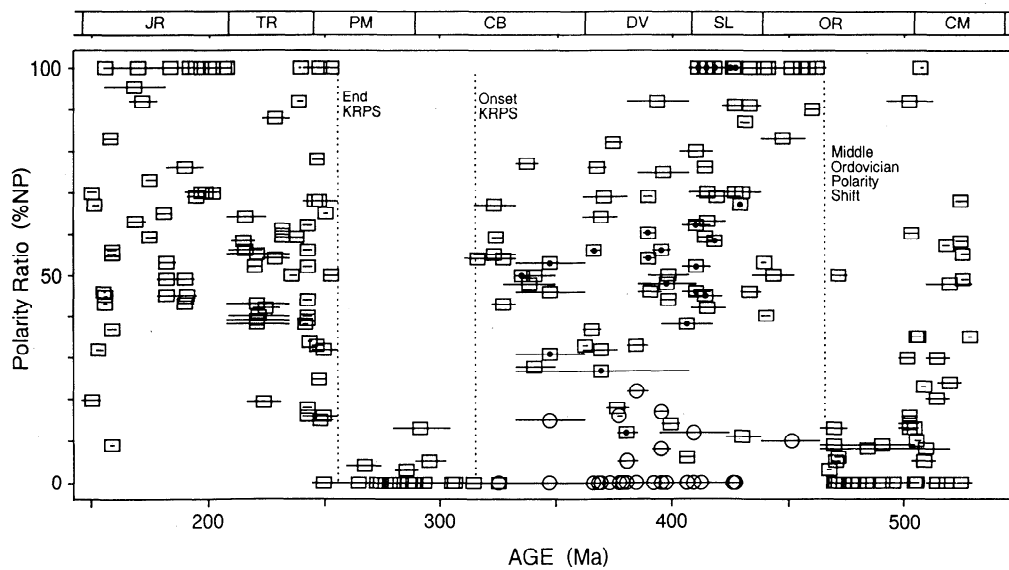
*Harland et al. [1990]* for the Cretaceous-Recent (Figure 1) and (2) selected paleomagnetic studies of Cambrian-Jurassic stratigraphic formations (Figure 2; Tables 1-3). These two data sources yield substantially different levels of temporal resolution for polarity bias estimates. The GPTS represents a continuous and generally well-dated record of geomagnetic field behavior over the last 150 m.y. based upon seafloor magnetic anomalies, such that field polarity at any given time, or polarity bias over any given interval of time, may be determined with considerable accuracy. In contrast, individual paleomagnetic studies of pre-Cretaceous units represent a sampling of geomagnetic field behavior over intervals of generally short (but unknown) duration at specific (but commonly not tightly age-constrained) times during the Phanerozoic.

Paleomagnetic studies were used to calculate polarity ratios for 278 Cambrian-Jurassic stratigraphic formations, groups, or series (Figure 2; Tables 1-3). The polarity data set includes two different types of studies, magnetostratigraphic and magnetotectonic, having different goals and employing different sampling schemes. In magnetostratigraphic studies, the primary goal is generally to determine the reversal stratigraphy of a section of interest, the sampling strategy involves collection of a large number of sites (i.e., stratigraphic horizons) consisting of one or a few samples, and paleomagnetic results are commonly published in the form of a measured section illustrating site declinations, inclinations, and polarity interpretations. In magnetotectonic studies, the primary goal is generally to obtain a reliable paleopole, the sampling strategy involves collection of a relatively small number of sites each consisting of a large number of samples in order to average out paleosecular variation, and paleomagnetic results are commonly published as stereonet plots showing individual site or sample poles and as summary data tables.

Owing to differences in the distribution of samples and the presentation of results between magnetostratigraphic and magnetotectonic studies, slightly different procedures were applied in calculating formation polarity ratios. For magnetostratigraphic studies that included a polarity zonation scheme exhibiting few sampling gaps, polarity ratios were calculated based on the cumulative thicknesses of *N* and *R* polarity magnetozones. For all magnetotectonic studies and for magnetostratigraphic studies that either lacked polarity zonation schemes or exhibited large



**Figure 1.** Polarity trend for the Late Jurassic to Recent (158-0 Ma) based on the geomagnetic polarity timescale (GPTS) of *Harland et al. [1990]* (shown at top). Trends were constructed by (1) determining polarity ratios for 2-m.y. segments of the GPTS (squares) and (2) calculating a running average for polarity ratios using an inverse distance-squared weight function ( $\lambda = 5$  m.y.). Major polarity discontinuities coincide with the onset and end of the Cretaceous Normal Polarity Superchron (dotted lines). Shown are the mean trend (thick line), range of the standard error of the mean (shaded), and standard deviation range (thin lines).



**Figure 2.** Polarity ratios for Cambrian-Jurassic formations ( $n = 278$ ). Squares, general polarity data (Table 1); squares with dots, British Siluro-Devonian "A" remanences (Table 2); circles, British Siluro-Devonian "B" remanences (Table 3). Symbols are located at formation age range midpoints; horizontal lines represent formation age ranges or uncertainty ranges for radiometric age estimates. Three major polarity discontinuities are present: the Middle Ordovician Polarity Shift and onset and end of the Kiaman Reversed Polarity Superchron (KRPS). Cambrian-Jurassic periods shown at top; timescale from *Harland et al.* [1990].

sampling gaps, polarity ratios were calculated based on the number of  $N$  and  $R$  polarity sites or samples (in all cases, stratigraphic intervals or paleomagnetic sites of uncertain polarity were disregarded). These procedures reflect slightly different underlying assumptions. In estimating polarity ratios from zonation schemes, it is assumed that stratigraphic thickness is an approximately linear function of time and that the relative cumulative thicknesses of  $N$  and  $R$  polarity magnetozones are proportional to the fractional durations of coeval  $N$  and  $R$  polarity chrons. In estimating polarity ratios from site paleopoles, it is necessary to adopt the less robust assumption that site locations were sufficiently randomized to yield an unbiased sampling of rock units within the stratigraphic interval of interest. As a rule, larger numbers of sites increase the probability of randomized site locations and decrease the probability of a systematic sampling bias (e.g., owing to presence of all sites within a single magnetozon). However, the possibility of nonrandomized site locations should be considered whenever a study yields uniform polarities (i.e., 0%NP or 100%NP) based on a relatively small number of sites.

The following criteria were established for inclusion of published studies in the polarity data set (Tables 1-3): (1) discrimination of a characteristic magnetic remanence using standard magnetic cleaning techniques, (2) evidence for a primary origin of the characteristic remanence as a DRM, ChRM, or TRM component acquired during or shortly after formation deposition or emplacement, (3) formation age known to one-third period or better, and (4) a minimum of nine study sites or stratigraphic horizons. Two types of evidence were accepted in support of a primary origin for a given remanence: (1) a positive reversal test (i.e., presence of antipodal or nearly antipodal dual polarities) or (2) a formation paleopole concordant with an established apparent polar wander path for the host craton (i.e., in agreement with other paleopoles of similar age and different from those of younger epochs). These criteria (Table 1, column QF) are equivalent to factors 6 and 7 of the quality factor scale of

*Van der Voo* [1990, 1993]. The criterion of a minimum of nine paleomagnetic sites or stratigraphic horizons is intended to reduce variance among formation polarity ratios owing to stochastic sampling factors (cf. Figure 6). For formations containing 1 or more dual-polarity sites, samples (rather than sites) were used in polarity ratio calculations on the assumption that a broad distribution of sites had resulted in each sample representing an independent test of field polarity [e.g., *McCabe et al.*, 1985].

For formations meeting these criteria, the characteristic magnetic remanence was assigned the corresponding stratigraphic age (for sedimentary and most volcanic units) or radiometric age (for intrusives and some volcanic units; Tables 1-3). The stratigraphic ages of some units have been refined using *O. E. Childs et al.* [Correlation of Stratigraphic Units of North America (COSUNA) Project (20 charts), Am. Assoc. of Petrol. Geol., Tulsa, Okla., 1983-1988] for the United States, *Stott and Aitken* [1991] for Canada, and *House et al.* [1977] and *Thirwall* [1988] for the British Isles. Geochronologic ages are based on the timescale of *Harland et al.* [1990], except for the Cambrian which has been revised according to *Bowring et al.* [1993]. The revised ages are (1) system boundaries: Precambrian-Cambrian (544 Ma) and Cambrian-Ordovician (505 Ma); (2) series boundaries: Early-Middle Cambrian (520 Ma) and Middle-Late Cambrian (510 Ma); and (3) stage boundaries: Manykaian-Tommotian (530 Ma), Tommotian-Atdabanian (527.5 Ma), Atdabanian-Botomian (525 Ma), and Solvan-Menevian (517 Ma). This revision affects formation ages assigned on a stratigraphic basis, but not those based on radiometric dating.

Polarity bias studies require knowledge of apparent polar wander paths (APWPs) for individual cratons in order to determine the hemisphere ( $N$  or  $S$ ) at the time of remanence acquisition and, hence, the correct polarity orientation of samples. Accurate APWPs are required to avoid uncertainties in orientation that might develop when a craton crosses the equator or experiences a large ( $>90^\circ$ ) rotation about a vertical axis following remanence acquisition. Most major cratons have well-established

Table 1. Cambrian-Jurassic Formation Polarity Data

No.	Formation	Rock Type <sup>a</sup>	Location	Epoch	Age Range				m	PR	S	M	QF	Source
					Upr	Lwr	Midpt	Dur						
1	Calcarei Diasprigni/Maiolica	S	Italy	Tithonian	152	148	150	4	163	70	2	2	R	Channell et al. [1984]
2	Morrison Fm	Sr	Colo.	Kimm-Tith	155	146	150	9	425	20	2	2	P,R	Steiner and Helsley [1975]
3	Canelo Hills volcanics	V	Ariz.	u-u JR	153	149	151	4	15	67	1	1	P,R	Kluth et al. [1982]
4	Djebel Oust locale	S	Tunisia	Kimmerdg	155	152	153	3	72	32	2	1	P,R	Nairn et al. [1981]
5	Aguilon section	S	Spain	Oxfordian	156	155	155	1	92	46	2	1	P,R	Steiner et al. [1985/86]
6	Jura Mt carbonates	S	Switz/France	Oxfordian	157	155	156	2	21	100 <sup>r</sup>	1	1	P	Johnson et al. [1984]
7	Piccola/Valle D.S. locales	S	Italy	Oxfordian	157	155	156	2	67	45	2	1	P,R	Channell et al. [1990]
8	Zalas/Rudno locales	S	Poland	Oxfordian	157	155	156	2	84	43	2	1	P,R	Ogg et al. [1991]
9	Djebel Oust locale	S	Tunisia	Calv-Oxfrd	161	155	158	6	42	83	2	1	P,R	Nairn et al. [1981]
10	Summerville Fm	Sr	Utah	Callovian	160	158	159	2	391	9 <sup>r</sup>	2	2	P,R	Steiner [1978]
11	Paczoltowice and 3 locales	S	Poland	Callovian	161	157	159	4	62	37	2	1	P,R	Ogg et al. [1991]
12	Krakow-Czestochowa units	S	Poland	Callovian	161	157	159	4	9	56	1	1	P,R	Kadzialko-Hofmold & Kruczyk [1987]
13	Piccola/Valle/Covolo locs.	S	Italy	Callovian	161	157	159	4	92	55	2	1	P,R	Channell et al. [1990]
14	Calcarei Bianchi/C. Diaspr.	S	Italy	Aal-Kimm	178	152	165	26	245	95	2	2	R	Channell et al. [1984]
15	Carabuey section	S	Spain	Bajocian	173	166	169	7	528	63	2	2	R	Steiner et al. [1987]
16	White Mt/Belknap/Monadn.	I	N.H./Vt.	m JR	185	155	170	30	12	100	1	1	P	Van Fossen and Kent [1990]
17	Corral Canyon volcanics	V	Ariz.	l-m JR	178	166	172	12	12	92	1	1	P,R	May et al. [1986]
18	Dun Caan/Ollach/Udm Fm	Sr	Scotland	Aalenian	178	173	175	5	85	73	2	2	R	Hailwood et al. [1991]
19	Maiolica Ls eq.	S	Switzerl.	Aalenian	178	173	175	5	56	59	2	2	R	Horner and Heller [1983]
20	Amm. Rosso/M. di M.S.	S	Italy	Toarcian	184	178	181	6	68	65	2	2	R	Channell et al. [1984]
21	Thouars section	S	France	Toarcian	186	179	182	7	100	53	2	2	R	Galbrun et al. [1988]
22	Ammonitico Rosso Ls	S	Spain	Toarcian	187	178	182	9	80	45	2	2	R	Galbrun et al. [1990]
23	Amm. Rosso/Maiolica Ls	S	Switzerl.	Toarcian	187	178	182	9	122	49	2	2	R	Horner and Heller [1983]
24	Draa Valley/Fourm-Zguid	I	Morocco	u-IJR	191	177	184	14	21	100 <sup>r</sup>	1	1	P	Hailwood and Mitchell [1971]
25	Corniola Fm	S	Italy	Pliensbch	194	187	190	7	126	49	2	2	R	Channell et al. [1984]
26	Siliceous/Amm. Rosso Ls	S	Switzerl.	Pliensbch	194	187	190	7	400	43	2	2	R	Horner and Heller [1983]
27	diabase dikes	I	Liberia	u-IJR	198	182	190	16	25	76	1	1	P,R	Dabrymple et al. [1975]
28	Cephalopoda ls	S	Hungary	Pliensbch	195	187	191	8	123	45	2	2	R	Marton et al. [1980]
29	Ironstone/Staites Fm	Sr	England	Pliensbch	195	189	192	6	31	100	1	1	P	Hijab and Tarling [1982]
30	Moenave Fm/Whitmr Mbr	Sr	Ariz./Utah	Sinn-Plns	199	191	195	8	13	69	1	1	P,R	Ekstrand and Butler [1989]
31	E & W Rock/Mt. Carmel	I	Conn.	m-IJR	200	190	195	10	28	100	1	1	P	Smith and Noltimier [1979]
32	Anari/Tapirapua Fm	V	Brazil	Sinemum	197	196	196	1	15	100	1	1	P	Montes-Lauar et al. [1994]
33	Piedmont diabase dikes	I	S.C.	m-IJR	203	191	197	12	24	100	1	1	P	Dooley and Smith [1982]
34	Kayenta Fm	Sr	Utah	Hett-Plns	205	190	197	15	197	70	2	2	P,R	Steiner and Helsley [1974]
35	Corniola Fm	S	Italy	Sinemum	203	194	199	9	20	70	1	2	R	Channell et al. [1984]
36	Freetown igneous complex	I	Liberia	uTR/IJR	220	180	200	40	10	70	1	1	P,R	Briden et al. [1971]
37	Moenave Fm/Dinosr Mbr	Sr	Ariz./Utah	Hett-Sinn	206	199	202	7	10	100	1	1	P	Ekstrand and Butler [1989]
38	Extrusive Zone	SrV	N.J./Pa.	Hettangn	208	206	207	2	57	100	2	1	P	McIntosh et al. [1985]
39	N. Mt./Caraq./Avalon bsits	IV	E. Canada	Hettangn	208	206	207	2	13	100	1	1	P	Hodoch and Hayatsu [1988]
40	Extrusive Zone	SrV	N.J.	Hettangn	208	206	207	2	11	100	1	1	P	Witte and Kent [1990]
41	Newark/Hartfd/Deerfd bsits	V	N.J./Cn./Ma.	Hettangn	208	206	207	2	15	100	1	1	P	Prevot and McWilliams [1989]
42	Passaic Fm/Wachtung bsits	SrV	N.J.	Norm-Hett	210	206	208	4	17	100	1	1	P	Van Fossen et al. [1986]
43	Passaic Fm	Sr	N.J./Pa.	Norian	220	210	215	10	26	58	2	1	R	Witte et al. [1991]
44	ODP sites 759/760	S	Exmouth Plt.	Norm-Rhtn	223	209	216	14	356	56	2	2	R	Galbrun et al. [1992]
45	Locketong/Passaic Fm	Sr	N.J./Pa.	Norm-Rhtn	225	208	216	17	360	64	2	1	P,R	McIntosh et al. [1985]
46	Barla Complex	S	Turkey	Norian	223	217	220	6	179	52	2	2	R	Gallet et al. [1993]
47	Chinle Fm	Sr	N.M.	Cam-Rhtn	235	208	221	27	351	38	2	2	P,R	Reeve and Helsley [1972]
48	Huangmaqing Fm	Sr	S. China	Cam-Rhtn	235	208	221	27	23	39	2	1	P,R	Opdyke et al. [1986]
49	Ankareh/Chugwater Fm	Sr	Idaho/Wyom.	Cam-Rhtn	235	208	221	27	14	43	1	1	P,R	Grubbs and Van der Voo [1976]
50	Tongchuan/Yanchang Fm	S	N. China	Cam-Rhtn	235	208	221	27	11	55	1	1	P,R	Yang et al. [1991]
51	Fleming Fjord Fm	Sr	Greenland	Cam-Norm	235	209	222	26	134	40	2	2	P,R	Reeve et al. [1974]
52	Stockton/Locketng/Passc Fm	Sr	Pa.	Cam-Norm	231	219	225	12	19	42	1	1	P,R	Witte and Kent [1989]
53	Abbott/Agamenticus intr.	I	Maine	l-uTR	233	217	225	16	16	19 <sup>r</sup>	1	1	P,R	Fang and Van der Voo [1988]
54	Chinle Fm	Sr	N.M.	Carnian	235	223	229	12	17	88 <sup>r</sup>	1	1	P,R	Molina-Garza et al. [1991]
55	Reifling Ls	S	Austria	Carnian	235	223	229	12	48	54	1	1	R	Gallet et al. [1994]
56	Bakirli Dag Gp	S	Turkey	Carnian	235	229	232	6	63	59	1	1	R	Gallet et al. [1994]
57	Bakirli Dag Gp	S	Turkey	Carnian	235	229	232	6	232	61	2	2	R	Gallet et al. [1992]
58	Bundsandstein/Muschelkalk	Sr	Spain	Ladinian	238	235	236	3	22	50	2	2	P,R	Turner et al. [1989]
59	Zhifang Fm	Sr	N. China	Anis-Ladn	241	235	238	6	17	59	1	1	P,R	Yang et al. [1991]
60	Bundsandstein	Sr	Spain	Anisian	241	238	239	3	21	92	2	2	P,R	Turner et al. [1989]
61	Prezzo/Buchenstein Fm	S	Italy	Anisian	240	239	240	1	43	100	2	1	P	Muttoni and Kent [1994]
62	upper Moenkopi Fm	Sr	Colo.	Scythian	243	241	242	2	383	38	2	2	P,R	Helsley and Steiner [1974]

Table 1. (continued)

No.	Formation	Rock Type <sup>a</sup>	Location	Epoch	Age Range				m	PR	S	M	QF	Source
					Upr	Lwr	Midpt	Dur						
63	Blind Fiord Fm	S	Can. Arctic	Scythian	245	241	243	4	142	52	2	2	R	Ogg and Steiner [1991]
64	Feixianguan/Jialingjiang Fm	Sr	China	Scythian	245	241	243	4	418	40	2	2	P,R	Steiner et al. [1989]
65	Yelang Fm	Sr	S. China	Scythian	245	241	243	4	9	56	1	1	P,R	Opdyke et al. [1986]
66	Moenkopi Fm	Sr	Colo.	Scythian	245	241	243	4	283	40	2	2	P,R	Larson et al. [1982]
67	Moenkopi Fm	Sr	Ariz.	Scythian	245	241	243	4	41	44	2	1	P,R	Elston and Purucker [1979]
68	Bundsandstein	Sr	Spain	Scythian	245	241	243	4	24	62	2	2	P,R	Turner et al. [1989]
69	Lioujiagou/Heshanggou Fm	Sr	N. China	Scythian	245	241	243	4	16	56	1	1	P,R	Yang et al. [1991]
70	Moenkopi Fm	Sr	Utah	Scythian	245	241	243	4	222	16	2	2	P,R	Lienert and Helsley [1980]
71	Moenkopi Fm	Sr	N.M.	Scythian	245	241	243	4	36	39	1	1	P,R	Molina-Garza et al. [1991]
72	Chugwater Fm	Sr	Wyom.	Scythian	245	241	243	4	546	18	2	2	P,R	Shive et al. [1984]
73	lower Moenkopi Fm	Sr	Colo.	Scythian	245	243	244	2	393	34	2	2	P,R	Helsley [1969]
74	Dalong/Feixianguan Fm	Sr	China	uPM/l-ITR	250	243	246	7	114	68	2	2	R	Heller et al. [1988]
75	Wargal/Chhidru Fm	S	Pakistan	u-uPM	250	245	247	5	35	78	1	2	P,R	Haag and Heller [1991]
76	Wujiaping/Changxing Fm	S	China	u-uPM	250	245	247	5	125	33	2	2	P,R	Steiner et al. [1989]
77	Biyulopaokutze section	Sr	China	u-uPM	251	245	248	6	16	25	1	1	R	McFadden et al. [1988]
78	Verrucano Lombardo Fm	Sr	Italy	uPM/ITR	256	241	248	15	34	68	2	1	P,R	Kipfer and Heller [1988]
79	Maubisse Fm	S	Timor	uPM/ITR	256	241	248	15	12	100 <sup>br</sup>	1	1	P	Wensink and Hartosukohardjo [1990]
80	various formations	Sr	N.M./Okla.	uPM	254	245	249	9	13	15	1	1	P,R	Peterson and Nairn [1971]
81	Massif des Maures	Sr	France	uPM	256	245	250	11	122	16	2	1	P,R	Merabet and Daly [1986]
82	Horcajo Fm	IV	Argentina	uPM	256	245	250	11	25	0 <sup>r</sup>	1	1	P	Rapalini and Vilas [1991]
83	Kamthi/Mangli beds	Sr	India	uPM	256	245	250	11	22	32	1	1	P,R	Klootwijk [1975]
84	Dewey Lake Fm	Sr	Texas	u-u-uPM	255	247	251	8	17	65	1	1	P,R	Molina-Garza et al. [1989]
85	Wargal Fm	S	Pakistan	l-uPM	256	250	253	6	78	50	2	2	P,R	Haag and Heller [1991]
86	Wargal Ls	S	Pakistan	l-uPM	256	250	253	6	57	100 <sup>r</sup>	2	1	P	Klootwijk et al. [1986]
87	Tambillos Fm	SV	Argentina	u-l-l-uPM	280	250	265	30	16	0	1	1	P	Rapalini and Vilas [1991]
88	upper Pictou Group	Sr	E. Canada	u-IPM	275	260	268	15	80	4	2	1	P,R	Symons [1990]
89	Abadla group	Sr	Morocco	IPM	290	256	273	34	13	0	1	1	P	Morel et al. [1981]
90	Bolzano volcanics	V	Italy	IPM	290	256	273	34	39	0	1	1	P	Zijderveld et al. [1970]
91	Bohuslän dikes	I	Sweden	IPM	290	256	273	34	17	0	1	1	P	Thorning and Abrahamsen [1980]
92	Speckled Sandstone	Sr	Pakistan	IPM	290	256	273	34	9	0	1	1	P	Wensink [1975]
93	Rotliegendes Fm	Sr	Germany	IPM	290	260	275	30	25	0	1	1	P	Mauritsch and Rother [1983]
94	Lodève basin groups	Sr	France	IPM	290	260	275	30	14	0	1	1	P	Merabet and Guillaume [1988]
95	Ingelside Fm	Sr	Colo.	m-IPM	283	270	277	13	34	0	2	2	P	Diehl and Shive [1979]
96	Exeter volcanic traps	V	England	l-IPM	285	273	279	12	22	0	2	1	P	Zijderveld [1967]
97	Abo Fm	Sr	N.M.	l-IPM	288	270	279	18	84	0	2	1	P	Steiner [1988]
98	Capas de la Ermita	Sr	Spain	l-IPM	290	270	280	20	15	0	2	2	P	Turner et al. [1989]
99	Supai/Cutler/Abo Fm	Sr	Az./N.M./Ut.	l-IPM	290	270	280	20	19	0	1	1	P	Peterson and Nairn [1971]
100	Cap aux Meules Fm	Sr	E. Canada	u-uCB/IPM	303	270	286	33	11	0	1	1	P	Tanczyk [1988]
101	Dunkard Fm	Sr	W.V.	u-uCB/IPM	292	282	287	10	101	3	2	1	P	Helsley [1965]
102	Säma intrusive	I	Sweden	u-uCB/IPM	301	273	287	28	19	0	1	1	P	Bylund and Patchett [1977]
103	Laborcita Fm	Sr	N.M.	l-l-IPM	290	288	289	2	114	0	2	1	P	Steiner [1988]
104	Minturn/Maroon Fm	Sr	Colo.	uCB/IPM	308	270	289	38	171	0	2	1	P	Miller and Opdyke [1985]
105	Casper Fm	Sr	Wyom.	uCB/IPM	310	270	290	40	233	0	2	2	P	Diehl and Shive [1981]
106	Strzeg./Kark./Karp./Kudowa	I	Poland	u-uCB/IPM	305	280	292	25	38	13	1	1	P	Halvorsen et al. [1989]
107	Supai Gp/Wescogame Fm	Sr	Ariz.	u-uCB	298	290	294	8	45	0	2	1	P	Steiner [1988]
108	Pictou Red Beds	Sr	E. Canada	u-uCB	303	290	296	13	40	5	1	1	P	Pan and Symons [1993]
109	Woniusi Fm	SV	China	uCB	323	290	306	33	21	0	1	1	P	Huang and Opdyke [1991]
110	El Adeb Larache Fm	S	Algeria	m-uCB	311	303	307	8	10	0	1	1	P	Henry et al. [1992]
111	Hassi Bch./Ain Ech Ch. Fm	Sr	Algeria	l-uCB	323	307	315	16	11	0	1	1	P	Daly and Irving [1983]
112	Black Prince Ls	S	Ariz.	l-l-uCB	323	311	317	12	82	54	2	1	P,R	Nick et al. [1991]
113	Maring/Shepody/Clare Fm	Sr	E. Canada	u-l-l-uCB	333	315	324	18	413	55	2	2	P,R	DiVenere and Opdyke [1990/1991a]
114	Hopewell Gp	Sr	E. Canada	u-l-l-uCB	333	315	324	18	15	67	1	1	P,R	Roy and Park [1969]
115	Mauch Chunk Fm	Sr	Pa.	u-ICB	328	323	325	5	101	59	2	2	P,R	DiVenere and Opdyke [1991b]
116	Loch Eil/Loch Arkaig dikes	I	Scotland	u-l-l-uCB	334	318	326	16	18	0 <sup>r</sup>	1	1	P	Esang and Piper [1984]
117	Mauch Chunk Fm	Sr	Pa.	u-ICB	333	323	328	10	23	43	1	1	R	Kent and Opdyke [1985]
118	Mauch Chunk Fm	Sr	Pa.	u-ICB	333	323	328	10	13	54	1	1	R	Kent [1988]
119	Central Massif volcanics	V	France	m-ICB	343	333	338	10	13	77 <sup>d</sup>	1	1	P,R	Edel et al. [1981]
120	Deer Lake Gp	Sr	E. Canada	m-ICB	350	328	339	22	25	48	1	1	P,R	Irving and Strong [1984]
121	Harz Mt. greywackes	S	Germany	m-ICB	350	333	341	17	32	28	2	1	P,R	Bachadse et al. [1983]
122	Issimura/Lower Kuttung	V	Australia	m-ICB	350	333	341	17	10	50	1	1	R	Luck [1973]
123	Mount Eclipse Ss	S	Australia	l/m-ICB	363	333	348	30	69	46	2	1	P,R	Chen et al. [1994]
124	Brewer Conglomerate	S	Australia	u-u-uDV	364	362	363	2	33	33	2	1	P,R	Chen et al. [1993]

Table 1. (continued)

No.	Formation	Rock Type <sup>a</sup>	Location	Epoch	Age Range				m	PR	S	M	QF	Source
					Upr	Lwr	Midpt	Dur						
125	Worange Pt Fm	S	Australia	m/u-uDV	370	362	366	8	63	37	2	1	P,R	Thrupp et al. [1991]
126	Pillara/Nullara/Napier Fm	S	Australia	m-uDV	372	364	368	8	31	76	2	1	P,R	Hurley and Van der Voo [1987]
127	Lochiel Fm	V	Australia	uDV	377	362	370	15	25	64	1	1	R	Luck [1973]
128	Terrenceville Fm	Sr	E. Canada	uDV	377	362	370	15	41	32	2	1	P,R	Kent [1982]
129	Subasi/Acha/Yingan locs.	Sr	W. China	u-m/uDV	381	362	371	19	54	69 <sup>e</sup>	1	1	P,R	Li et al. [1990]
130	Comerong volcanics	V	Australia	u-m/l-uDV	379	372	375	7	11	82	1	1	P	Schmidt et al. [1986]
131	Gilif Hills volcanics	V	Sudan	u-m/l-uDV	382	372	377	10	11	18 <sup>r</sup>	1	1	P,R	Bachtadse and Briden [1991]
132	Compton Fm	Sr	Quebec	u-l/l-mDV	390	381	385	9	15	33	1	1	P,R	Seguin et al. [1982]
133	Traveler Rhyolite	V	Maine	u-l DV	392	388	390	4	13	69	1	1	P,R	Sparsos and Kent [1983]
134	Wood Bay Fm	Sr	Spitsbergen	m/u-l DV	396	386	391	10	121	46	2	1	P,R	Jelenska and Lewandowski [1986]
135	"Old Red Ss" red beds	Sr	Iran	l/l-mDV	408	381	394	27	13	92 <sup>tr</sup>	1	1	P,R	Wensink [1983]
136	Snowy River volcanics	V	Australia	l DV	408	386	397	22	40	75	2	1	P,R	Schmidt et al. [1987]
137	Peel Sound Fm	Sr	Can. Arctic	u-l-l DV	402	396	399	6	39	44	1	1	P,R	Dankers [1982]
138	Dniester River units	Sr	Ukraine	l/m-l DV	408	390	399	18	10	50	1	1	P,R	Smethurst and Kramov [1992]
139	Eastport Fm	ISrV	Maine	l-l DV	404	396	400	8	14	14 <sup>r</sup>	1	1	P,R	Kent and Opdyke [1980]
140	Hersey Fm	ISr	Maine	uSL/l-l DV	410	404	407	6	16	6 <sup>r</sup>	1	1	P,R	Kent and Opdyke [1980]
141	Honningsvåg Complex	I	Norway	uSL/l-l DV	418	404	411	14	10	80	1	1	P,R	Torsvik et al. [1992b]
142	Bloomsburg Fm	Sr	Pa. (R)	m-uSL	418	412	415	6	68	76	2	1	P,R	Stamatakis and Kodama [1991]
143	Bloomsburg Fm	Sr	Pa. (Dw,Mr)	m-uSL	418	412	415	6	32	100	1	1	P	Stamatakis and Kodama [1991]
144	Bloomsburg Fm	Sr	Pa.	m-uSL	418	412	415	6	17	59	1	1	P,R	Kent [1988]
145	Ringerike Sandstone	Sr	Norway	uSL	424	408	416	16	19	63	1	1	P,R	Douglass [1988]
146	Barrandian Basin units	ISV	Czechland	uSL	424	408	416	16	10	70 <sup>h</sup>	1	1	P,R	Tait et al. [1994]
147	Wabash Fm	S	Indiana	uSL	424	409	416	15	89	42	2	1	P,R	McCabe et al. [1985]
148	Laidlaw/Douro/Hawkins	SV	Australia	u-l/l-uSL	430	411	420	19	16	69	1	1	R	Luck [1973]
149	Slite Beds	S	Gotland	l-u-ISL	430	427	428	3	29	100	1	1	P	Claesson [1979]
150	Springdale Grp	Sr	E. Canada	ISL	434	422	428	12	10	70	1	1	P,R	Hoddy and Buchan [1994]
151	Springdale Grp	SrV	E. Canada	ISL	434	422	428	12	11	91	1	1	P,R	Potts et al. [1993a]
152	Lawrenceton Fm	SrV	E. Canada	ISL	439	424	431	15	9	11 <sup>r</sup>	1	1	P,R	Gales et al. [1989], Lapointe [1979]
153	Wigwam Fm/Botwood Grp	SrV	E. Canada	ISL	439	424	431	15	23	70	1	1	P,R	Buchan and Hoddy [1992]
154	Rose Hill Fm	Sr	Md./W.V.	u-l-ISL	434	430	432	4	23	87	2	1	P,R	French and Van der Voo [1979]
155	King George IV Lake units	SrV	E. Canada	l-ISL	439	430	434	9	11	91	1	1	P,R	Buchan and Hoddy [1989]
156	Wigwam Fm	Sr	E. Canada	l-ISL	439	430	434	9	13	46	1	1	P,R	Lapointe [1979]
157	Dunn Point Fm	V	E. Canada	uOR/mSL	449	419	434	30	16	100	1	1	P	Van der Voo and Johnson [1985]
158	Juniata Fm	Sr	Pa.	u-u-uOR	441	439	440	2	11	100	1	1	P,R	Miller and Kent [1989]
159	Juniata Fm	Sr	Pa.	u-u-uOR	441	439	440	2	17	53	1	1	P,R	Van der Voo and French [1977]
160	Builth Wells dolerites	I	England	u-uOR	443	439	441	4	10	40	1	1	P,R	Piper and Briden [1973]
161	Martinsburg Fm	S	Pa.	l-u-uOR	443	441	442	2	35	100	2	1	P	Housen et al. [1993]
162	Thouars Massif	I	France	uOR/ISL	453	435	444	18	18	50	1	1	P,R	Perroud and Van der Voo [1985]
163	Breidden Hill volcanics	IV	England	uOR	458	439	448	19	12	83	1	1	P,R	Piper and Stearn [1975]
164	Carrock Fell intrusives	I	England	uOR	464	439	452	25	11	100	1	1	P	Briden and Morris [1973]
165	Borrowdale volcanics	V	England	l-l-uOR	464	449	456	15	27	100	1	1	P	Briden and Morris [1973]
166	Borrowdale volcanics	V	England	l-l-uOR	464	449	456	15	27	100	1	1	P	Faller et al. [1977]
167	Bluffer Pond Fm	IV	Maine	u-m/l-uOR	466	453	459	13	11	100	1	1	P	Potts et al. [1993b]
168	Chickamauga Sprgp	S	Tenn.	l-l-uOR	464	458	461	6	10	90	1	1	P,R	Watts and Van der Voo [1979]
169	Dalby Ls	S	Sweden	u-m/l-uOR	467	460	463	7	23	100	1	1	P,R	Torsvik and Trench [1991b]
170	Skövde/Gullhögen/Ryd Fm	S	Sweden	l-u-mOR	469	467	468	2	43	3 <sup>h</sup>	2	2	P,R	Torsvik and Trench [1991b]
171	Builth Wells inlier	V	Wales	u-l-mOR	472	469	470	3	11	0	1	1	P	Briden and Mullan [1984]
172	Builth Wells inlier	V	Wales	u-l-mOR	472	469	470	3	18	0	1	1	P	Trench et al. [1991b]
173	Builth Wells inlier	V	Wales	u-l-mOR	472	469	470	3	18	0	1	1	P	McCabe et al. [1992]
174	Drummondville-Actonvale	SV	Quebec	mOR	476	464	470	12	23	13	2	1	P,R	Seguin [1977]
175	Robert's Arm Gp	V	E. Canada	mOR	476	464	470	12	11	9	1	1	P,R	Van der Voo et al. [1991]
176	Builth volcanics	V	England	u-l-mOR	473	469	471	4	15	0	1	1	P	Piper and Briden [1973]
177	Holen/Vämb Ls	S	Sweden	u-l-mOR	473	469	471	4	17	5 <sup>h</sup>	1	2	P,R	Torsvik and Trench [1991b]
178	Mweelrea ignimbrites	V	Ireland	m-l-mOR	474	470	472	4	17	6	1	1	P	Morris et al. [1973]
179	Powell/Evert/St. Peter Fm	S	Arkansas	l-mOR	476	469	472	7	50	50 <sup>r</sup>	2	2	P,R	Farr et al. [1993]
180	Suri Fm	SV	Argentina	l-mOR	476	469	472	7	30	0	1	1	P	Valencio et al. [1980]
181	Shelve Inlier	V	Wales	l-l-mOR	476	472	474	4	11	0 <sup>i</sup>	1	1	P	McCabe and Channell [1990]
182	Orthoceras Ls	S	Sweden	u-l/l-mOR	493	469	481	24	19	0	1	1	P	Perroud et al. [1992]
183	Orthoceras Ls	S	Sweden	u-l/l-mOR	493	469	481	24	21	0	1	1	P	Torsvik and Trench [1991c]
184	Moulin de Chateaup. Fm	Sr	France	u-lOR	493	476	484	17	10	0	1	1	P	Perroud et al. [1986]
185	Younger Gabbros	I	Scotland	l/mOR	503	467	485	36	32	0	1	1	P	Sallomy and Piper [1973a]
186	Graafwater Fm	Sr	S. Africa	l/mOR	505	464	485	41	12	8	1	1	P,R	Bachtadse et al. [1987]

Table 1. (continued)

No.	Formation	Rock Type <sup>a</sup>	Location	Epoch	Age Range				m	PR	S	M	QF	Source
					Upr	Lwr	Midpt	Dur						
187	Pont-Réan Fm	Sr	France	IOR	505	476	491	29	11	0	1	1	P	Cogné [1988]
188	St. George Gp	S	E. Canada	IOR	505	476	491	29	9	0	1	1	P	Deutsch and Prasad [1987]
189	Moreton's Harbor Gp	I	E. Canada	IOR	505	476	491	29	23	9	1	1	P,R	Johnson et al. [1991]
190	Treffgarne volcanics	V	Wales	u-l-IOR	500	493	496	7	10	0	1	1	P	Torsvik and Trench [1991a]
191	Oneota Dolomite	S	Ia./Wi./Mn.	l-IOR	505	498	502	7	50	30	2	1	P,R	Jackson and Van der Voo [1985]
192	Shallow Bay/Green Pt Fm	S	E. Can. (Sp)	uCM/IOR	506	500	503	6	18	16	2	2	R	Ripperdan [1990]
193	Shallow Bay/Green Pt Fm	S	E. Can. (Bp)	uCM/IOR	507	498	503	9	81	14	2	2	R	Ripperdan [1990]
194	Green Point Fm	S	E. Can. (Gp)	uCM/IOR	507	498	503	9	95	13	2	2	R	Ripperdan [1990]
195	Florida Mountains	I	N.M.	l-IOR	513	493	503	20	24	92 <sup>r</sup>	1	1	P	Geissman et al. [1991]
196	Dayangcha section	S	China	uCM/IOR	507	501	504	6	81	60 <sup>j,r</sup>	2	2	R	Ripperdan [1990]
197	Royer Dolomite	S	Okla.	u-uCM	506	505	505	1	32	0	1	1	P	Nick and Elmore [1990]
198	Chatsworth Ls/Ninmaroo Fm	S	Australia	uCM/IOR	507	503	505	4	44	13	2	2	R	Ripperdan [1990]
199	Wilberns Fm	S	Texas	uCM/IOR	507	504	506	3	21	35	2	2	R	Ripperdan [1990]
200	Welge/Morgan Crk/Pnt Pk	S	Texas	m-uCM	507	506	506	1	20	0	1	1	P	<sup>k</sup> Van der Voo et al. [1976]
201	Riley/Wilberns Fm	S	Texas	uCM	508	505	506	3	100	10	2	1	P,R	Farr and Gose [1991]
202	Peerless Fm	S	Colo.	m/u-uCM	508	506	507	2	75	35 <sup>1</sup>	2	1	P	Peck et al. [1986]
203	Taun Sauk Ls	S	Missouri	u-l-uCM	509	508	508	1	9	100 <sup>r</sup>	1	1	P	Dunn and Elmore [1985]
204	Cap Mountain Ls	S	Texas	l-uCM	510	508	509	2	43	23	2	1	P,R	Watts et al. [1980]
205	Kyrshabakty/Batyrbay sects.	S	Kazakhstan	m-uCM	514	504	509	10	20	5 <sup>m</sup>	2	2	R	Ripperdan [1990]
206	Connemara Gabbros	I	Ireland	mCM/IOR	520	500	510	20	12	8	1	1	P	Morris et al. [1973]
207	Hudson Fm	Sr	Australia	mCM	520	510	515	10	13	0	1	1	P	Luck [1972]
208	Salt Pseudomorph Beds	Sr	Pakistan	mCM	520	510	515	10	10	20 <sup>n</sup>	1	1	P,R	Wensink [1972]
209	Giles Crk/Shannon Fm	S	Australia	mCM	520	510	515	10	40	30	2	1	P,R	Klootwijk [1980]
210	Bourinot Gp	S	E. Canada	l-mCM	520	517	519	3	12	0	1	1	P	Johnson and Van der Voo [1985]
211	Bourinot Gp	V	E. Canada	l-mCM	520	517	519	3	44	57	2	1	P,R	Johnson and Van der Voo [1985]
212	Jutana Fm	S	Pakistan	u-l-l-mCM	525	515	520	10	21	24	2	1	P,R	Klootwijk et al. [1986]
213	Tapeats Ss	Sr	Ariz.	l-mCM	530	510	520	20	129	48	2	1	P,R	Elston and Bressler [1977]
214	Eninta Ss	S	Australia	<sup>o</sup> ICM	528	523	525	5	110	58	2	2	R	Kirschvink [1978]
215	Box Hole/Allua/Todd Rvr	S	Australia	<sup>o</sup> ICM	528	523	525	5	120	68	2	2	R	Kirschvink [1978]
216	Khewra Ss	Sr	Pakistan	m/u-ICM	530	520	525	10	9	0 <sup>r</sup>	2	1	P	Klootwijk et al. [1986]
217	Perekhod Fm	S	Siberia	m-ICM	528	525	526	3	257	55 <sup>q</sup>	2	1	R	Kirschvink and Rozanov [1984]
218	Box Hole Fm	S	Australia	<sup>p</sup> ICM	528	525	526	3	30	49	2	2	R	Kirschvink [1978]
219	Pestrotsvet/Perekhod Fm	S	Siberia	l-ICM	530	528	529	2	128	35 <sup>q</sup>	2	1	R	Kirschvink and Rozanov [1984]

Rock types: I, intrusive; S, sedimentary (Sr, redbeds); V, volcanic. Age ranges given in Ma/m.y. m, number of paleomagnetic sites or samples. PR, polarity ratio (given as %NP, percent normal polarity). S, basis for polarity ratio calculation: 1, sites; 2, samples. M, method of polarity ratio calculation: 1, number of sites or samples; 2, thickness of magnetozones. QF, quality factors supporting primary remanence acquisition: P, concordant paleopole; R, antipodal or nearly antipodal dual polarities.

<sup>a</sup> Cumulative frequency distributions (e.g., Figure 4) and mean deviations from the long-term polarity trend (e.g.,  $P_r(t) - \mu_r(t)$ ) are similar for all rock types (I, S, Sr, and V), indicating that systematic lithologic biases probably do not exist.

<sup>b</sup> Assumes SH paleolocation and 100° CCW postdepositional rotation (consistent with paleogeographic constraints).

<sup>c</sup> Combined with data from Smith and Piper [1979].

<sup>d</sup> Assumes 45° CW postdepositional rotation; near-equatorial paleolocation, no latitudinal constraint.

<sup>e</sup> Assumes NH location and 80°-90° CW postdepositional rotation.

<sup>f</sup> Assumes 30° CW postdepositional rotation; near-equatorial paleolocation, no latitudinal constraint.

<sup>g</sup> Assumes SH paleolocation and 140° CCW postdepositional rotation.

<sup>h</sup> 16%NP (l-u-mOR) and 24%NP (u-l-mOR) polarity ratios based on individual samples.

<sup>i</sup> Postulated Late Ordovician remagnetization unlikely; inconsistent with dominantly normal field polarity.

<sup>j</sup> Post-Cambrian rotation of Yangtze block unconstrained, N/R orientation uncertain; polarity ratios roughly balanced in either case.

<sup>k</sup> Combined with data from Watts et al. [1980] and Loucks and Elmore [1986].

<sup>l</sup> Postulated CRM of probable Late Cambrian age.

<sup>m</sup> Assumes SH paleolocation and 30°-50° CW postdepositional rotation.

<sup>n</sup> Assumes SH paleolocation and 30°-40° CW postdepositional rotation.

<sup>o</sup> Areyonga and Ross River sections; ages estimated as Atdabanian and early Lenian.

<sup>p</sup> Valley Dam section; age estimated as Atdabanian.

<sup>q</sup> Craton probably rotated 180° relative to orientation assumed in original paper (T. H. Torsvik, personal communication, 1995).

<sup>r</sup> Formations excluded at step 3 of polarity bias analysis (see text for discussion).

Table 2. British Siluro-Devonian "A" Remanences

No.	Formation	Rock		Epoch	Age Range				m	Paleopole		C <sup>a</sup>	PR	S	M	Source
		Type	Locat.		Up	Lwr	Midpt	Dur		Long	Lat					
A1	Browgill Fm	Sr	Engl	u-l-ISL	431	430	430	1	12	314	-14		67	1	1	Channell <i>et al.</i> [1993]
A2	E. Mendip Hills	V	Engl	l-u-ISL	429	428	428	1	9	271	+13	H	100	1	1	Torsvik <i>et al.</i> [1993]
A3	Salrock Fm	Sr	Irl	u-ISL	430	424	427	6	30	288	-2	H	100	1	1	Smethurst and Briden [1988]
A4	Salrock Fm	Sr	Irl	u-ISL	430	424	427	6	26	295	-23		100	1	1	Morris <i>et al.</i> [1973]
A5	Bunnamohau Fm	Sr	Irl	u-ISL	430	424	427	6	8 <sup>f</sup>	334	-28	H	100	1	1	Smethurst and Briden [1988]
A6	Lorne Plateau	V	Scot	l-l-uSL	424	415	419 <sup>d</sup>	9	29	321	+2		100	1	1	Latham and Briden [1975]
A7	Ratagan	I	Scot	l-l-uSL	422	416	419 <sup>d</sup>	6	12	346	-15		58	1	1	Turnell [1985]
A8	Lintrathen	V	Scot	l-uSL	422	410	416 <sup>d</sup>	12	8 <sup>f</sup>	327	-34	D	100	1	1	Trench and Haughton [1990]
A9	Glenbervie <sup>b</sup>	V	Scot	l-uSL	422	410	416 <sup>d</sup>	12	77	330	-4	P	100	1	1	Trench and Haughton [1990]
A10	Arrochar <sup>c</sup>	I	Scot	uSL	422	408	415	14	11	325	-6		45	1	1	Briden [1970]
A11	Comrie	I	Scot	uSL	416	408	412 <sup>d</sup>	8	28	287	-6		100	1	1	Turnell [1985]
A12	Lower ORS	V	Scot	uSL/l-IDV	417	405	411	12	34	320	-5		62	1	1	Sallomy and Piper [1973]
A13	Lower ORS	V	Scot	uSL/l-IDV	417	405	411 <sup>d</sup>	12	83	318	+2	1	52	1	1	Torsvik [1985]
A14	Lower ORS	V	Scot	uSL/l-IDV	417	405	411 <sup>d</sup>	12	37	315	-20	2	46	1	1	Torsvik [1985]
A15	Lower ORS	Sr	Wales	uSL/l-IDV	418	396	407	22	13	307	-7	H	38	1	1	Channell <i>et al.</i> [1992]
A16	Lower ORS	Sr	Wales	u-uSL/l-IDV	411	386	398	25	44	297	+3	H	48 <sup>g</sup>	2	1	Setiabudidayana <i>et al.</i> [1994]
A17	Cheviot Hills	V	Engl	m-IDV	400	392	396 <sup>d</sup>	8	16	323	+4		56	1	1	Thorning [1974]
A18	Sarclet Ss	Sr	Scot	u-IDV	393	388	390	5	10	344	-28	1	60	1	1	Storhaug and Storetvedt [1985]
A19	Sarclet Ss	Sr	Scot	u-IDV	393	388	390	5	39	326	-9	2	54	1	1	Storhaug and Storetvedt [1985]
A20	Esha Ness	V	Shet	mDV	386	377	381	9	8 <sup>f</sup>	314	-21		12	1	1	Storetvedt and Torsvik [1985]
A21	W. Midland Valley	V	Scot	IDV-ICB	408	333	370	75 <sup>e</sup>	9	322	-14	H	27	1	1	Torsvik <i>et al.</i> [1989]
A22	Hoy/Radwick	Sr	Ork	m-uDV	370	365	367	5	39	326	-23	B	56	1	1	Storetvedt and Meland [1985]
A23	E. Midland Valley	V	Scot	ICB	363	333	348	30	13	332	-14	H	31	1	1	Torsvik <i>et al.</i> [1989]
A24	Kinghorn	V	Scot	ICB	363	333	348	30	17	340	-15		53	1	1	Wilson and Everitt [1963]
A25	Derbyshire	V	Engl	u-u-ICB	338	334	336	4	10	336	-14		50	1	1	Piper <i>et al.</i> [1991]

See Table 1 for explanation of table legend.

<sup>a</sup> Magnetic component (as identified in original study).

<sup>b</sup> Includes Lintrathen.

<sup>c</sup> Includes Garabal and Glen Fyne.

<sup>d</sup> Age assignment from Thirwall [1988].

<sup>e</sup> Not used in polarity trend construction (age range > 1/3 period).

<sup>f</sup> Not used in polarity trend construction ( $m < 9$ ).

<sup>g</sup> Based on negative inclinations corresponding to *N* polarity; Mesozoic remanences possible.

Phanerozoic APWPs, e.g., North America [Mac Niocaill and Smethurst, 1994], Baltica [Torsvik *et al.*, 1991a, 1992a], East Avalonia [Trench and Torsvik, 1991; Torsvik *et al.*, 1993], and Gondwana [Irving and Irving, 1982; Van der Voo, 1993], and it should be noted that a large majority of the formation polarity data of the present study is derived from these landmasses. On the other hand, many small cratons have incompletely reconstructed APWPs (especially for the Paleozoic), and formations in many mobile tectonic belts have experienced poorly constrained amounts of postdepositional rotation. In some cases, such uncertainties can be resolved by paleogeographic constraints: for example, the equatorial position of Baltica in the Late Silurian favors a southerly paleolatitude (23°S) for Armorica, although this necessitates 140° of postdepositional rotation of the Barrandian Basin [Tait *et al.*, 1994]. However, an independent paleolatitudinal check on block rotations is not possible for remanences acquired in near-equatorial settings [e.g., Edel *et al.*, 1981]. Uncertainties in polarity orientations are footnoted in Tables 1-3.

To summarize, formation selection criteria have been carefully defined and consistently applied in order to produce a high-quality polarity data set. Any studies not present in the data set that meet these criteria have been inadvertently overlooked rather than intentionally excluded. The selection criteria excluded a number

of excellent paleomagnetic studies owing to (1) an insufficient number of sites [e.g., Storetvedt and Torsvik, 1985], (2) insufficient age control or an overly broad stratigraphic range [e.g., Smith, 1987], and (3) lack of evidence for a primary magnetic component [e.g., Seguin and Petryk, 1986]. No remanences of known secondary origin were used in this analysis (exceptions in Table 3 discussed below) because such remanences generally have poor age constraints. Although secondary remanences are potentially useful in construction of APWPs in the absence of firm age constraints [e.g., Seguin and Petryk, 1986], they cannot be used in a similar manner for reconstruction of polarity bias patterns.

The selection criteria used in the present study are substantially stricter than those applied by Irving and Pullaiah [1976]. Although they compiled nearly 800 polarity ratios, studies were included that contained a minimum of two sites ("localities") or five samples. The effect of a lower site minimum is to sharply increase the number of units exhibiting single-polarity results (i.e., 0%NP or 100%NP), which increases the variance among polarity ratios for any given stratigraphic interval (cf. Figure 2). Furthermore, although one can assume that Irving and Pullaiah attempted to restrict their data set to formations containing primary magnetic remanences, many pre-1970s paleomagnetic studies reported characteristic components that

Table 3. British Siluro-Devonian "B" Remanences

No.	Formation	Rock		Epoch	Age Range				Paleopole							Source
		Type	Locat.		Up	Lwr	Midpt	Dur	m	Long	Lat	C <sup>a</sup>	PR	S	M	
B1	Tourmak./Glensaul	IV	Irl	uOR	464	439	452	25	29	349	-31		10	1	1	<i>Deutsch and Storetvedt</i> [1988]
B2	E. Mendip Hills	V	Engl	l-u-ISL	429	428	428	1	4	339	-25	I	0	1	1	<i>Torsvik et al.</i> [1993]
B3	Bunnamohau Fm	Sr	Irl	u-ISL	430	424	427	6	8	331	-35	I	0	1	1	<i>Smethurst and Briden</i> [1988]
B4	Salrock Fm	Sr	Irl	u-ISL	430	424	427	6	29	333	-28	I	0	1	1	<i>Smethurst and Briden</i> [1988]
B5	Dingle Group	Sr	Irl	uSL	418	408	413	10	13	335	-32	B	0	1	1	<i>Storetvedt et al.</i> [1993]
B6	Dingle Group	Sr	Irl	uSL	418	408	413	10	12	330	-44	A	0	1	1	<i>Storetvedt et al.</i> [1993]
B7	Helmsdale	I	Scot	uSL/l-IDV	425	395	410	30	17	355	-31	B	12	1	1	<i>Torsvik et al.</i> [1983]
B8	Helmsdale	I	Scot	uSL/l-IDV	425	395	410	30	21	352	-49	A	0	1	1	<i>Torsvik et al.</i> [1983]
B9	Lower ORS	Sr	Wales	uSL/l-IDV	418	396	407	22	38	338	-40	L	0	1	1	<i>Channell et al.</i> [1992]
B10	Lower ORS	Sr	Wales	u-uSL/l-IDV	411	386	398	25	67	341	-41	I	0	1	1	<i>Setiabudidaya et al.</i> [1994]
B11	Cheviot Hills	I	Engl	IDV	399	393	396 <sup>c</sup>	6	5	330	-41	A2	0	1	1	<i>Mitchell et al.</i> [1993]
B12	Cheviot Hills	I	Engl	IDV	399	393	396 <sup>c</sup>	6	18	347	-30	B	17	1	1	<i>Mitchell et al.</i> [1993]
B13	Cheviot Hills	V	Engl	u-l-IDV	400	392	396 <sup>c</sup>	8	25	354	-34		8	1	1	<i>Storetvedt et al.</i> [1992]
B14	Llandstadwell Fm	Sr	Wales	m-IDV	396	390	393	6	6	334	-39		0	1	1	<i>Stearns and Van der Voo</i> [1987]
B15	Caithness ORS	Sr	Scot	u-l/l-mDV	390	381	385	9	27	329	-27	B	22	1	1	<i>Storetvedt and Torsvik</i> [1983]
B16	Caithness ORS	Sr	Scot	u-l/l-mDV	390	381	385	9	9	343	-51		0	1	1	<i>Tarling et al.</i> [1976]
B17	Foyers ORS	Sr	Scot	mDV	386	377	381	9	26	336	-46	A2	0	1	1	<i>Storetvedt et al.</i> [1990]
B18	Foyers ORS	Sr	Scot	mDV	386	377	381	9	81	350	-29	B	5	1	1	<i>Storetvedt et al.</i> [1990]
B19	Orkney dikes	I	Ork	u-mDV	381	377	379	4	32	340	-20	B	0	1	1	<i>Storetvedt and Ottera</i> [1988]
B20	Eday Group	V	Ork	u-mDV	381	377	379	4	6	347	-8		0	1	1	<i>Robinson</i> [1985]
B21	Eday Group	Sr	Ork	u-mDV	381	377	379	4	6	343	-40		0	1	1	<i>Robinson</i> [1985]
B22	Orkney dikes	I	Ork	u-mDV	381	377	379	4	42	343	-44	A	0	1	1	<i>Storetvedt and Ottera</i> [1988]
B23	John O'Groats Ss	Sr	Scot	u-u-mDV	379	377	378	2	12	325	-24	B	0	1	1	<i>Storetvedt and Carmichael</i> [1979]
B24	John O'Groats Ss	Sr	Scot	u-u-mDV	379	377	378	2	43	344	-54	A	16	1	1	<i>Storetvedt and Carmichael</i> [1979]
B25	Orkney lavas	V	Ork	u-m/l-uDV	381	367	374	14	7	330	-24		0	1	1	<i>Storetvedt and Petersen</i> [1972]
B26	W. Midland Valley	V	Scot	IDV-ICB	408	333	370	75	23	343	-43	I	0	1	1	<i>Torsvik et al.</i> [1989]
B27	Portishead Beds	Sr	Engl	uDV	377	362	369	15	10	338	-32		0	1	1	<i>Morris et al.</i> [1973]
B28	Upper ORS	Sr	Engl	l-u-ISL	377	362	369	15	4	327	-24	I	0	1	1	<i>Torsvik et al.</i> [1993]
B29	Duncansby	V	Scot	uDV	377	362	369	15	20	329	-24	B	0 <sup>d</sup>	1	1	<i>Storetvedt et al.</i> [1978]
B30	Upper ORS	Sr	Engl	l-u-ISL	377	362	369	15	4	341	-28	H	0	1	1	<i>Torsvik et al.</i> [1993]
B31	Iloy/Radwick	SrV	Ork	m-uDV	370	365	367	5	7	362	-48	A	0	1	1	<i>Storetvedt and Meland</i> [1985]
B32	E. Midland Valley	V	Scot	ICB	363	333	348	30	3	354	-38	I	0	1	1	<i>Torsvik et al.</i> [1989]
B33	Garlestone Hill	IV	Scot	ICB	363	333	348	30	33	344	-27		15	1	1	<i>Rother and Storetvedt</i> [1991]
B34	Loch Eil <sup>b</sup>	I	Scot	u-l/l-uCB	334	318	326	16	15	355	-35		0	1	1	<i>Esang and Piper</i> [1984]

See Table 1 for explanation of table legend.

<sup>a</sup> Magnetic component (as identified in original study).

<sup>b</sup> Includes Loch Arkalg.

<sup>c</sup> Age assignment from *Thirwall* [1988].

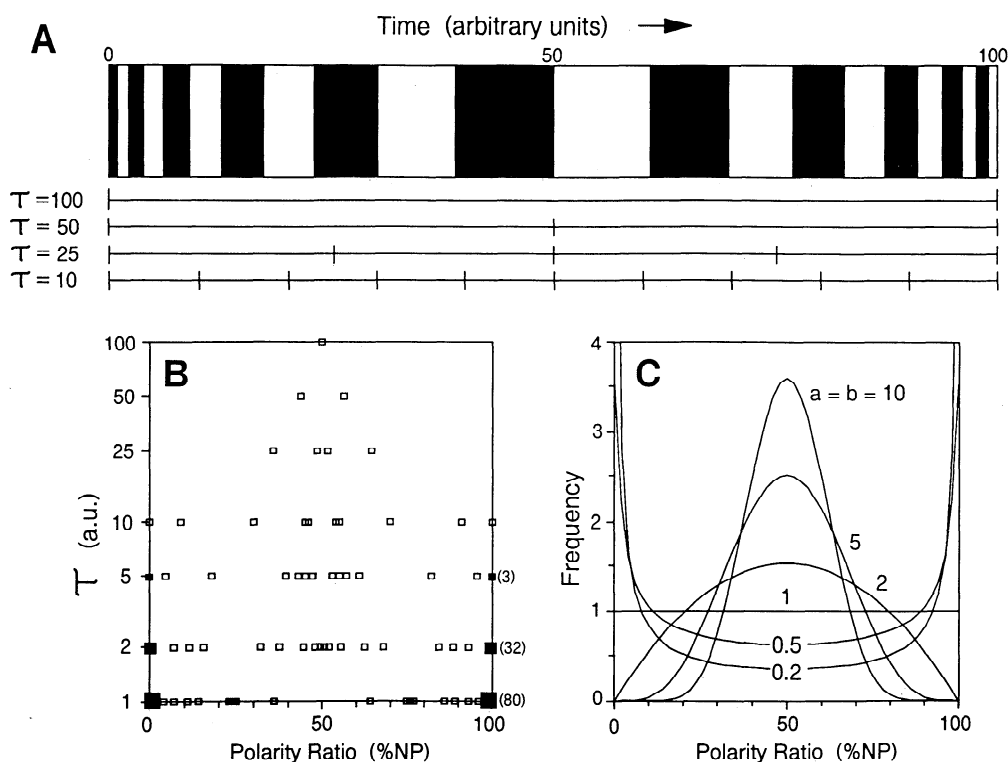
<sup>d</sup> Some samples contain a weak antipodal *N* polarity component.

have since been shown to have been insufficiently cleaned, to contain magnetic components with overlapping spectra, or to represent secondary magnetizations [e.g., *Smethurst and Khramov*, 1992]. Most of the studies utilized in this analysis postdate Irving and Pullaiah's work; the majority of them are cited in the paleopole appendix of *Van der Voo* [1993].

### Characteristic Timescale

Polarity ratios are meaningful only in relation to some specified characteristic timescale ( $\tau$ ; Figure 3). Instantaneous measurements of field polarity ( $\tau \approx 0$ ) are either reversed (i.e., 0%NP) or normal (i.e., 100%NP) except during relatively brief polarity transition intervals. On the other hand, at long time intervals ( $\tau > 100$  m.y.), all polarity ratios converge on the Phanerozoic mean (i.e., 50%NP). Thus estimates of polarity bias are most useful at some intermediate range of characteristic

timescales. The procedure utilized by *Irving and Pullaiah* [1976] as well as by the present study averages polarity orientations at two steps: (1) in calculating a formation polarity ratio from a set of sample or site polarities and (2) in calculating a polarity trend (i.e., a running average) from formation polarity ratios. The characteristic timescale associated with a formation polarity ratio  $\tau_F$  is the duration of the stratigraphic interval over which sample polarities were determined, and the characteristic timescale of a group of formation polarity ratios  $\bar{\tau}_F$  is the mean duration of the corresponding set of stratigraphic intervals. Because polarity trends average formation polarity ratios within a specified temporal window  $\lambda$ , the characteristic timescale associated with a polarity trend  $\tau_T$  is a function of both  $\bar{\tau}_F$  and  $\lambda$ . Therefore it is necessary to estimate a characteristic timescale at each step in the construction of polarity trends. *Irving and Pullaiah* [1976] calculated polarity trends from formation polarity ratios at values of  $\lambda$  from 5 to 100 m.y. (their Figure 13), but they did not



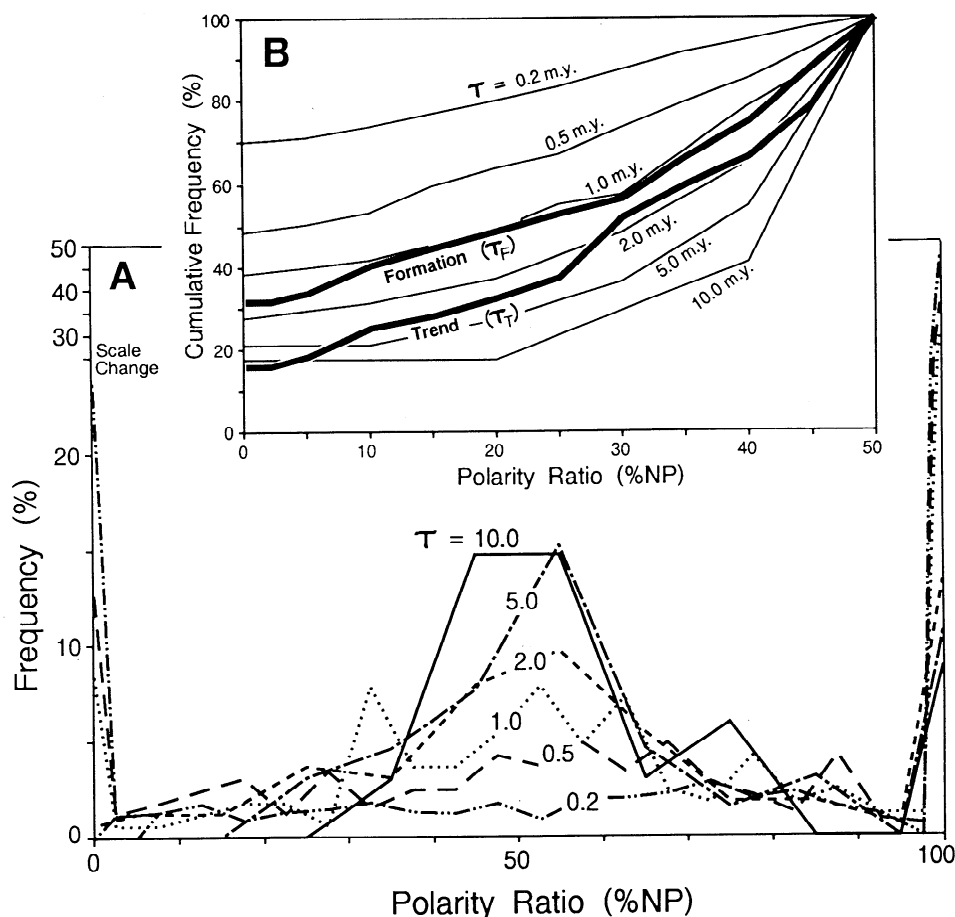
**Figure 3.** Explanation of characteristic timescale ( $\tau$ ): instantaneous geomagnetic field polarity ( $\tau \approx 0$ ) is either reversed (i.e., 0%NP) or normal (i.e., 100%NP) except during brief transition intervals; measurements averaged over progressively longer time intervals yield polarity ratios that converge on 50%NP. (a) Example of subdivision of a synthetic geomagnetic polarity timescale for calculation of polarity ratios at values of  $\tau$  ranging from 10 to 100 arbitrary time units. (b) Polarity ratios calculated from Figure 3a at values of  $\tau$  from 1 to 100 time units; these yield discrete frequency distributions that cluster toward 0% and 100%NP at small values of  $\tau$  and converge on 50%NP at large values of  $\tau$  (parenthetical values indicate number of polarity ratios at 0 and 100%NP for values of  $\tau$  of 1, 2, and 5 time units). (c) Continuous beta functions equivalent to the discrete frequency distributions in Figure 3b; the beta functions are defined by the nondimensional parameters ( $a, b$ ), in which  $a = b$  owing to symmetry about the interval mean (i.e., 50%NP) and in which  $a$  progressively increases from  $<1$  at short values of  $\tau$  to  $>1$  at long values of  $\tau$ . Note that (1) beta parameters  $a$  and  $b$  are not equivalent to  $\tau$ , (2) beta distribution frequency ( $y$  axis in Figure 3c) corresponds to polarity-ratio density ( $x$  axis in Figure 3b), (3)  $a = 1$  when reversal frequency  $f \approx 1/\tau$ , and (4) any randomly-distributed linear function that is subsampled at a range of values of  $\tau$  will yield beta distributions.

estimate  $\bar{\tau}_p$ , and hence the temporal significance of their results is unclear.

For polarity ratios calculated from the GPTS (Figure 1), it is possible to specify  $\bar{\tau}_p$ . Different values of  $\bar{\tau}_p$  yield different polarity-ratio frequency distributions (Figure 4). At short values of  $\bar{\tau}_p$  (e.g., 0.2 m.y.), most intervals (70%) are entirely of either N or R polarity, and intervals of mixed polarity are approximately uniformly distributed over the range 1-99%NP. At intermediate values of  $\bar{\tau}_p$  (e.g., 1.0 m.y.), a smaller proportion of intervals (38%) exhibit a single polarity, and mixed-polarity intervals exhibit weak clustering around 50%NP. At long values of  $\bar{\tau}_p$  (e.g., 10 m.y.), relatively few intervals exhibit a single polarity (18%), and mixed-polarity intervals cluster strongly about 50%NP. For purposes of mathematical description, polarity-ratio frequency distributions (Figures 3b and 4a) can be modeled using a beta function (Figure 3c) [Ross, 1984]. Comparisons among groups of polarity ratios are facilitated by transformation of frequency distributions to cumulative functions (Figure 4b). In constructing cumulative distributions, a useful simplifying procedure is to assume symmetry about the interval midpoint (i.e., 50%NP) and

combine the frequencies of complementary polarity ratios (e.g., 25%NP with 75%NP). This procedure assumes that the N and R polarity states are equivalent, which is widely although not universally accepted [McFadden *et al.*, 1987; Jacobs, 1994].

For polarity ratios determined from paleomagnetic studies of pre-Cretaceous units (Figure 2),  $\bar{\tau}_p$  cannot be specified but, rather, is a function of the average duration of stratigraphic intervals sampled for paleomagnetic analysis. Maximum estimates of the timescales ( $\tau_p$ ) associated with sampled stratigraphic intervals are provided by formation age ranges (Tables 1-3), but actual values of  $\tau_p$  are probably shorter in most cases because (1) the full stratigraphic ranges of formations are rarely sampled in paleomagnetic studies and (2) formation age ranges are commonly overestimated owing to uncertainties in biostratigraphic and radiometric dating. Although it is generally not possible to determine the degree to which a reported formation age range exceeds  $\tau_p$  for an individual formation, it is possible to estimate  $\bar{\tau}_p$  for a group of formations by comparing the cumulative frequency distribution of their polarity ratios to those calculated from the GPTS at various values of  $\bar{\tau}_p$ . The 278



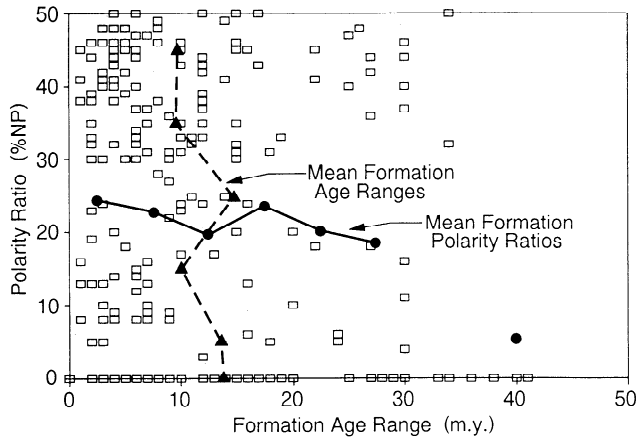
**Figure 4.** (a) Frequency distributions and (b) cumulative frequency distributions of polarity ratios calculated at values of  $\tau$  from 0.2 to 10 m.y. for the interval 0-158 Ma of the GPTS of *Harland et al.* [1990]. Approximately symmetric distributions of polarity ratios about the interval mean (Figure 4a) permits summation of complementary frequencies (i.e., 25%NP and 75%NP) prior to calculation of cumulative distributions (Figure 4b). Also shown are cumulative distributions for polarity ratios of Cambrian-Jurassic formations ( $\tau_F$ ; Tables 1-2) and for the polarity trend of Figure 12 ( $\tau_T$ ;  $\lambda = 5$  m.y.). Comparison of cumulative frequency distributions for Cambrian-Jurassic formations and the Cretaceous-Recent GPTS indicate that formation polarity ratios and polarity trends exhibit characteristic timescales  $\tau_F$  and  $\tau_T$  of circa 1.0-1.5 m.y. and 2-5 m.y., respectively.

Cambrian-Jurassic formations of this study have an average reported age range of 12 m.y. (Tables 1-3) but their polarity ratios yield a mean characteristic timescale  $\bar{\tau}_F$  of circa 1.0-1.5 m.y. (Figure 4b), an order-of-magnitude difference attributable to a combination of the factors cited above. An important assumption underlying this comparative procedure is that geomagnetic field behavior during the Cretaceous-Recent is representative of that of the Phanerozoic as a whole and therefore that similar cumulative frequency distributions of polarity ratios would be observed at similar values of  $\bar{\tau}_F$  for any comparably long geologic interval (i.e., >100 m.y.).

Further evidence that reported formation age ranges are substantially greater than the durations of sampled stratigraphic intervals is provided by lack of a relationship between formation age ranges and polarity ratios (Figure 5). If the durations of sampled stratigraphic intervals were nearly equal to formation age ranges, then polarity-ratio frequency distributions would exhibit greater clustering toward 50%NP for groups of formations of longer duration (e.g., Figures 3b and 4a). However, because formations in 5-m.y. age range classes (i.e., from 1-5 m.y. to 26-30 m.y.) exhibit similar polarity-ratio distributions, the mean

duration of sampled stratigraphic intervals for formations in all age range classes is probably as short as that of the shortest class (1-5 m.y.). This observation is consistent with a  $\bar{\tau}_F$  of circa 1.0-1.5 m.y. based on comparative analysis of Cambrian-Jurassic polarity ratio distributions with the Cretaceous-Recent GPTS (Figure 4b).

As discussed above, the characteristic timescale of a polarity trend  $\tau_T$  is dependent on both the timescale associated with formation polarity ratios  $\bar{\tau}_F$  and the width of the temporal window used in trend calculation  $\lambda$ . Because individual formation polarity ratios are averaged in calculating polarity trends, frequency distributions of the latter exhibit fewer extreme values (i.e., 0%NP or 100%NP) and more intermediate values (i.e., approaching 50%NP) than the former. Narrow windows (i.e., small  $\lambda$ ) result in minimal averaging of formation polarity ratios and a minimal shift toward 50%NP in the frequency distributions of trend polarity ratios, yielding a value of  $\tau_T$  only slightly larger than that of  $\bar{\tau}_F$  (Figure 4b). Broad windows (i.e., large  $\lambda$ ) result in greater averaging of formation polarity ratios and a larger shift toward 50%NP in the frequency distributions of trend polarity ratios, yielding a value of  $\tau_T$  substantially larger than that of  $\bar{\tau}_F$ .



**Figure 5.** Polarity ratio versus age range for Cambrian-Jurassic formations (Tables 1 and 2). Owing to symmetry about the interval mean, polarity ratios of 50-100%NP are plotted as the complementary values (i.e., 50-0%NP). Calculation of mean formation polarity ratios for 5-m.y. age range classes (circles) and mean formation age ranges for 10% polarity bias classes (triangles) reveals no significant relationship between polarity ratios and age ranges. The lack of such a relationship conflicts with observations for the GPTS (Figure 4) and suggests that most reported formation age ranges substantially exceed the duration of the paleomagnetically sampled stratigraphic intervals within formations.

Polarity trends constructed for the 278 Cambrian-Jurassic formations of this study yield values of  $\tau_r$  of circa 2.5 m.y. for  $\lambda = 5$  m.y. (Figure 4b). Although the mean characteristic timescale for formation polarity ratios  $\bar{\tau}_p$  cannot be specified, values of  $\tau_r$  can be adjusted to some degree by altering window width  $\lambda$ .

## Methods

### Calculation of Polarity Trends

Polarity trends provide a means to characterize secular variation in geomagnetic polarity bias (e.g., Figure 1). In this study, polarity trends are calculated as weighted running averages of formation polarity ratios in which weight factors are based on an inverse distance-squared function:

$$\Gamma_i(t) = 1 / (((A_i - t) / \lambda)^2 + 1) \quad (1)$$

$$\bar{\mu}_p(t) = i \sum_i^n (P_i \cdot \Gamma_i(t)) / i \sum_i^n \Gamma_i(t) \quad (2)$$

$$\bar{\sigma}_p(t) = i \sum_i^n (((P_i - \bar{\mu}_p(t))^2 \cdot \Gamma_i(t)) / (i \sum_i^n \Gamma_i(t) - 1))^{0.5} \quad (3)$$

$$\sigma_{\bar{\mu}_p}(t) = \bar{\sigma}_p(t) / (i \sum_i^n \Gamma_i(t))^{0.5} \quad (4)$$

where  $\Gamma_i(t)$  is the weight factor of formation  $i$  at time  $t$ ,  $\bar{\mu}_p(t)$  is the mean polarity ratio at time  $t$ ,  $\bar{\sigma}_p(t)$  is the standard deviation of polarity ratios at time  $t$ ,  $\sigma_{\bar{\mu}_p}(t)$  is the standard error of the mean polarity ratio at time  $t$ ,  $A_i$  is the midpoint age of formation  $i$ ,  $P_i$  is the polarity ratio of formation  $i$ ,  $\lambda$  is a scale factor controlling the width of the weighting window (5 m.y., unless otherwise noted),  $n$  is the total number of formations in the data set, and  $i \sum_i^n \Gamma_i(t)$  is the weighted number of formations at time  $t$ . In polarity trend figures (e.g., Figure 1), a standard deviation range, i.e.,  $\bar{\mu}_p(t) \pm 1\bar{\sigma}_p(t)$ , and a standard error range,

i.e.,  $\bar{\mu}_p(t) \pm 1\sigma_{\bar{\mu}_p}(t)$ , are shown as measures of the variability of formation polarity ratios and of the uncertainty of  $\bar{\mu}_p(t)$  as an estimate of geomagnetic polarity bias at time  $t$ , respectively. Methodologically, use of an inverse distance-squared weight function is an improvement on the method of Irving and Pullaiah [1976], who calculated polarity trends using moving 5- to 100-m.y.-wide rectangular windows (i.e., within which all polarity ratios were given uniform weight). The weight function used in this study reduces smoothing effects and allows greater temporal resolution in polarity trends.

### Analysis of Polarity Ratio Variance

Assuming the presence of a primary remanence, individual formations would yield perfect estimates of ambient geomagnetic field polarity if they were stratigraphically complete, deposited at a constant rate, and fully sampled, and a series of such formations would yield a smoothly varying polarity-ratio trend if the remanences were precisely dated. However, none of these conditions are fully met in paleomagnetic studies, and, as a consequence, the polarity ratios of coeval formations vary considerably. For example, the Cambrian-Jurassic data set contains age intervals exhibiting both low (e.g., 500-465, 315-260 Ma) and high degrees of variability among formation polarity ratios (e.g., 435-365, 255-240 Ma; Figure 2). Construction of an accurate Phanerozoic polarity trend would be assisted by evaluation of the factors underlying this variability and selective exclusion of formation polarity ratios that were unrepresentative of field bias for a given age interval. In order to facilitate this analysis, the following discussion will identify (1) factors contributing to polarity-ratio variance, (2) paleomagnetic characteristics diagnostic of these factors, and (3) intervals within the Cambrian-Jurassic data set that exhibit "excess" polarity-ratio variance, i.e., greater than expected for a binomial variable (i.e., geomagnetic field polarity).

Formation polarity ratios are imperfect estimators of ambient field polarity for a variety of reasons. A formation that contains a primary magnetic remanence and that is sampled in an unbiased manner may yield a polarity ratio different from that of the age interval of interest owing to (1) stochastic depositional bias (e.g., resulting from stratigraphic incompleteness) or (2) systematic depositional bias (e.g., sedimentation or volcanic activity occurring preferentially during magnetochrons of a given polarity owing to a common extrinsic control). A paleomagnetic study may fail to obtain an unbiased estimate of the polarity ratio of a given formation owing to (3) stochastic sampling factors, (e.g., unintentional sampling of units of a single polarity) or (4) systematic sampling bias (e.g., heavy sampling of a bed or outcrop that is especially well-preserved or accessible). A formation polarity ratio may be unrepresentative of a given epoch owing to dating problems, e.g., (5) an incorrectly estimated stratigraphic or radiometric age for the formation or (6) an age for the characteristic remanence that substantially postdates formation deposition or emplacement. Unrepresentative formation polarity ratios also may result from (7) complex magnetizations, e.g., the presence of components with overlapping magnetic spectra, or partial magnetic overprints that preferentially obscure components of a given polarity. Finally, even if all formations of a given age contain primary magnetic components that are representative of ambient field conditions during remanence acquisition, the age interval as a whole may exhibit high variance as a result of (8) low geomagnetic reversal rates, i.e.,  $<1/\bar{\tau}_p$ , yielding a high proportion of single-polarity ratios (0%NP or 100%NP; Figure 3b).

Certain paleomagnetic characteristics may assist in diagnosis of factors contributing to polarity-ratio variance among coeval formations. Stochastic depositional or sampling biases and systematic sampling biases should be random in their direction of operation for different locales and studies and, for a group of coeval formations, result in broadening of the polarity-ratio distribution (i.e., increased variance about a fixed mean). Systematic depositional biases may become apparent if the effect is regional in operation and rock units from different areas exhibit systematic differences in polarity ratios; global biases are unlikely to be recognized. Inaccurate age estimates are unlikely to be apparent if the degree of misdating is minor (as is commonly the case for formation ages) but may be fairly obvious if misdating is substantial (as is commonly the case for remanence ages), in which case a formation polarity ratio may occur as an "outlier" in a distribution of polarity ratios for coeval rock units. Secondary remanence acquisition should be suspected in particular when a formation yields a polarity ratio similar to that expected for the succeeding polarity bias interval. The effect of complex magnetizations is unpredictable; close scrutiny of magnetic results is necessary but not always sufficient to recognize such problems. Low reversal frequencies may be inferred when magnetostratigraphic studies of a given age interval consistently yield a small number of magnetozones. Although sources of time-dependent polarity-ratio variance may not be uniquely identifiable in all cases, paleomagnetic characteristics such as these may assist in distinguishing among different sources of variance.

A major source of polarity-ratio variance at all age intervals, and the only one that is readily quantifiable, is that associated with sampling of a binomial variable (i.e., geomagnetic field polarity). Even if all formations of a given age contained primary remanences exhibiting polarities in true proportion to ambient field polarity, stochastic factors associated with sampling nonetheless would result in a range of measured polarity ratios both within and between formations. This is because different samples (e.g., individual paleomagnetic studies) drawn from a large binomial population (e.g., all potential polarity measurements for a given formation or age interval) will yield somewhat different proportions of the two possible outcomes (i.e.,  $N$  and  $R$  polarity). A binomial probability model can be used to calculate the amount of variance expected among the means of multiple samples drawn from such a population (e.g., among the polarity ratios of a group of coeval formations). Comparison of the expected variance with that observed among polarity ratios of a group of coeval formations may assist in determining whether such variance is exclusively due to sampling of a binomial variable or whether additional sources of variance are likely to be present.

Application of a binomial probability model to polarity bias analysis requires calculation of (1) the mean of each sample consisting of  $m$  independent trials drawn from a binomial population (i.e., a formation polarity ratio based on  $m$  paleomagnetic sites or samples) and (2) the mean and variance of the means of multiple samples drawn from the same binomial population (i.e., the mean and variance of polarity ratios of a group of coeval formations). Because individual paleomagnetic analyses have two discrete outcomes ( $N$  and  $R$ ), sample polarity may be viewed as a binomial variable having a probability mass function with parameters  $(1, p)$ :

$$\Phi(j) = m! / (j! \cdot (m-j)!) \cdot p^j \cdot (1-p)^{m-j} \quad (5)$$

in which  $\Phi(j)$  is the probability of encountering exactly  $j$  successes in a sample consisting of  $m$  independent trials, and  $p$

and  $1-p$  are the probabilities of success and failure for each trial, respectively. With respect to paleomagnetic analyses,  $\Phi(j)$  is the probability of encountering exactly  $j$  normal-polarity samples out of a total of  $m$  samples from a formation deposited during an age interval of polarity bias  $p$ . The polarity ratio for an individual formation  $P_i$  is equal to  $j/m$ .

A binomially distributed population has a mean  $\mu$  equal to  $p$  and a variance  $\sigma^2$  equal to  $p \cdot (1-p)$ , which is independent of population size. Samples drawn from such a binomial population also have a mean  $\mu_p$  equal to  $p$ , but sample variance  $\sigma_p^2$  is dependent on sample size  $m$ :

$$\sigma_p^2 = p \cdot (1-p) / (m-1) \quad (6)$$

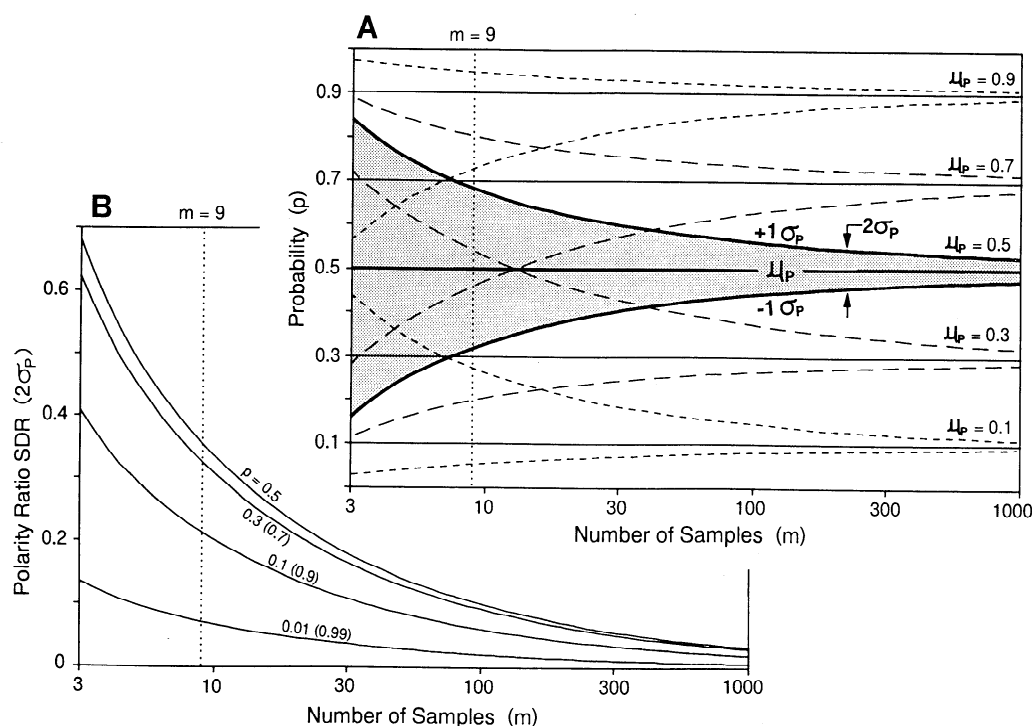
For ease of graphic depiction, sample variances  $\sigma_p^2$  will be converted to standard deviation ranges (SDR)  $2\sigma_p$  (i.e., encompassing 68% of all sample means; Figure 6):

$$2\sigma_p = 2 \cdot [p \cdot (1-p) / (m-1)]^{0.5} \quad (7)$$

With respect to paleomagnetic analyses,  $\bar{\mu}_p(t)$ ,  $\bar{\sigma}_p^2(t)$ , and  $2\bar{\sigma}_p(t)$  represent the age-dependent mean, variance, and SDR of a set of formation polarity ratios calculated from sample sizes of  $m$  for an age interval of polarity bias  $p$ . In this context,  $\bar{\mu}_p(t)$  provides an estimate of field polarity  $p$  at time  $t$ , and  $2\bar{\sigma}_p(t)$  is a measure of the variability of coeval formation polarity ratios (Figure 6).

The utility of the binomial probability model lies in its potential for identification of age intervals in which a substantial fraction of formation polarity ratios are unlikely to have been produced by sampling of a binomial variable. Such intervals may be identified by comparing age-dependent variance among formation polarity ratios with that expected for equivalent binomial distributions. If a group of coeval formations yield a polarity-ratio SDR  $2\bar{\sigma}_p(t)$  close to that expected (generally 0.1-0.3; Figure 7a) for a binomial variable of equivalent  $m$  and  $p$ , it is likely to consist largely of polarity ratios that are representative of field polarity during the age interval of interest. On the other hand, if a group of coeval formations yield a polarity-ratio SDR  $2\bar{\sigma}_p(t)$  close to that expected (0.68; Figure 7a) for a random distribution (i.e., a uniform probability mass function over the range 0-1.0), it may contain a large proportion of unrepresentative polarity ratios. In the latter case, selective exclusion of "discordant" formation polarity ratios (i.e., ratios that differ considerably from those of coeval formations) may yield a more accurate representation of secular patterns of polarity bias.

The expected polarity-ratio SDR  $2\sigma_p$  for a binomial variable depends on (1) field polarity bias  $p$  and (2) formation sample size  $m$  (Figure 6b). For sets of a given sample size  $m$ ,  $2\sigma_p$  is largest at  $p = 0.5$  and decreases as  $p$  approaches 0 or 1.0; the rate of decrease is greatest at the extremes, and the effect on  $2\sigma_p$  is most pronounced at values of  $p < 0.1$  and  $> 0.9$ . At any given probability  $p$ ,  $2\sigma_p$  decreases with increasing sample size  $m$ ; however, the rate of change in  $2\bar{\sigma}_p$  decreases markedly with increasing sample size, and variations in sample size at large  $m$  have relatively little effect on  $2\bar{\sigma}_p$  (Figure 6b). Comparison of observed formation polarity-ratio variance (equation (3)) with that expected for a binomial variable (equations (6) and (7)) requires estimation of field polarity bias  $p$  and formation sample size  $m$  for the age interval of interest. Estimates of  $p$  and  $m$  at time  $t$  are provided by mean formation polarity ratio  $\bar{\mu}_p(t)$  (equation (2)) and median formation sample size  $\bar{m}(t)$  (Figure 7b). With regard to estimation of formation sample size  $m$ , the median is preferable to the mean as it is a more conservative measure of central



**Figure 6.** Binomial probability model for evaluation of the origin of age-dependent variance of formation polarity ratios. Assuming that each trial (paleomagnetic site or sample) is an independent test of field polarity during an interval of fixed polarity bias  $p$ , a set of samples will yield a formation polarity ratio  $P_i$ , and multiple sets of  $m$  samples from formations of age  $t$  will yield a mean polarity ratio  $\mu_p(t)$  with a standard deviation  $\sigma_p(t)$ . (a) Means  $\mu_p$  and (a and b) standard deviation ranges (SDR)  $2\sigma_p$  calculated for sets of polarity ratios at values of  $p$  ranging from 0.01 to 0.99 and values of  $m$  ranging from 3 to 1000. For a given value of  $m$ , polarity ratio SDR is maximized at  $p = 0.5$  and decreases as  $p$  approaches 0 or 1.0; at all values of  $p$ , polarity ratio SDR decreases with larger values of  $m$ . The binomial probability model can be used to (1) identify age intervals characterized by "excess" variance (e.g., owing to the presence of unrepresentative polarity ratios or problematic remanences) and (2) provide a basis for adoption of a minimum sample size limiting inclusion of paleomagnetic studies in the polarity data set (Tables 1-3). The minimum sample size chosen for this study ( $m = 9$ ) represents a compromise: a smaller minimum would result in larger standard errors of the mean  $\sigma_{\mu_p(t)}$  and less accurate estimates of  $p$  (owing to inverse covariance of  $\sigma_{\mu_p(t)}$  with  $m^{0.5}$ ; equation (4)), but a larger minimum would reduce the number of studies meeting the sample size hurdle.

tendency in skewed distributions (such as age-dependent sample sizes) and yields larger values of  $2\sigma_p(t)$ , thereby maximizing estimates of polarity-ratio variance.

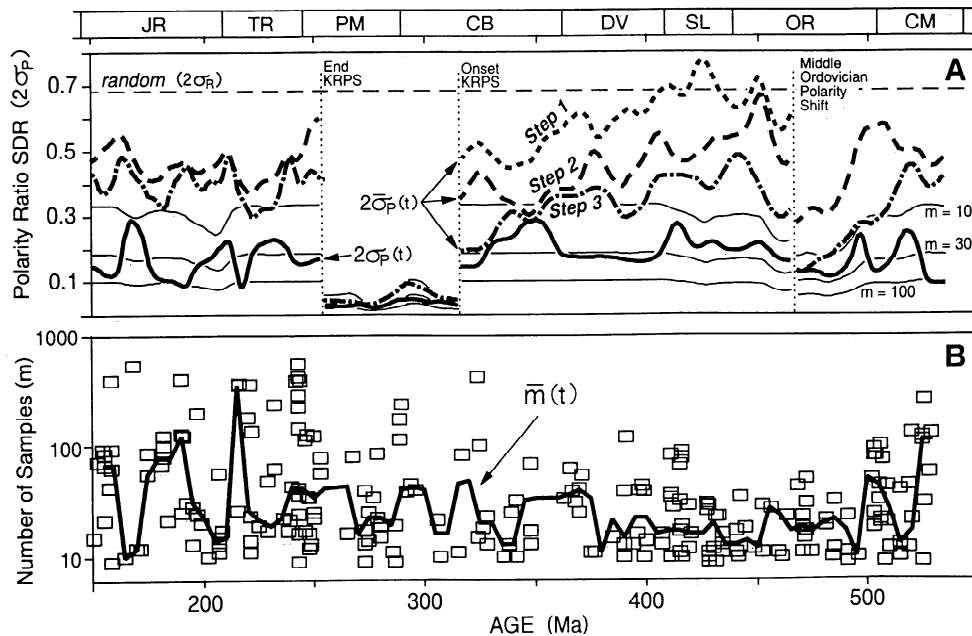
## Analysis of Polarity Data

### Cambrian-Jurassic Polarity Trend

The Cambrian-Jurassic polarity data set (Figure 2; Tables 1-3) exhibits a moderately coherent pattern of secular variation in formation polarity ratios, providing the basis for construction of polarity trends (equations (1)-(4)). However, polarity ratios within some epochs are highly variable (Figure 7a), necessitating consideration of the sources of such age-dependent variance. Identification of formation polarity ratios contributing to excess variance would permit selective exclusion of unrepresentative polarity ratios and, hopefully, more accurate reconstruction of Phanerozoic polarity trends. In practice, it is difficult to apply a simple test or set of criteria that can objectively identify problematic polarity ratios. The approach used in the following analysis will be to (1) calculate age-dependent polarity-ratio

variance in order to identify epochs exhibiting greater than average variance, (2) identify formations within epochs of high variance that exhibit discordant polarity ratios, and (3) review the methodology and results of the original studies to evaluate potential sources of anomalous polarity bias. Because the degree of subjectivity is likely to increase with greater selective exclusion of polarity data, polarity trends will be calculated in three steps corresponding to different degrees of data "filtering." The trend of step 1 will be based on an "unfiltered" data set (Tables 1-3); that of step 2 on a "weakly filtered" data set (Tables 1 and 2 only), from which the highly problematic British Siluro-Devonian "B" remanences are excluded; and that of step 3 on a "strongly filtered" data set, from which additional problematic formation polarity ratios are excluded for reasons discussed below.

**Unfiltered data set (step 1).** The unfiltered data set includes all formation polarity ratios in Tables 1-3 ( $n = 278$ ) and yields the polarity trend of Figure 8. Only the Middle Paleozoic portion of the step 1 polarity trend is shown, because other portions of the trend are identical to those calculated in step 2 (see below). The trend exhibits strong  $N$  polarity bias during the early Late Ordovician, moderate  $N$  polarity bias during the late Late



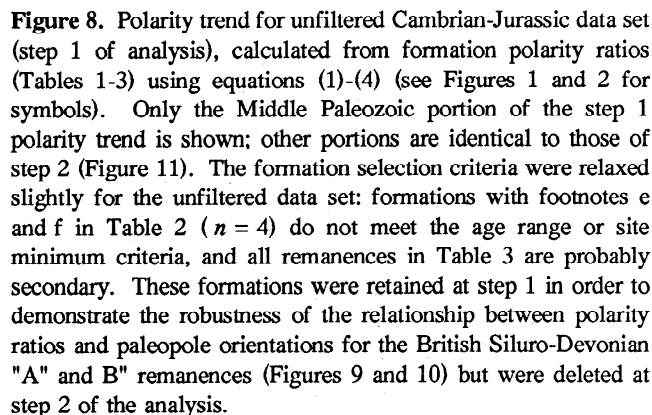
**Figure 7.** Comparison of observed age-dependent variance among formation polarity ratios with that expected for a binomial variable (i.e., geomagnetic field polarity). (a) Observed polarity-ratio standard deviation ranges (SDRs)  $2\bar{\sigma}_p(t)$  for the unfiltered (step 1), weakly filtered (step 2), and strongly filtered data sets (step 3; thick dashed and dotted lines, calculated from equation (3)); expected SDRs  $2\sigma_p(t)$  for a binomial variable with  $p = \mu_p(t)$  and  $m = \bar{m}(t)$  (thick solid line); expected SDRs for a binomial variable with  $p = \mu_p(t)$  and  $m = 10, 30$ , and  $100$  (light solid lines; these are included because  $\bar{m}(t)$  is frequently calculated from a small weighted number of samples  $i \Sigma_i \Gamma_i(t)$  and its age-dependent variance may not be significant); and expected SDRs  $2\sigma_r$  for a random variable (i.e.,  $0.68$ ; thin dashed line). If observed SDRs are equal to those expected for a binomial variable with  $p = \mu_p(t)$  and  $m = \bar{m}(t)$ , then all polarity-ratio variance may be attributable to stochastic sampling factors. Conversely, if observed SDRs are larger than those expected for a binomial variable, then excess variance is present that must be due to factors other than sampling of a binomial variable. Observed SDRs (step 1) are mostly intermediate between those expected for binomial and random variables; selective filtering of unrepresentative formation polarity ratios (steps 2 and 3) substantially reduces excess variance. (b) Number of paleomagnetic samples per formation  $m$  (symbols) for the strongly filtered data set (Tables 1 and 2); and median sample size  $\bar{m}(t)$  (thick line), which was calculated using an unweighted 10-m.y. moving window.

Ordovician-Late Silurian, and weak to moderate  $R$  polarity bias during the Early Devonian-mid-Carboniferous (with a mid-Devonian minimum of circa 20%NP). Sources of polarity-ratio variance may be investigated through calculation of age-dependent polarity-ratio SDRs  $2\bar{\sigma}_p(t)$  (equation (3); Figure 7a). Low values of  $2\bar{\sigma}_p(t)$  (i.e.,  $0.1$ - $0.3$ ) are consistent with variance arising from sampling of a binomial variable, whereas high values (i.e.,  $\geq 0.68$ ) indicate a randomized distribution in which additional factors have contributed to polarity-ratio variance. Polarity-ratio variance for the Middle Paleozoic portion of the step 1 trend (Figure 8) ranges from  $0.5$  to  $0.8$ , whereas the expected variance for a binomial variable is between  $0.15$  and  $0.25$  (Figure 7a), implying that most of the variance is of nonbinomial origin and is due to one or more of the factors discussed above.

**Weakly filtered data set (step 2).** Selective exclusion of formation polarity ratios contributing to excess variance would be desirable in order to produce a more accurate representation of Phanerozoic polarity trends. The most logical approach is to evaluate first those epochs containing the largest amounts of excess variance. Although the unfiltered data set contains some excess variance through most of the Cambrian-Jurassic interval, the Late Ordovician-Late Devonian (circa 460-360 Ma) exhibits a broader distribution of polarity ratios and greater amounts of

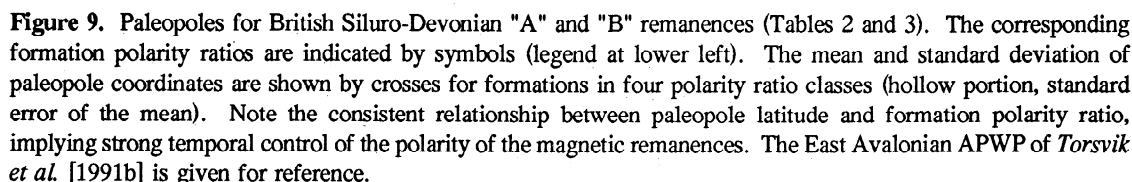
excess variance than other intervals (Figures 2 and 7a). While the existence of excess variance does not imply a particular source, concentration of variance in a given age interval may indicate the presence of a relatively high proportion of problematic formation polarity ratios and warrant further investigation.

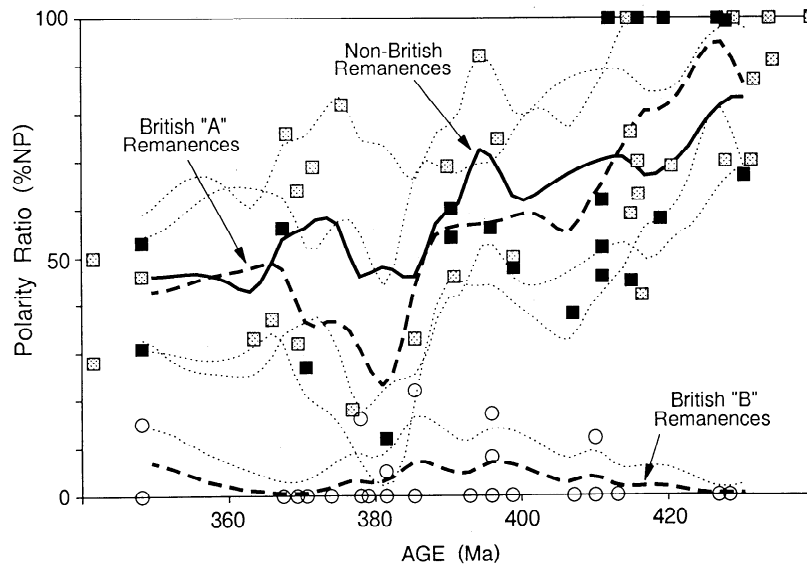
The Siluro-Devonian portion of the polarity data set is dominated by studies from the British Isles (Tables 2 and 3), reflecting extensive research on the history of closure of the Iapetus Ocean [e.g., *Torsvik et al.*, 1991b, 1993; *Channell et al.*, 1992, 1993] and of transform offsets and rotations within the Caledonian Orogen [e.g., *Smethurst and Briden*, 1988; *Storetvedt and Otterå*, 1988; *Storetvedt et al.*, 1990; *Trench and Haughton*, 1990]. This work has also generated a number of APWPs for East Avalonia (i.e., Britain and Ireland south of the Caledonian suture and north of the Hercynian suture), but its Middle Paleozoic drift history remains contentious owing to uncertainty whether the British Siluro-Devonian paleofield is more accurately represented by magnetic components having moderate downward inclinations with southerly declinations and yielding paleopoles at  $0^\circ$ - $20^\circ$  ("A" remanences; Table 2) or those having shallow downward inclinations with southerly declinations and yielding paleopoles at  $25^\circ$ - $50^\circ$  ("B" remanences; Table 3). In the former case, a major cusp in the East Avalonian APWP coincided with



Differing interpretations of the drift history of East Avalonia are dependent on a primary versus secondary origin of the "A" and "B" remanences (Tables 2 and 3) [Torsvik *et al.*, 1989; Storetvedt *et al.*, 1990; Torsvik *et al.*, 1991b]. Although discussion to date has focused on paleopoles, formation polarity ratios can assist in resolution of the debate (Figure 10). "A" remanences exhibit polarity ratios of 12-100%NP with the majority between 30 and 70%NP (n.b. the 12%NP Esha Ness ratio may be a stochastic effect of small sample size), whereas "B" remanences exhibit polarity ratios of 0-22%NP with the majority of entirely *R* polarity. The primary versus secondary origin of these remanence groups may be tested by comparing their polarity trends with that of coeval non-British formations. Both British "A" and non-British remanences exhibit strong *N* polarity bias in the Silurian and roughly balanced polarities in the Devonian, whereas British "B" remanences exhibit strong *R* polarity bias throughout the Siluro-Devonian (Figure 10). The strong concordance of polarity ratios from British "A" and non-British formations favors a primary origin for most or all of these remanences, and the lack of concordance of British "B" polarity ratios indicates that most or all of these remanences are likely to be of secondary origin. Strong *R* polarity bias in combination with midlatitude paleopoles favors an origin for British "B" remanences as Kiaman-age (re)magnetizations.

Exclusion of the British "B" remanences (Table 3) results in a "weakly filtered" data set consisting of 240 formations (Tables 1 and 2; n.b. exclusion of 4 formations in Table 2, footnotes e and f). This data set yields a polarity trend characterized by



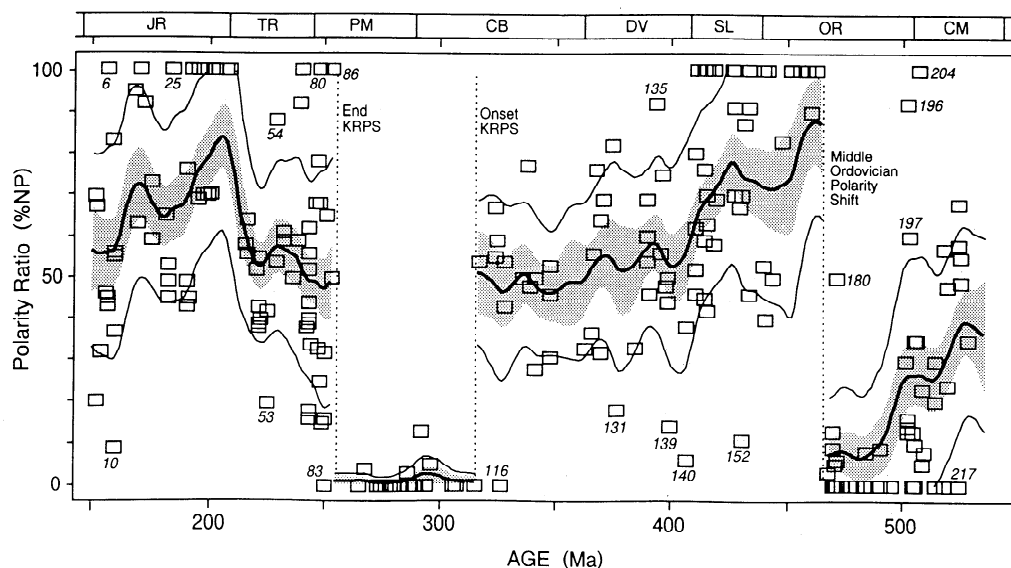


**Figure 10.** Polarity ratios and trends for British "A" (solid squares), British "B" (open circles), and non-British remanences (shaded squares) of Siluro-Devonian age (Tables 1-3). The polarity trend for British "A" remanences (upper dashed line) is nearly identical to that for non-British formations (solid line), but both are dissimilar to the polarity trend for British "B" remanences (lower dashed line; standard deviation ranges are shown as dotted lines for all trends). This pattern implies that British "A" remanences are of probable syndepositional/synemplacement origin and British "B" remanences are not. Strong *R* polarity bias suggests that the latter are Kiaman-age (re)magnetizations. A small number of non-British formations also exhibit strong *R* polarity bias (<20%NP;  $n = 4$ ; nos. 131, 139, 140, and 152) and are not shown here owing to problematic origins (discussed in text).

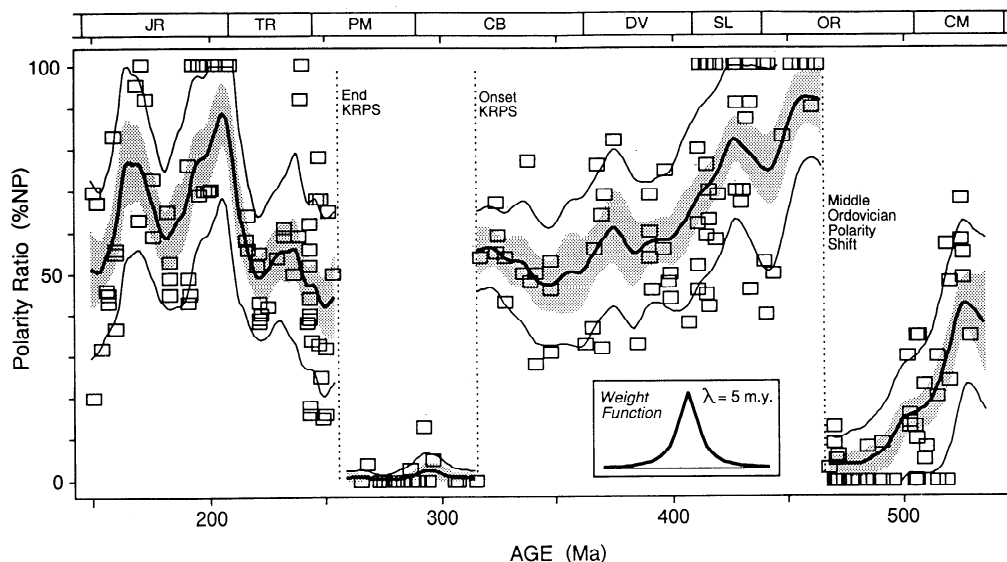
strong *N* polarity bias in the Late Ordovician, moderate to strong *N* polarity bias in the Silurian, and roughly balanced polarities in the Early Devonian to mid-Carboniferous (Figure 11). In relation to the unfiltered data set, the weakly filtered data set of step 2 exhibits somewhat greater *N* polarity bias (circa 5-10%) throughout the Siluro-Devonian interval and lacks a *R* polarity excursion in the mid-Devonian. Without filtering of the British "B" remanences of probable Kiaman age, a mid-Devonian *R* polarity excursion might have been considered an independent first-order

feature of the Phanerozoic geomagnetic record (Figure 8). An additional effect of step 2 filtering is a substantial reduction (circa 30-70%) in excess polarity-ratio variance among Siluro-Devonian formations (Figure 7a).

**Strongly filtered data set (step 3).** The ability to identify formations contributing to excess polarity-ratio variance as well as the probable source of that variance for British Siluro-Devonian units is a function of the large number of paleomagnetic studies of that age (Tables 2 and 3;  $n = 59$ ). For other age intervals, the



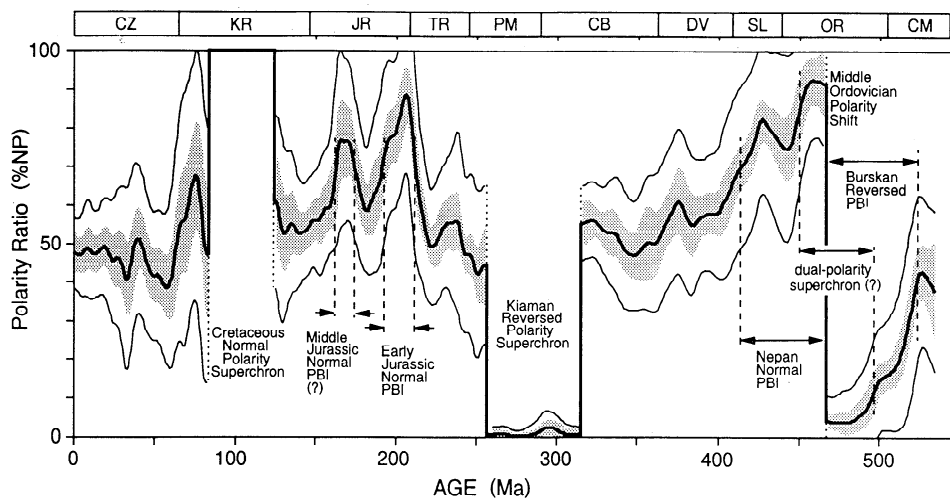
**Figure 11.** Polarity trend for weakly filtered Cambrian-Jurassic data set (step 2 of analysis), which is based on formation polarity ratios of Tables 1 and 2 (symbols;  $n = 240$ ) and excludes British Siluro-Devonian "B" remanences ( $n = 34$ ; Table 3). Lines and symbols as in Figure 8; numbered symbols are formation polarity ratios deleted in step 3 for reasons discussed in text (keyed to Table 1).



**Figure 12.** Polarity trend for strongly filtered Cambrian-Jurassic data set (step 3 of analysis;  $n = 221$ , Tables 1 and 2). Lines and symbols as in Figure 8; the weight function used in calculation of running averages is shown in inset.

quantity of published paleomagnetic data is generally insufficient to carry out a similar analysis, and other evidence must be used to infer sources of polarity-ratio variance. In step 3, the remaining Cambrian-Jurassic polarity data will be evaluated for unrepresentative polarity ratios, and 8% of the formations in Tables 1 and 2 ( $n = 19$ ) will be deleted to yield a slightly smaller data set ( $n = 221$ ) exhibiting a substantially more coherent pattern of secular polarity variation. Formations were excluded from the "strongly filtered" data set if they exhibit (1) a polarity ratio that is "discordant" with respect to those of coeval formations and (2) problematic results with regard to magnetic cleaning of samples, dating of formations, or constraints on timing of remanence acquisition. In the author's opinion, the strongly filtered data set of step 3 permits a more accurate reconstruction of first-order polarity trends than the unfiltered or weakly filtered data sets of the preceding steps.

The Cambrian-Jurassic polarity trends produced by the weakly filtered data set (step 2; Figure 11) and the strongly filtered data set (step 3; Figure 12) are rather similar. Both trends exhibit the same major first-order polarity features: (1) increasing  $R$  polarity bias from the Late Cambrian to the Middle Ordovician, (2) decreasing  $N$  polarity bias from the Late Ordovician to the Late Silurian, (3) strong  $R$  polarity bias in the mid-Carboniferous to mid-Permian (KRPS), and (4) moderate  $N$  polarity bias during two intervals in the Early and Middle Jurassic. The main effects of data filtering at step 3 were to enhance polarity features that were already apparent at step 2 and to modify slightly the structure of some of these features (Figures 11 and 12). With respect to polarity-ratio variance, the strongly filtered data set (step 3) exhibits a substantial reduction in variance over the other data sets (Figure 7a). Polarity-ratio SDRs  $2\sigma_p(t)$  for the strongly filtered data set are 0.2-0.5, only slightly larger than the



**Figure 13.** Polarity trend for the Phanerozoic, composited from the GPTS-based Cretaceous-Recent trend (Figure 1) and the strongly filtered Cambrian-Jurassic trend (Figure 12). First-order polarity bias features of the Phanerozoic geomagnetic record are labeled. Note the possible existence of a "dual-polarity superchron" during the Ordovician containing a single major polarity transition (the Middle Ordovician Polarity Shift).

values  $2\sigma_p(t)$  expected for a binomial population (i.e., 0.1-0.3), suggesting that a substantial amount (circa 50-90%) of excess variance among formation polarity ratios has been eliminated through data filtering.

### Phanerozoic Polarity Trend

A Phanerozoic polarity trend (Figure 13) was composited from the GPTS-based trend for the Cretaceous-Recent (Figure 1) and the strongly filtered trend for the Cambrian-Jurassic (Figure 12). Despite different sources for the pre- and post-150 Ma polarity bias estimates, standard procedures and characteristic timescales were utilized in trend construction for the entire Phanerozoic: (1) a  $\tau_p$  of 2 m.y. was used in calculating GPTS-based polarity ratios for the Cretaceous-Recent, comparable to that for Cambrian-Jurassic formations (Figure 4b), and (2) a constant  $\lambda$  of 5 m.y. was employed in calculating weighted running averages. For trend calculations, the Phanerozoic was subdivided into six age intervals with interval boundaries coincident with major polarity discontinuities, i.e., onset and end of the CNPS, onset and end of the KRPS, and the Middle Ordovician Polarity Shift (cf. Figures 1 and 2). Continuous trends were not calculated across major polarity discontinuities to avoid smoothing of polarity shifts that may have been rather abrupt.

A number of features of the Phanerozoic polarity trend are of potential significance in understanding geomagnetic field behavior, including (1) a mean field polarity of circa 50%NP at longer timescales (>300 m.y.), (2) strong deviation of field polarity from the long-term mean during about half of the Phanerozoic, (3) delimitation of major polarity excursions to well-defined age intervals of circa 10-60 m.y. duration, and (4) relatively abrupt transitions between polarity bias intervals, most of which appear to have occurred in less than 5 m.y. (see discussion of timing below). A relationship of possible significance is the apparent alternation of polarity states among successive major polarity bias intervals, i.e., *R-N-R-N* for the Cambro-Ordovician Reversed PBI, Ordovician-Silurian Normal PBI, Permo-Carboniferous KRPS, and Cretaceous CNPS. The validity of this relationship depends on the significance attached to two relatively short (circa 10-15 m.y.) *N* polarity bias intervals in the Early and Middle Jurassic (Figure 13). The most unusual feature of the pre-KRPS record is an abrupt transition from strong *R* polarity to strong *N* polarity bias during the Llandeilo, herein termed the Middle Ordovician Polarity Shift (MOPS).

## Discussion

### Polarity Bias Intervals

The Phanerozoic is characterized by a number of discrete age intervals of fairly uniform polarity bias separated from adjacent intervals by relatively abrupt polarity shifts (Figure 13). Some of these polarity bias intervals (PBIs) are well-known (e.g., the CNPS and KRPS) and others less so (e.g., intervals of strong *R* and *N* polarity bias in the Early and Middle Paleozoic). The following discussion will (1) identify and temporally delimit major intervals of polarity bias through the Phanerozoic, (2) review polarity data for critical published studies in each interval, and (3) consider factors contributing to unrepresentative polarity ratios, including those of 19 formations that were deleted at step 3 of the polarity trend analysis (identified in Figure 11 and Table 1, footnote r).

**Early Cambrian.** Early Cambrian formations (Tommotian-Attabanian-Lenian, 530-520 Ma) exhibit roughly balanced polarities (24-68%NP; nos. 212-219), but strong *R* polarity bias

is encountered by the late Middle Cambrian (Menevian, 515-510 Ma; nos. 206-209, all formation numbers keyed to Table 1). The polarity transition may have occurred at the Early-Middle Cambrian boundary (circa 520 Ma) [cf. *Gillett and Van Alstine*, 1979] or during the early Middle Cambrian (Solvan, 520-515 Ma), but precise dating is not possible at present. *Johnson and Van der Voo* [1985] may have sampled across the polarity transition: sedimentary units of the Bourinot Group assigned to the late Solvan stage exhibit 0%NP (no. 210), whereas underlying but poorly dated volcanic units of the same group exhibit 57%NP (no. 211). The only strongly discordant polarity ratio among Early Cambrian formations is that of the Khewra Sandstone in Pakistan (0%NP; no. 216) [*Klootwijk et al.*, 1986]. Strong *R* polarity bias would be consistent with Middle Cambrian-Middle Ordovician field polarities, suggesting either that the formation is younger than its current age assignment or that remanence acquisition was postdepositional.

**Middle Cambrian-Middle Ordovician.** The Middle Cambrian to Middle Ordovician is characterized by pronounced *R* polarity bias, with an increase in the degree of bias from moderate to strong during the Early Ordovician. Formations of late Middle Cambrian (Menevian) to early Early Ordovician (Tremadoc) age exhibit a broad range of polarity ratios, although a large majority are between 0%NP and 35%NP (nos. 191-210), whereas formations of late Early and early Middle Ordovician (Arenig-Llanvirn) age almost uniformly exhibit polarity ratios <10%NP (nos. 170-190). The transition from moderate to strong *R* polarity bias probably occurred in the late Tremadoc or close to the Tremadoc-Arenig boundary (circa 500-493 Ma) [cf. *Trench et al.*, 1991a]. This interval of *R* polarity bias coincides with a reversal rate minimum reported by *Johnson et al.* [1995]. In recognition of early Russian paleomagnetic research on the Paleozoic, I propose designating this Middle Cambrian-Middle Ordovician polarity feature the Burskan Reversed Polarity Bias Interval [cf. *Khranov*, 1987, p. 114].

The transition between the Burskan Reversed PBI and the succeeding interval of strong *N* polarity bias probably occurred during the Llandeilo (468-464 Ma), because formations of Llanvirn age exhibit dominantly *R* polarities (nos. 170-181) and those of Caradoc age dominantly *N* polarities (nos. 161-169). The transitional phase may have lasted a few million years and been characterized by frequent reversals and roughly balanced polarities [*Trench et al.*, 1991a]. I propose designating this polarity feature the Middle Ordovician Polarity Shift (MOPS).

A few Middle Cambrian-Middle Ordovician units exhibit polarity ratios that are discordant with respect to those of the majority of coeval formations. In contrast to most formations spanning the Cambro-Ordovician boundary (nos. 192-199), the Florida Mountains pluton exhibits strong *N* polarity bias (92%NP; no. 195) [*Geissman et al.*, 1991]. Dominance of a single polarity in an intrusive unit may be an indication of either a stochastic "depositional" bias (e.g., rapid cooling and a short  $\tau_p$ ) [*Ghiorso*, 1991] or a systematic sampling bias (e.g., owing to sample collection along a single exfoliation surface). The slightly older Taum Sauk Limestone member of the Dresbachian Bonnetterre Formation also yielded strong *N* polarity bias (100%NP; no. 203) [*Dunn and Elmore*, 1985], which may be reflect a stochastic sampling or depositional bias associated with small sample size ( $m = 9$ ) or the limited stratigraphic (3.0 m) and age range (circa 1 m.y.) of the study interval. The Powell, Everton, and St. Peter formations of Arkansas exhibit a polarity ratio (50%NP; no. 179) [*Farr et al.*, 1993] that is markedly discordant with those of other formations of Llanvirn age.

Farr *et al.* [1993] regarded magnetic component B as primary owing to broad consistency with published Lower Ordovician-Lower Silurian paleopoles, and the large number of stratigraphic horizons sampled ( $m = 50$ ) and the thickness (100-150 m) and duration (circa 7 m.y.) of the study intervals make stochastic sampling or depositional biases unlikely. On the other hand, a non-Fisherian vector distribution and incomplete isolation of magnetic components are suggestive of extended postdepositional remanence acquisition, and a remanence acquired both prior to and following the MOPS would be consistent with the mixed  $N$  and  $R$  polarities observed in these formations (Figure 11).

**Late Ordovician-Late Silurian.** The Late Ordovician to Late Silurian is characterized by pronounced  $N$  polarity bias. Formations of Late Ordovician age mostly exhibit polarity ratios  $>90\%$ NP (nos. 157-169), whereas those of Silurian age exhibit ratios ranging between 40%NP and 100%NP (nos. 141-156, Table 1, and A1-A14, Table 2). A progressive decrease in the degree of  $N$  polarity bias during this interval is apparent, although the decline may have been stepwise rather than continuous. The transition from nearly uniform  $N$  polarities to mixed polarities with a strong  $N$  bias is probably close to the Ordovician-Silurian boundary (circa 440 Ma), the proportion of strong  $N$  polarity ratios ( $>90\%$ NP) decreases within the late Wenlock or early Ludlow (circa 428-420 Ma) [cf. Trench *et al.*, 1993], and strong  $N$  polarity ratios ( $>90\%$ NP) disappear entirely close to the Siluro-Devonian boundary (Figure 12). In recognition of early Russian paleomagnetic research on the Paleozoic, I propose designating this Late Ordovician-Late Silurian polarity feature the Neplan Normal Polarity Bias Interval [cf. Khramov, 1987, p. 114].

Discordant polarity ratios are exhibited by three Late Ordovician-Silurian formations. The Lawrenceton Formation of Newfoundland yields a polarity ratio of 11%NP (no. 152) [Gales *et al.*, 1989], which may reflect a stochastic sampling bias owing to small sample size ( $m = 9$ ). The Builth Wells dolerites of England (40%NP; no. 160) [Piper and Briden, 1973] and the Thouars Massif of France (50%NP; no. 162) [Perroud and Van der Voo, 1985] also yield anomalously low polarity ratios that are possibly due to a stochastic sampling or "depositional" bias. However, uncertainty exists regarding the age of the Builth Wells dolerites, which were originally dated as Ashgillian based on stratigraphic relations but might be as young as Late Llandoveryan [Piper and Briden, 1973], and younger ages for either intrusive emplacement or remanence acquisition (e.g., Early Silurian) would be more consistent with balanced polarities. Other factors potentially contributing to the discordant polarity ratio of the Builth Wells dolerites include emplacement over an extended interval [Trench *et al.*, 1991b] or incomplete isolation of magnetic components [McCabe and Channell, 1991].

Divergent polarity ratios are commonly obtained in separate studies of a single formation, as shown by a number of Late Ordovician-Silurian formations that have been subject to multiple paleomagnetic analyses. The Juniata Formation in Pennsylvania yielded polarity ratios of 53%NP and 100%NP (nos. 158 and 159) [Van der Voo and French, 1977; Miller and Kent, 1989], the Wigwam Formation in Newfoundland 46%NP and 70%NP (nos. 153 and 156) [Lapointe, 1979; Buchan and Hodych, 1992], the Springdale Group in Newfoundland 70%NP and 91%NP (nos. 150 and 151) [Potts *et al.*, 1993a; Hodych and Buchan, 1994], and the Bloomsburg Formation 59-100%NP (nos. 142-144) [Kent, 1988; Stamatakis and Kodama, 1991]. In some cases, the spread in observed polarity ratios may be consistent with stochastic sampling factors (i.e., associated with sampling of

a binomial population). However, in the case of the Juniata Formation, Miller and Kent [1989] suggested that many of the  $R$  polarity sites of Van der Voo and French [1977] were affected by a Kiaman-age synfolding remagnetization, and the polarity ratio of the former study (100%NP) is more consistent with other Late Ordovician polarity data (Figure 11).

**Early Devonian-mid-Carboniferous.** Elimination of the British Siluro-Devonian "B" remanences (Table 3) revealed that the Early Devonian to mid-Carboniferous is characterized by roughly balanced polarities. Most formation polarity ratios fall in the range of 27-82%NP (nos. 112-138, Table 1, and A15-A25, Table 2), although a few formations exhibit markedly discordant polarity ratios. The Hersey and Eastport formations exhibit polarity ratios of 6%NP and 14%NP (nos. 139 and 140) [Kent and Opdyke, 1980] for characteristic remanences that were interpreted as primary, but a strong  $R$  polarity anomaly and other considerations may indicate that these units experienced a Kiaman-age remagnetization [Roy, 1982]. Polarity discordance of the "Old Red Sandstone" of Iran (92%NP; no. 135) [Wensink, 1983] may be due either to small sample size ( $m = 13$ ; concentrated at a few stratigraphic horizons) or to misdating of the formation (i.e., strong  $N$  polarity bias would be more consistent with a Late Silurian rather than an Early Devonian age; Figure 11). The Gilif Hills volcanics in Sudan exhibit an anomalously low polarity ratio (18%NP; no. 131) [Bachtadse and Briden, 1991] possibly owing to small sample size ( $m = 11$ ); a paleopole located on the Devonian portion of the Gondwanan APWP supports the current age assignment and argues against a Kiaman-age remagnetization.

**Mid-Carboniferous-Late Permian.** The Mid-Carboniferous to Late Permian coincided with the Kiaman Reversed Polarity Superchron, a circa 60 m.y. interval of nearly uniform  $R$  polarities. The KRPS was probably initiated during the Westphalian A stage (circa 310-315 Ma) [Roy and Morris, 1983]; the lower boundary may be located within the Hopewell Group of Newfoundland, in which lower Westphalian A units are of mixed polarity and upper Westphalian A-Westphalian B units of  $R$  polarity [Roy and Park, 1969; DiVenere and Opdyke, 1990, 1991a]. Other formations that constrain the age of onset of the KRPS include mixed-polarity paleosols in the Morrowan Black Prince Limestone (circa 323-311 Ma; no. 112) [Nick *et al.*, 1991];  $R$  polarities in the late Atokan-early Missourian Mintum Formation (circa 310-302 Ma; no. 104) [Miller and Opdyke, 1985];  $R$  polarities in the upper Namurian-lower Moscovian Hassi Bachir and Ain Ech Chebbi formations (circa 323-307 Ma; no. 111) [Daly and Irving, 1983]; and radiometrically dated volcanic units of  $N$  polarity (Mirannie Volcanics;  $321 \pm 4$  Ma) and  $R$  polarity (Durham and unnamed tuffs;  $312 \pm 3$  Ma) in the Hunter Valley, Australia (type area for KRPS) [Théveniaut *et al.*, 1994]. Khramov [1987] identified mixed polarities in the Bashkirian stage and dominantly  $R$  polarities with a few short  $N$  chrons in the Moscovian stage, placing the boundary on the Russian platform at the stratigraphic equivalent of the upper Westphalian A stage (circa 311 Ma).

The age of termination of the KRPS is uncertain owing to difficulties in interregional correlation of Upper Permian units [Heller *et al.*, 1988; Steiner *et al.*, 1989]. Many formations of Late Tatarian age (circa 248-245 Ma) exhibit mixed polarities (nos. 74-79). However, because the Lower/Upper Tatarian stage boundary is defined on the basis of appearance of  $N$  polarity chrons [Khramov, 1987], magnetostratigraphically based age assignments for Upper Permian formations lack independent

constraints [e.g., *McFadden et al.*, 1988]. If mixed polarities are verified in units of Early Tatarian and Kazanian age (Guadalupian Series equivalents, circa 255-248 Ma; nos. 81-86) [*Peterson and Nairn*, 1971; *Klootwijk et al.*, 1986; *Haag and Heller*, 1991; *Théveniaut et al.*, 1994], then the end of the KRPS may predate the Early/Late Tatarian boundary and fall within the early Late Permian (circa 255-250 Ma). An apparent 12-m.y. mid-Permian gap (i.e., 265-253 Ma) in the polarity data set (Table 1) is largely an artifact of imprecise (i.e., broad) age constraints on Lower Permian units.

**Late Permian-Triassic.** The Late Permian and Triassic are characterized by roughly balanced polarities but greater than average variance in formation polarity ratios. In the Late Permian, polarity ratios for individual formations range from 0 to 100%NP with only weak clustering about the 50%NP midpoint (nos. 74-86; Figure 11). High polarity-ratio variance may be a consequence of low geomagnetic reversal rates, which increased gradually from circa 0.3-1.0/m.y. in the Late Permian to circa 2-4/m.y. in the Early Triassic [e.g., *Heller et al.*, 1988; *Steiner et al.*, 1989; *Haag and Heller*, 1991]. Low reversal rates are likely to contribute either to a stochastic sampling bias, in which limited sampling of a succession comprised of a few thick magnetozones yields a polarity ratio unrepresentative of the succession as a whole, or to a stochastic depositional bias, in which even thorough sampling of a succession yields a polarity ratio unrepresentative of the age interval of interest. Reversal rates that are lower than  $1/\bar{\tau}_r$  will yield noncentralized distributions and high polarity-ratio variance (Figure 3b).

Low reversal frequencies may account for the divergent polarity ratios of 50%NP and 100%NP reported for the Upper Permian Wargal Limestone of Pakistan (nos. 85 and 86) [*Klootwijk et al.*, 1986; *Haag and Heller*, 1991]. The Upper Permian Horcajo Formation of Argentina may exhibit a 0%NP for the same reason, but it is also possible that the formation is older than its assigned age and represents a Kiaman magnetization (no. 82) [*Rapalini and Vilas*, 1991]. On the other hand, low reversal frequencies are probably not responsible for polarity-ratio variance among Early Triassic formations owing to a large difference in the mean ratios exhibited by the Moenkopi and Chugwater formations of western North America (33±10%NP,  $n = 7$ ; nos. 62, 66-67, 70-73) and coeval formations in China, Spain, and the Canadian Arctic (53±7%NP,  $n = 5$ ; nos. 63-65, 68-69). A possible explanation for this anomaly is that Early Triassic redbeds in western North America exhibit a stochastic depositional bias in favor of *R* polarity chrons, which is supported by broad regional correlation of Lower Triassic magnetozones [*Helsley*, 1969; *Shive et al.*, 1984].

The Middle and Upper Triassic are mostly characterized by balanced polarities, although formations of Anisian (early Middle Triassic) age exhibit moderate to strong *N* polarity bias (59-100%NP, nos. 59-61). However, owing to the short duration of the Anisian (1.6 m.y.) [*Harland et al.*, 1990], this interval is unlikely to represent more than a *N* polarity chron. Two Upper Triassic formations exhibit discordant polarity ratios: an anomalously high ratio for the Chinle Formation (88%NP; no. 54) [*Molina-Garza et al.*, 1991], which may be due to a stochastic sampling bias or to a Jurassic-age remagnetization, and an anomalously low ratio for the Abbott/Agamenticus intrusives (19%NP; no. 53) [*Fang and Van der Voo*, 1988], which may be related to stochastic sampling or "depositional" biases or to rapid postemplacement cooling.

**Jurassic.** During the Jurassic, the geomagnetic field may have fluctuated between intervals of balanced polarity and strong

*N* polarity bias, although considerable uncertainty has existed regarding the age and duration of the latter intervals. Early studies of seafloor magnetic anomalies identified a *N* polarity "Jurassic Quiet Zone" (JQZ) in the Callovian-Oxfordian [*McElhinny and Burek*, 1971; *Larson and Hilde*, 1975], but later land-based magnetostratigraphic studies [*Ogg and Steiner*, 1985; *Steiner et al.*, 1985/86; *Channell et al.*, 1990; *Ogg et al.*, 1991] and reanalysis of the seafloor magnetic anomaly record [*Handschumacher et al.*, 1988] demonstrated that the Late Jurassic is characterized by frequent reversals. The absence of well-defined magnetic stripes in oceanic lithosphere of Jurassic age is probably due to factors other than a lack of reversals: (1) weak geomagnetic field intensity, resulting in large secular variations in dipole moment and weak magnetization of seafloor basalts, (2) high-frequency reversals, preventing resolution of narrow seafloor magnetic stripes, or (3) complex, nonvertical transition zones between adjacent marine magnetic anomalies owing to diachronous cooling of vertical crustal segments through magnetic blocking points [*Cande et al.*, 1978; *Handschumacher et al.*, 1988].

Despite lack of confirmation of the JQZ, intervals of strong *N* polarity bias may exist in the Early and Middle Jurassic [cf. *Johnson et al.*, 1995]. The early Early Jurassic (Hettangian-Sinemurian) is characterized by strong *N* polarity bias (69-100%NP; nos. 30-42). Latest Triassic-earliest Jurassic igneous units in rift basins of eastern North America exhibit almost uniformly *N* polarity (e.g., nos. 38-42). Primary remanence acquisition in these units is demonstrated by similar magnetic vectors in interbedded basalts and redbeds and by consistency with published Late Triassic-Early Jurassic paleopoles, and the large number of paleomagnetic sites and broad geographic distribution makes sampling biases unlikely [*McIntosh et al.*, 1985]. Several magnetostratigraphic studies have recorded strong *N* polarity bias in the Hettangian (100%NP) followed by moderate *N* polarity bias in the Sinemurian (circa 70%NP; nos. 30, 34-35) [*Ekstrand and Butler*, 1989; *Ogg*, 1995]. Coeval volcanic units in Brazil, the Anari and Tapirapua formations, also yield 100%NP (no. 32) [*Montes-Lauar et al.*, 1994].

The mid-Early to early Middle Jurassic (Pliensbachian-Aalenian) is characterized mainly by balanced polarities (nos. 18-28), although strong *N* polarity bias (76-100%NP) is observed in intrusives from Morocco and Liberia (nos. 24 and 27) [*Hailwood and Mitchell*, 1971; *Dalrymple et al.*, 1975]. Polarity discordance in these units may be the result of misdating of the intrusives (e.g., K-Ar dates that are too young) or of stochastic sampling or "depositional" biases.

The mid-Middle Jurassic (Bajocian-Bathonian) may be characterized by *N* polarity bias, as suggested by formation polarity ratios between 63%NP and 100%NP (nos. 14-17). In the most densely sampled and biostratigraphically well-dated study of this interval, pelagic limestones at Carabuey, Spain, yielded moderate *N* polarity bias (63%NP; no. 15) [*Steiner et al.*, 1987]. Strong *N* polarity bias was encountered in the Calcari Bianchi and Calcari Diasprigni limestones in Italy (95%NP; no. 14) [*Channell et al.*, 1984], in the White Mountains and related intrusives in Vermont and New Hampshire (100%NP; no. 16) [*Van Fossen and Kent*, 1990], and in the Corral Canyon volcanics in Arizona (92%NP; no. 17) [*May et al.*, 1986]. However, the reliability of polarity ratios from the latter three formations is limited by broad dating uncertainties and/or small sample sizes. Thus the polarity character of the Bajocian-Bathonian interval is uncertain at present, and further work will be required to test the existence of a Middle Jurassic Normal Polarity Bias Interval. Such an interval

would have implications for the debate regarding the Jurassic portion of the North American APWP [May and Butler, 1986; May et al., 1986; Van Fossen and Kent, 1990; Witte and Kent, 1990].

The late Middle-Late Jurassic (Callovian-Tithonian) is characterized mainly by balanced polarity ratios (nos. 1-13), although two formations exhibit markedly discordant ratios. Blue limestones in Oxfordian strata of Switzerland (100%NP; no. 6) [Johnson et al., 1984] contain a pre-folding magnetic component that was tentatively interpreted as primary, but late Miocene folding does not tightly constrain the age of remanence acquisition, and a strong *N* polarity bias may indicate acquisition during the CNPS. Polarity data of the Summerville Formation (9%NP; no. 10) [Steiner, 1978] may be problematic owing to high dispersion of characteristic magnetic vectors, possibly as a result of incomplete cleaning or overlapping magnetic spectra [May and Butler, 1986], and to a discrepancy between the depositional and apparent magnetic ages of the formation [Witte and Kent, 1990]. An independent test of geomagnetic polarity bias is provided by the M21-M38 magnetic anomaly model of Handschumacher et al. [1988], which yields circa 55-60%NP for the Callovian-Kimmeridgian interval.

**Cretaceous-Recent.** The most salient feature of this interval is the Cretaceous Normal Polarity Superchron (CNPS), representing a 41-m.y.-long episode of strong *N* polarity bias (124-83 Ma) [Harland et al., 1990] punctuated by a few short *R* polarity chrons (Figure 1) [Tarduno et al., 1992; Ogg, 1995]. Onset of the CNPS was preceded by an increase in *N* polarity bias beginning at circa 130 Ma, and its termination was marked by a progressive increase in reversal frequencies and dampened oscillations in polarity bias about 50%NP. Apart from the CNPS, most of the Cretaceous-Recent exhibits balanced polarities at a timescale of 5 m.y. Deviations from 50%NP are small but significant owing to the high resolution afforded by the Cretaceous-Recent GPTS [Harland et al., 1990]: the main polarity features are intervals of weak *R* polarity bias (40-45%NP) at 30-35 Ma and 45-60 Ma, and an interval of weak *N* polarity bias (55-65%NP) at 70-80 Ma. Since 20 Ma, geomagnetic field polarity has exhibited little variation from 50%NP at timescales as short as 2 m.y. (Figure 1).

### Comparison With Previous Studies

A number of studies have attempted to reconstruct a GPTS for the entire Phanerozoic [e.g., Creer, 1975; Irving and Pullaiah, 1976; Khramov, 1987; Ogg, 1995], although the Early-Middle Paleozoic portion of almost all such studies relies extensively on older Russian sources [e.g., Khramov, 1958, 1973; Khramov et al., 1965]. Much of the older Russian paleomagnetic data predates modern demagnetization techniques and may be contaminated by unrecognized secondary magnetic overprints [Smethurst and Khramov, 1992]. Bearing this caveat in mind, a comparison of Early-Middle Paleozoic polarity patterns between the present study and existing polarity timescales is warranted. The GPTS of Khramov [1987] exhibits dominantly *R* polarity throughout the Paleozoic, although the Caradoc-Llandovery is recognized as an interval of dominantly *N* polarity. Irving and Pullaiah [1976] identified three pre-KRPS "bias intervals": (1) a Cambrian-Middle Ordovician *R* polarity interval, (2) a Late Ordovician-Silurian *N* polarity interval, and (3) a Devonian-Permian *R* polarity interval (their Figure 15). Although broadly similar to results of the present study, significant differences exist with regard to the detailed structure of these records. In particular, Irving and Pullaiah [1976] identified the Early Cambrian and Early

Devonian-Early Carboniferous as intervals of *R* polarity bias, which may reflect inclusion of unrecognized Kiaman-age magnetizations (cf. balanced polarities of this study; Figure 13).

Phanerozoic geomagnetic patterns may also be examined through relative reversal rate studies [McElhinny, 1971; Johnson et al., 1995]. Relative reversal rates are calculated for successive time windows as the ratio of the number of studies of mixed polarity (i.e., exhibiting both polarities in any proportion) to the total number of studies. Strictly speaking, the resulting curves are based neither on reversal rates nor polarity bias but represent a proxy for both parameters, which generally covary [Cox, 1981]. In addition, the technique does not fully utilize a large proportion of available information because (1) all studies having polarity ratios >0%NP and <100%NP are rated as "mixed" and (2) studies exhibiting strong *R* polarity (0%NP) and strong *N* polarity (100%NP) bias are not distinguished. These drawbacks may be compensated by analysis of a larger database: using a filtered version ( $n = 1233/4096$ ) of the Global Paleomagnetic Database of McElhinny and Lock [1993], Johnson et al. [1995] identified intervals of low reversal frequency corresponding to four of the six intervals of geomagnetic polarity bias recognized in the present study: (1) CNPS, (2) Early Jurassic, (3) KRPS, and (4) Early-Middle Ordovician (their Figure 3; cf. Figure 13).

### Utility of Phanerozoic Polarity Bias Curve

Establishment of a standard polarity curve for the Phanerozoic may permit utilization of geomagnetic polarity bias for evaluation of the primary character of remanences in a manner analogous to the use of APWPs to evaluate formation paleopoles. A "polarity bias test," in which a formation polarity ratio is compared with a standard polarity curve (e.g., Figure 13), will quickly identify those ratios that are anomalous for a given age. Such a test has advantages and disadvantages. In its favor, polarity bias is a fundamental parameter of the geomagnetic field, and identical age-dependent patterns of polarity bias should be encountered on all cratons (e.g., Figure 10). This is in contrast to paleopoles, which are a function of the unique drift history of each craton and which generally are not amenable to intercratonic comparisons for the Paleozoic and earlier epochs. On the downside, formation polarity ratios are inherently rather variable owing to the diverse factors discussed above, and polarity concordancy or discordancy can neither prove nor disprove a particular origin for a given remanence. Polarity bias may provide an additional test for evaluating the origin of magnetic remanences and is likely to be most effective when applied (1) to a large group of paleomagnetic studies and (2) in conjunction with paleopole and field tests (as in the British Siluro-Devonian example of Figures 9 and 10). As shown above, polarity-ratio distributions for groups of remanences can be assessed in relation to a binomial probability model in a manner that is comparable to the use of Fisher statistics to test paleopole distributions.

### Relationship of Geomagnetic Polarity to Geotectonic Events

Intervals of strong geomagnetic polarity bias have been proposed to correlate with episodes of mantle plume activity and intensified mantle overturn, e.g., the mid-Cretaceous CNPS [Gaffin, 1987; Larson, 1991a] and the Early Jurassic Normal Polarity Bias Interval [Johnson et al., 1995]. Onset of the CNPS coincided with breakup of East and West Gondwana and opening of the South Atlantic and Indian oceans during the Early Cretaceous (circa 130-120 Ma), which has been linked to elevated mantle heat flow, hotspot activity, and ocean crust production

rates [Peate *et al.*, 1990; Larson, 1991a; Larson and Olson, 1991; Storey *et al.*, 1992]. The Early Jurassic Normal PBI coincided with strong synrift igneous activity during the Hettangian-Sinemurian (205-195 Ma) in eastern North America [e.g., Dooley and Smith, 1982; Smith, 1987; deBoer *et al.*, 1988; Van Fossen and Kent, 1990; Holbrook and Kelemen, 1993], northwestern Africa [e.g., Hailwood and Mitchell, 1971; Briden *et al.*, 1971; Dalrymple *et al.*, 1975], and southern Africa and Brazil [Siedner and Mitchell, 1976; Montes-Lauar *et al.*, 1994].

Other than for the CNPS, there has been little systematic examination of relationships between geomagnetic field behavior and coeval geotectonic events. A Permo-Carboniferous superplume eruption was postulated by Larson [1991b], but this was based largely on an inferred analogy between the KRPS and CNPS rather than on evidence of widespread anorogenic volcanism of this age. Arguments against a Permo-Carboniferous superplume event include (1) lack of a coeval first-order eustatic highstand [Vail *et al.*, 1977; Algeo and Soslavinsky, 1995], as would be expected for an interval of accelerated mid-ocean ridge spreading rates, and (2) extensive coeval continental glaciation, strong latitudinal temperature gradients, and low atmospheric CO<sub>2</sub> levels [e.g., Frakes *et al.*, 1992; Crowley and North, 1991; Berner, 1994], which are inconsistent with the elevated rates of CO<sub>2</sub> outgassing that presumably would accompany a superplume eruption (as during the Cretaceous).

The KRPS appears to be more closely correlated with coeval orogenic events than with any evidence of a superplume eruption. The onset of the KRPS in the mid-Carboniferous (circa 315-310 Ma) was bracketed by two peak phases of the Variscan-Alleghenian Orogeny, correlative with the European Namurian C-Westphalian A (circa 325-315 Ma) and Westphalian C stages (circa 305 Ma) [Ahrendt *et al.*, 1983; Rast, 1983; Ziegler, 1989; Malavieille *et al.*, 1990] and with the North American Morrowan (Wichita orogeny) and late Atokan-Desmoinesian stages (Arbuckle/Ouchita orogeny) [Ham and Wilson, 1967; Dallmeyer *et al.*, 1986; Secor *et al.*, 1986; St. Peter, 1993]. The latter orogenic phase was roughly coincident with suturing of Laurussia and Gondwana, as indicated by large cusps in the APWPs of North America and northern Eurasia at circa 310-300 Ma [Irving and Irving, 1982; DiVenere and Opdyke, 1991a]. Temporal correlations between the KRPS and coeval major orogenic events imply a common causal mechanism. The significance of this observation is that geomagnetic superchrons may be linked not only to superplume eruptions in divergent plate environments but also to some aspect of mantle convection associated with convergent plate settings. Furthermore, this implies that superchrons may not be directly causally related to superplumes, but, rather, that both may be expressions of some underlying aspect of mantle convection. Although detailed consideration of potential geomagnetic-geotectonic links is beyond the scope of the present paper, such relationships have the potential to provide important insights on geodynamo processes.

## Conclusions

1. Construction of a Phanerozoic geomagnetic polarity trend using polarity data from the Cretaceous-Recent GPTS and 278 Cambrian-Jurassic formations results in recognition of five or six first-order polarity features: (1) the Middle Cambrian-Middle Ordovician Burskan Reversed PBI (polarity bias interval), (2) the Late Ordovician-Late Silurian Nepan Normal PBI, (3) the mid-Carboniferous-Late Permian Kiaman Reversed

Polarity Superchron, (4) the Early Jurassic Normal PBI, (5) the Middle Jurassic Normal PBI(?), and (6) the Cretaceous Normal Polarity Superchron.

2. A combination of strong geomagnetic polarity bias (both *R* and *N*) and low reversal rates [Johnson *et al.*, 1995] may support the existence of a "dual-polarity superchron" during the Ordovician containing a single major polarity transition, the Middle Ordovician Polarity Shift (MOPS).

3. Cambrian-Jurassic formation polarity data represent estimates of geomagnetic field bias at an average characteristic timescale ( $\tau_p$ ) of 1.0-1.5 m.y., and the smoothed Phanerozoic trend reflects geomagnetic field bias at a characteristic timescale ( $\tau_f$ ) of 2-5 m.y.

4. About 50% of age-dependent variance among formation polarity ratios results from paleomagnetic sampling of a binomial variable (i.e., geomagnetic field polarity), and the remaining variance is due to other factors, including stochastic or systematic depositional or sampling biases, incorrect age estimates for formations or characteristic remanences, complex magnetizations, and low epochal reversal frequencies.

5. Reconstruction of an accurate Phanerozoic polarity trend permits use of a "polarity bias test" to evaluate a primary versus secondary origin for magnetic remanences. As an example, British "A" remanences (paleopole latitudes = 0°-20°; polarity ratios = 30-100%NP) exhibit polarity concordance with non-British remanences throughout the Siluro-Devonian, whereas British "B" remanences (paleopole latitudes = 25°-50°; polarity ratios = 0-20%NP) are strongly discordant, suggesting that the latter are largely or entirely of secondary origin.

6. Links between geomagnetic field behavior and major geotectonic events may provide important insights on mantle processes and their relationship to geodynamo operation. Although the CNPS was probably related to a mid-Cretaceous superplume eruption, the KRPS and, possibly, other first-order Phanerozoic polarity bias intervals may have been precipitated by mantle processes linked to geotectonic events in convergent plate environments.

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