Mean Paleomagnetic Poles for the Major Continents and the Pacific Plate

Richard G. Gordon and Rob Van der Voo

1. ABSTRACT

Apparent polar wander is the motion of Earth's spin axis relative to a reference frame that is usually fixed relative to a tectonic plate or stable interior of a continent. The main method for estimating the past position of Earth's spin axis is through paleomagnetism, the investigation of the magnetic memory of rocks. Mean paleomagnetic poles, which average poles over about half a geologic period and typically differ in mean age by ~20 to 30 millions of years, are presented for the major cratons over Phanerozoic time and are presented for more closely spaced ages for the Pacific plate since Late Jurassic time.

2. INTRODUCTION

Paleomagnetism is the study of Earth's past magnetic field through investigation of the magnetic memory of rocks. Among the branches of geophysics, paleomagnetism holds a special place for several reasons, not least of which was its pivotal role in providing support for the theory of continental drift. It is also special because most of the central problems of paleomagnetism are not concerned merely with the present Earth, as are most branches of geophysics, but with the history of Earth's solid surface over millions, tens of millions, hundreds of millions, or billions of years. Paleomagnetism is a tool for quantitative investigations of the tectonic history of Earth. Almost every modern paleomagnetic analysis is ultimately concerned with whether an estimated (i.e., observed) paleomagnetic direction differs significantly either from a known or hypothesized direction or from some other estimated direction.

In this chapter we briefly summarize what is known about the apparent polar wander (APW) paths of the stable portions of major continents over Phanerozoic time and of the Pacific plate since Late Jurassic time. With many caveats, including some discussed below, the paleomagnetic poles and their associated confidence limits can reasonably be considered a set of constraints on the crustal and mantle history of Earth.

What we cannot do here at all in this highly compact format is give any of the documentation of our sources of data, much less report on any of the field or laboratory investigations upon which these data rest, or discuss specific ambiguities in the data. The main data source used here for continental paleomagnetic poles and confidence limits is Van der Voo [46]. Sources for Pacific plate data are cited herein.

2.1 Apparent Polar Wander

APW is the position as a function of time of the intersection of Earth's spin axis with its surface as viewed from a reference frame attached to a finite-sized and stable portion of the surface of the solid Earth, which is most commonly a major craton, such as the stable interior of North America. This definition has some inherent problems, some trivial and some profound. The Earth's spin axis intersects its surface at two places, the north and south poles. Herein we use

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R. G. Gordon, Department of Geological Sciences, Northwestern University, Evanston, IL 60208-2150

R. Van der Voo, Department of Geological Sciences, University of Michigan, Ann Arbor, Michigan 48109-1063

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only the north pole as a reference. This can be a nontrivial ambiguity for ancient APW when sparse sampling in time, combined with the unknown polarity of Earth's paleomagnetic field, makes unclear whether a pole is a north pole or a south pole. A less important ambiguity, negligible for present purposes, is that on short time scales of about a year, the spin axis transiently differs from Earth's axis of maximum moment of inertia, through the annual- and Chandler-wobble.

The key assumption in going from paleomagnetic observations to APW is the axial geocentric dipole hypothesis, that the time-average of Earth's magnetic field is that of a geocentric dipole aligned with Earth's spin axis. Paleomagnetists uniformly view APW as a continuous curve, provided that each point is understood to represent an average over an interval long enough (tens of thousands of years or longer) to sample the full range of geomagnetic secular variation.

It is convenient to think of APW as consisting of two parts— the motion of the plates relative to the deep mantle and true polar wander, i.e., the motion of the whole earth relative to the spin axis by the process described by Goldreich and Toomre [10]. For example, if one were completely confident that true polar wandering was negligible, it might be possible therefore to use what is known about plate motion to specify long time intervals of APW with just a few adjustable parameters, as Gordon et al. [15] and May and Butler [26] have attempted with very simple models.

2.1.1. Path construction. Many methods have been used for specifying APW paths or segments of APW paths. Here we specify a sequence of point estimates differing in age typically by 20 or 30 million years. This approach is most valid for intervals in which APW was small, that is, small in comparison with the dispersion of individual paleomagnetic poles due to uncertainty in pole position and small in comparison with the confidence limits of the resulting pole. A key advantage of this approach is simplicity of application— once the data in the interval have been identified, the pole and confidence limits can be calculated either using the oceanic plate method of Gordon and Cox [11] or, more commonly, by the application of Fisher statistics [8].

There are several disadvantages to this approach, as there are for all the alternatives. First, over time intervals as long as half a period, APW is non-negligible, successive poles from continents typically being separated by ~10° [46]. Thus, for accuracies better than ~10°, the pole cannot be thought of as representative of the entire half-period-long interval. Either the true age of the estimated pole is uncertain to about half a period or the true error in pole position for any precisely stated age is much more uncertain than implied by the confidence limits of the pole. If APW during the half-period was very smooth, if the pole moved along a great circle at a constant velocity, and if the included paleomagnetic poles have an average age near the middle of the interval, then the mean pole could be a good estimate of the average position of the pole during the half-period. However, if APW were more complex during the interval, e.g., reversing direction half-way through the interval as the North American pole appears to have done about 200 Ma [15, 26], then this method gives a biased estimate of the pole position and tends to give estimates of the rate and total length of APW that are less than the true rate and length.

Thus, readers who use these APW paths presented herein should be aware that what is presented are not the data, but a reduction of these data that is valid only insofar as the underlying assumptions discussed above are valid. It is not uncommon to see APW paths referred to as "data", but we emphasize that they are models having a large number of adjustable parameters.

2.1.2. Data selection. Although two-thirds of Earth's surface is covered by oceanic crust, the available data are dominated by those from the continents for two reasons. First, it is impractical to obtain oriented samples from oceanic crust except in oceanic islands, which are nearly always very young. Second, the oldest seafloor is very young (~170 Ma) relative to the oldest continental surface (> 3 Ga).

Various sets of criteria for minimum reliability or for data selection, all with similar intent, are in use by different workers in paleomagnetism. The data incorporated into the estimation of the continental paths described herein were filtered using seven criteria set forth by Van der Voo [46 and work cited therein]: (1) The rock age is well determined and the magnetization can reasonably be assumed to be the same age as the rock. (2) There are enough samples, small enough dispersion, and small enough confidence limits on the mean, specifically there are more than 25 samples, the precision parameter is at least 10 (corresponding to a two-dimensional angular standard deviation of at most 25.6°), and the radius of the cone of 95% confidence is 16° or less. (3) The samples have been adequately demagnetized and vector subtraction or principal component analysis have been used to analyze the demagnetization data. (4) Field tests constrain the age of magnetization. (5) There is sufficient structural control to correct the magnetization for post-magnetization changes in orientation and there is enough evidence to indicate that the sampling sites are tectonically coherent with the relevant craton or block. (6) Reversals are present. (7) The paleomagnetic poles do not resemble any poles that are younger by more than a period.

The filter used by Van der Voo [46], whose paths are reproduced herein, are that only data meeting at least 3 of these criteria are included. See Van der Voo [46] for further details including the very long tables of data on which these paths are based. Acton and Gordon [3] describe a different approach for selection and rejection of continental paleomagnetic poles, which would reject more poles than does Van der Voo's filter. The difference in filter mainly reflects the difference in intended applications and the level of accuracy and resolution both desired and attainable from the more recent, better studied intervals investigated by Acton and Gordon.

For Pacific plate APW, the criteria of data selection usually have a similar intent, but are qualitatively different because Pacific plate data are qualitatively different. In a few special cases the requirement of well-determined rock age has been relaxed. Numbers of samples, precision of magnetization directions, and demagnetization are considered only when the magnetic results are based on oriented samples instead of measurements of the magnetic field intensity at the sea surface. Structural control and tectonic coherence are in nearly every case negligible problems for Pacific plate paleomagnetism [cf., 3].

2.2 APW Paths of the Major Continents

The major continents are North America, Greenland, Europe, Siberia, North and South China, and the Gondwana elements of South America, Africa, Madagascar, India, Australia, and Antarctica. All continents consist of older Precambrian nuclei on which Paleozoic and younger sediments were deposited. In this section we present the Phanerozoic APW paths of these continents. Results herein have not been compiled for post-Eocene times. Readers in search of Oligocene paleomagnetic poles are referred to Acton and Gordon [3]. This section follows chapter 5 of Van der Voo [46], to which the reader is referred for further details.

2.2.1. North America, Greenland, and Europe. North America and Europe are paleomagnetically the best studied continents of the world with 400 individual paleomagnetic poles for the Cambrian through Eocene periods [46]. Poles incorporated from North America come from the craton and its disturbed margin. Poles from displaced terranes, i.e., terranes known to have moved relative to stable North America in the distant past, are incorporated only for those intervals since those terranes became firmly attached to North America. Hence, poles for Appalachian displaced terranes north of New York City (41°N) have been included only for Devonian and younger times. Similarly, poles for Appalachian displaced terranes south of New York City have been included only for Late Carboniferous and younger times. Results from terranes in Mexico, in the western North American cordilleras, and in Alaska have been excluded. For two regions of the disturbed margin, the Colorado Plateau (including its surroundings in Colorado, Arizona, and New Mexico) and the northern part of the Pennsylvania Salient in the Appalachian fold and thrust belt, a correction for inferred rotation relative to the stable interior of North America has been applied to the poles before their incorporation into the path. The resulting individual poles have been combined to obtain a set of mean paleomagnetic poles for North America and Europe for time intervals from Early Cambrian to early Tertiary (Table 1). Some of these are shown in Figure 1 with and without correction for the opening of the Atlantic.

The European craton was taken as that part of the continent now found in Scandinavia, as well as the Russian Platform between the Urals and the Paleozoic or younger mobile belts at the surface or buried in Denmark, Germany, Poland, western Podolia (Ukraine), Romania, and Bulgaria. The European cratonic part during Paleozoic time is called Baltica. A second ancient element in Europe lies in the northern part of the British Isles. This area of Scotland and northern Ireland throughout the Paleozoic is thought to have formed part of the combined North American-Greenland continent (called Laurentia) and includes what is called the Lewisian basement that used to be continuous with Greenland. Pre-Late Silurian results from the northern British Isles may not be representative of Baltica (="Stable" Europe). From other terranes, only latest Silurian and younger results were included from the Midland Craton and its margins, only latest Carboniferous and younger results were included from Hercynian Europe, and no results were included from Alpine Europe including the large Hercynian massifs therein and the Moesian Platform (in Romania and Bulgaria).

Poles from Greenland are so sparse that only a very sparse APW path can be constructed for it. See Van der Voo [46] and Acton and Gordon [3] for a discussion of the relatively abundant early Tertiary paleomagnetic

Table 1. Mean Paleopoles from North America and Europe

Age interval	North America				Stable Europe			
	Pole	N	K	A_{95}	Pole	N	K	A_{95}
Tl (37–66)	82, 168	17	63	5	78, 177	20	75	4
†Tl (37–66)	†77, 173	26	43	4				
Ku (67–97)	68, 192	5	250	5	72, 154	5	146	6
†Ku (67–97)	†68, 192	7	227	4				
Kl (98–144)	69, 194	8	149	5	70, 193	4	41	15
Ju, uJm (145–176)	67, 133	8	44	9	66, 191	3	73	15
lJm, Jl (177–195)	68, 93	10	193	4	70, 126	4	86	10
Tru/Jl (196–215)	61, 81	15	68	5				
Tru, uTrm (216–232)	52, 96	7	180	5	52, 133	5	29	14
Trl/m, Trl (233–245)	52, 110	11	190	3	52, 150	13	103	4
Pu (246–266)	52, 120	5	371	4	50, 160	6	85	7
Pl (267–281)	45, 123	14	218	3	47, 164	21	134	3
Cu/Pl, Cu (282–308)	40, 128	15	314	2	41, 169	21	165	3
Cm, Cl, Du/Cl (309–365)	29, 131	20	49	5	25, 159	5	45	12
Du, Dm/Du (366–378)	30, 110	8	20	13	27, 151	6	38	10
Dm, Dl (379–397)	24, 108	5	23	16	24, 151	5	82	8
Su/Dl (398–414)	4, 95	4	75	11	3, 135	14	24	8
†Su/Dl (398–414)	†4, 97	5	78	9				
Su, Sm (415–429)	18, 127	2	-	-	20, 161	11	44	6
Ou/Sl, Ou, Om (430–467)	18, 146	9	16	13				
*Same, N. Britain only					*13, 181	9	24	10
Ol/m, Ol (468–505)	17, 152	3	31	23	-24, 230	2	-	-
*Same, N. Britain only					*16, 212	1	-	-
Ꞓu, Ꞓm, Ꞓ (506–542)	9, 158	8	28	11				
Ꞓl (543–575)	5, 170	6	22	15	11, 231	2	-	-

Mean north paleopoles for each continent are given in their own reference frames [46]. The mean paleopoles were determined from individual poles that are listed in Van der Voo [46] and meet 3 or more of 7 criteria (described in the text). Age abbreviations: T=Tertiary, K=Cretaceous, J=Jurassic, Tr=Triassic, P=Permian, C=Carboniferous, D=Devonian, S=Silurian, O=Ordovician, Ꞓ=Cambrian, l=early, m=middle, u=late. Ages in millions of years before present are given in parentheses and are from the time scale of the Decade of North American Geology [28]. N, K, and A_{95} respectively are the number of individual paleopoles averaged, the precision parameter, and the radius of the cone of 95% confidence about the mean pole [8]. Pole positions are given in latitude (positive when north, negative when south) and east longitude.

* Great Britain north of the Iapetus suture only. For pre-Middle Silurian times the Baltic Shield and Russian Platform, exclusive of Caledonian Europe, are listed separately without an asterisk.

† Includes also the results from Greenland (rotated into the North American reference frame).

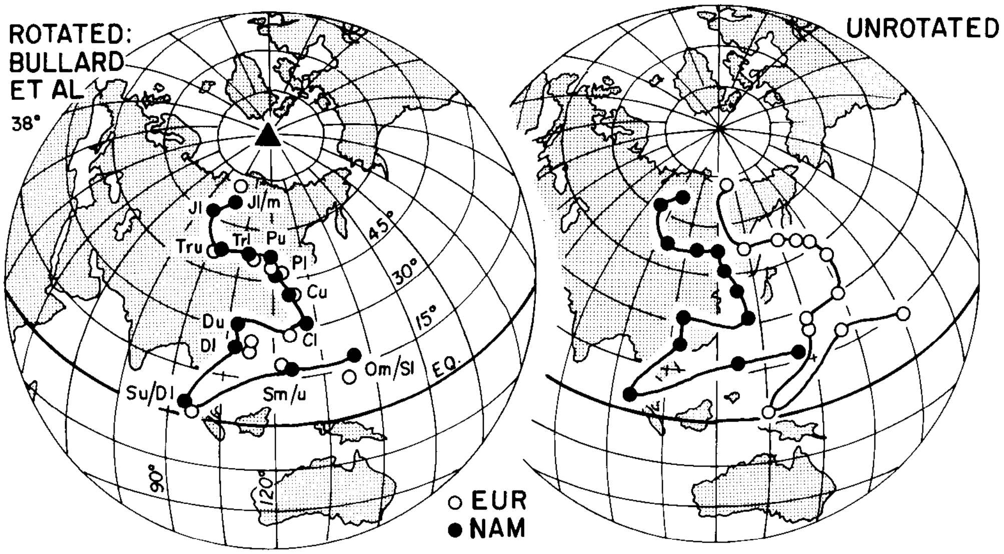

Fig. 1. Apparent polar wander paths (north poles) for Europe and North America for the interval from Middle Ordovician through Early Jurassic time. The plot on the right shows the North American poles in a reference frame attached to the present location of North America and shows the European poles in a reference frame attached to the present location of Europe. The left-hand side identically repeats the North American path but shows the European path reconstructed into the North American reference frame using the reconstruction of Bullard et al. [4]. The large triangle is the Euler pole of this rotation; the rotation angle is 38°. Age abbreviations are explained in Table 1. For pre-Middle Silurian times, only European paleomagnetic poles from northern Britain have been used. From Van der Voo [46].

poles from Greenland.

2.2.2. The Gondwana continents. Paleomagnetic poles for the Gondwana continents total less than 350 for Africa, South America, Antarctica, Australia, India, and Madagascar combined [46]. A major part of this paleo-supercontinent is cratonic including most of Africa, most of South America, Madagascar, India south of the Himalayan Front, Australia west of the eastern fold belts, and East Antarctica. The break-up of Gondwana is well documented and thought to have been initiated in Middle Jurassic time. In contrast, the timing of the assembly of Gondwana is poorly known. Much of cratonic Gondwana was last deformed or displaced relative to adjacent cratonic elements by the late Precambrian to early Paleozoic Pan-African orogeny, which formed (pre-Ordovician) mobile belts around and between the older Archean and earlier Proterozoic nuclei [46]. There remain many unanswered questions about the APW path of Gondwana, especially for Paleozoic time.

Each pole for each of the six now separate elements are given in its present reference frame in Table 2a. The Cambrian to earliest Jurassic subset of these poles is given in Table 2b after reconstruction into a common northwest African reference frame. The errors and precisions quoted in Table 2b are identical to those in 2a and neglect the presumably significant errors induced by the reconstruction.

Table 3 gives the Early Cambrian to Early Jurassic Gondwana paleomagnetic poles combined in the northwest African reference frame. Readers should note how very large some of the confidence limits are on these combined poles. Figure 2 shows a smooth curve drawn through the Late Carboniferous to Early Jurassic mean Gondwana poles, as well as the individual mean poles from each continent. Individual poles from the Gondwana continents are plotted in their separate reference frames attached to the present positions of their host cratons (Figure 3a) and are also plotted after rotation into a common northwest African reference frame (Figure 3b). The large decrease in dispersion of the data when reconstructed into the northwest African reference frame gives strong support to the Gondwana hypothesis, though the data cannot decisively distinguish between different Gondwana reconstructions that have been proposed. Figure 4 shows the individual

Table 2a. Mean Paleopoles for the Phanerozoic of Gondwana

Age Group	Africa				South America				India				Australia				Antarctica				Madagascar			
	Pole	N	K	A_{95}	Pole	N	K	A_{95}	Pole	N	K	A_{95}	Pole	N	K	A_{95}	Pole	N	K	A_{95}	Pole	N	K	A_{95}
Tl (37–66)	81, 185	4	77	11	79, 76	2			43, 285	10	24	10	61, 301	7	38	10								
Ku (67–97)	67, 245	12	60	6	85, 214	6	56	9	21, 295	7	47	9	56, 318	1							68, 231	6	103	7
Kl (98–144)	56, 263	6	105	7	84, 224	7	107	6	12, 299	2			41, 338	6	17	17								
Ju (145–176)	57, 251	7	22	13	85, 73	3	293	7	2, 310	2			48, 349	6	29	13	52, 30	6	89	7				
Jl (177–195)	72, 249	10	108	5									48, 357	3	562	5	49, 46	4	125	8				
Jl/Tru (196–215)	71, 214	2			71, 74	2			10, 310	1											74, 277	1		
Tru (216–232)	56, 253	2			79, 78	6	45	10					32, 350	1										
Trl (233–245)					63, 149	1			-6, 305	3	321	7	31, 338	2							66, 292	1		
Pu (246–266)					80, 110	5	77	9	4, 283	1			36, 321	3	37	21								
Pl (267–281)	32, 246	5	51	11	62, 174	3	399	6					46, 302	1										
Cu (282–308)	40, 217	3	20	28	54, 165	9	42	8	-18, 291	1			62, 322	2										
Cl (309–365)	21, 227	4	20	21									84, 141	1										
Du (366–378)	5, 197	2											62, 203	6	19	16								
Dl (379–397)					12, 130	2							77, 80	3	5	60								
Dl/Su (398–414)																								
Sm/Su (415–429)	43, 189	1											58, 173	3	4	68								
Sl/Om (430–467)	-35, 158	2											-2, 215	2										
Ol (468–505)	-38, 189	3	15	33	-4, 122	1							18, 199	3	22	27	9, 202	5	39	12				
€u (506–542)	-61, 162	5	3	50	-49, 194	3	15	33					18, 203	8	13	16								
€l (543–575)	-17, 90	2							35, 219	5	28	15	28, 178	4	12	27								

Mean north paleopoles for each of the Gondwana continents are given in their own reference frames [46]. The mean paleopoles were determined from individual poles that are listed in Van der Voo [46] and meet 3 or more of 7 criteria. Abbreviations and convention are the same as in Table 1.

Table 2b. Rotated Mean Paleopoles for the Phanerozoic of Gondwana

Age Group	Africa				South America				India				Australia*				Antarctica				Madagascar			
	Pole	N	K	A_{95}	Pole	N	K	A_{95}	Pole	N	K	A_{95}	Pole	N	K	A_{95}	Pole	N	K	A_{95}	Pole	N	K	A_{95}
Jl (177–195)	72, 249	10	108	5									63, 259	3	562	5	74, 272	4	125	8				
Tru/Jl(196–215)	71, 214	2			71, 217	2			67, 251	1											68, 232	1		
Tru(216–232)	56, 253	2			67, 236	6	45	10					52, 283	1										
Trl (233–245)					43, 222	1			50, 259	3	321	7	43, 276	2							65, 254	1		
Pu(246–266)					61, 236	5	77	9	43, 224	1			34, 261	3	37	21								
Pl (267–281)	32, 246	5	51	11	36, 234	3	399	6					28, 242	1										
Cu(282–308)	40, 217	3	20	28	31, 225	9	42	8	33, 251	1			45, 230	2										
Cl (309–365)	21, 227	4	20	21									43, 182	1										
Du(366–378)	5, 197	2											17, 184	6	19	16								
Dl (379–397)					7, 177	2							53, 175	3	5	60								
Su/Dl (398–414)																								
Sm-u(415–429)	43, 189	1											19, 168	3	4	68								
Om-Sl (430–467)	-35, 158	2											-48, 189	2										
Ol (468–505)	-38, 189	3	15	33	-2, 162	1							-26, 172	3	22	27	-30, 183	5	39	12				
€u(506–542)	-61, 162	5	3	50	-74, 200	3	15	33					-26, 176	8	13	16								
€l (543–575)	-17, 90	2							5, 162	5	28	15	-10, 157	4	12	27								

Mean north paleopoles for each of the Gondwana continents are given in the Northwest Africa reference frame [46]. The mean paleopoles were determined from individual poles that are listed in Van der Voo [46] and meet 3 or more of 7 criteria. Abbreviations and conventions are as in Table 1. The rotation parameters are from Lottes and Rowley [25] and for pre-Middle Jurassic times as follows: South America to Northwest Africa, Euler pole at 53°N, 325°E, angle 51.01° counterclockwise; India to Northwest Africa, Euler pole at 26.67°N, 37.29°E, angle 69.37° clockwise; Australia to Northwest Africa, Euler pole at 28.13°S, 66.79°W, angle 52.06° counterclockwise; Antarctica to Northwest Africa, Euler pole at 12.36°S, 33.81°W, angle 53.29° counterclockwise, and Madagascar to Northwest Africa, Euler pole at 14.9°S, 82.35°W, angle 15.7° counterclockwise.

* Australian means include Paleozoic results from the eastern foldbelt.

Table 3. Overall Mean Poles For Gondwana in Different Reconstructions

Age Interval	Pole[1]	N	K	A_{95}	Pole[2]	N	K	A_{95}	Pole[3]	N	K	A_{95}
J1 (177–195)	70, 260	3	138	11	65, 258	3	137	11	67, 250	3	162	10
Tru/Jl (196–215)	70, 230	4	163	7	67, 230	4	102	9	64, 256	4	23	20
Tru(216–232)	60, 261	3	32	22	58, 261	3	29	23	56, 260	3	75	14
Trl (233–245)	52, 253	4	20	21	50, 250	4	19	22	45, 264	4	13	26
Pu(246–266)	47, 242	3	17	31	44, 243	3	15	33	43, 256	3	48	18
Pl (267–281)	32, 241	3	156	10	30, 242	3	88	13	27, 244	3	176	9
Cu(282–308)	38, 231	4	37	15	34, 233	4	37	15	32, 239	4	14	25
Cl (309–365)	34, 207	2			31, 209	2			27, 210	2		
Du(366–378)	11, 191	2			9, 192	2			5, 196	2		
Dl (379–397)	30, 176	2			28, 179	2			25, 182	2		
Su/Dl (398–414)												
Sm-u(415–429)	31, 177	2			29, 179	2			25, 183	2		
Om-Sl (430–467)	-43, 172	2			-44, 170	2			-48, 175	2		
Ol (468–505)	-25, 176	4	19	22	-26, 175	4	19	22	-30, 180	4	12	27
€u(506–542)	-55, 176	3	10	42	-55, 173	3	11	40	-58, 172	3	16	32
€l (543–575)	-9, 138	3	4	71	-7, 140	3	4	73	-1, 144	3	3	110

Mean north paleopoles for each of the Gondwana continents (Table 2a and Van der Voo [46]) are given in the Northwest Africa reference frame for different reconstructions. (1) Rotation parameters of Lottes and Rowley [25]; Africa is assumed to have been composed of three distinct plates; see the legend of Table 2b for rotation parameters for the other continents. (2) Rotation parameters of Scotese and McKerrow [38]; Africa is assumed to have been a single plate; all rotations are counterclockwise (ccw) and with respect to Africa: South America, Euler pole at 45.5°N, 327.8°E, angle 58.2°; India, 28.1°S, 213.3°E, angle 66.5°; Australia, 24.63°S, 297.36°E, angle 55.92°; Antarctica, 9.68°S, 328.19°E, angle 58.54°; Madagascar, 1.7°S, 272.2°E, angle 22.2°. (3) Rotation parameters of Smith and Hallam [39]; Africa is assumed to have been a single plate; South America to Africa, Euler pole at 44°N, 329.4°E, angle 57° ccw; India to Africa, 25.5°S, 201.34°E, angle 44.97° ccw; Australia to Africa, 11.92°S, 294.59°E, angle 58.51° ccw; Antarctica to Africa, 1.3°N, 324°E, angle 58.4° ccw; Madagascar to Africa, 9°S, 313°E, angle 15° ccw.

Gondwana poles and a combined smoothed path from Early Cambrian to early Carboniferous time in a northwest African reference frame. There is a broad range of opinions of how the Ordovician poles are connected during Silurian and Devonian time to the late Paleozoic poles; some of these options imply very fast rates of APW of ~4° per million years (cf. figure 5.15 of Van der Voo [46]). Van der Voo [46] concludes that there will be no simple solution for this ambiguity until many more reliable poles are obtained from cratonic Gondwana from Silurian and Devonian rocks.

2.2.3. Siberia. Late Cambrian and younger poles for Siberia have thus far been obtained almost entirely by paleomagnetists from Russia. Unfortunately many of the original publications are not directly accessible, and non-Russian paleomagnetists must rely on published summaries for the available paleomagnetic poles [27, 42, 21, and pers. comm. from A. N. Khramov to RVdV, 1990]. Many results are apparently not fully based on directional analysis, and details of demagnetization and field tests are generally unreported. Thus, the summary poles (Table 4) should be treated with caution, if not skepticism.

For post-Permian poles, readers are advised to use the European reference poles because Eurasia—including stable Europe, Kazakhstan, and Siberia—was a single continent since the formation of the Urals, which formed in a collision of Europe, Kazakhstan, and Siberia no later than in Permian time, and perhaps earlier [17, 50, 49]. Apparently reliable and well-clustered groupings of paleomagnetic poles are available for Late Cambrian and Ordovician times from Siberia. The Silurian and Devonian poles from Siberia suggest that it drifted northward, but the Devonian poles are suspected of being secondary magnetizations [46].

2.2.4. North and South China. Poles for South China lie in the Pacific Ocean when plotted in the reference frame of South China (Figure 5, Table 5). The

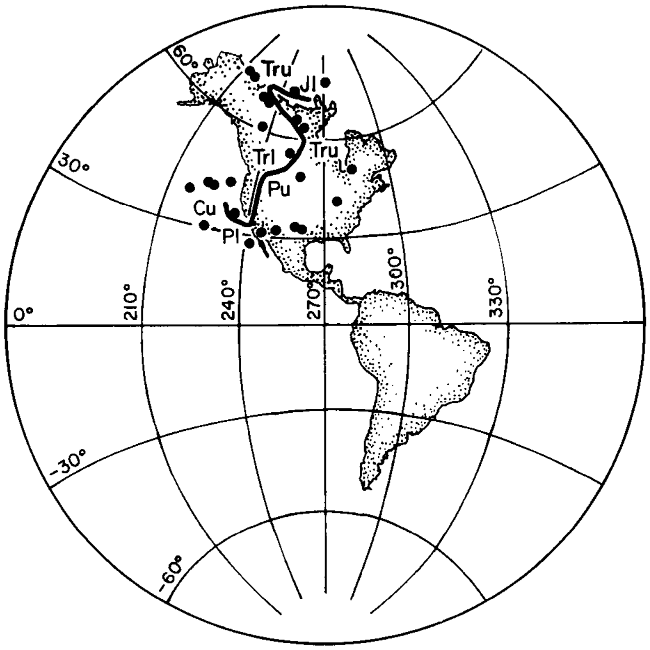

Fig. 2. Mean paleomagnetic north poles for each Gondwana continent and combined Gondwana apparent polar wander path for late Carboniferous through Early Jurassic time (in northwest African coordinates from Tables 2b and 3). From Van der Voo [46].

North China paleomagnetic poles for Triassic and Permian time mainly fall in Europe and northern Africa when plotted in the reference frame of North China (Figure 5, Table 5). Recently obtained Silurian and Devonian poles for North China indicate a mid-Paleozoic path different from that sketched in Figure 5, with poles lying in the Pacific Ocean southwest of North America [48]. The Late Permian paleomagnetic poles of the two blocks appear well determined and provide strong evidence for post-Permian movement between the two blocks. Paleomagnetic poles from the two blocks for Cretaceous time are more or less consistent with one another and are consistent with those from Siberia, Europe, and North America rotated into a Eurasian reference frame. The available poles for both North China and South China indicate low to equatorial paleolatitudes.

2.3 APW of the Pacific Plate

All the APW paths presented above have been for continents or components of continents. Here we present an APW path for the Pacific plate (Figure 6, Table 6), which is nearly entirely oceanic. Because the oldest seafloor in the Pacific, ~175 Ma, is much younger than the oldest rocks on continents, the Pacific APW path cannot span nearly as long an interval.

Current estimates of Pacific APW come from several types of data: (1) seamount poles, (2) paleocolatitudes from azimuthally unoriented cores, (3) identification of equatorial sediment facies in drill cores, and (4) the shapes and amplitudes of marine magnetic

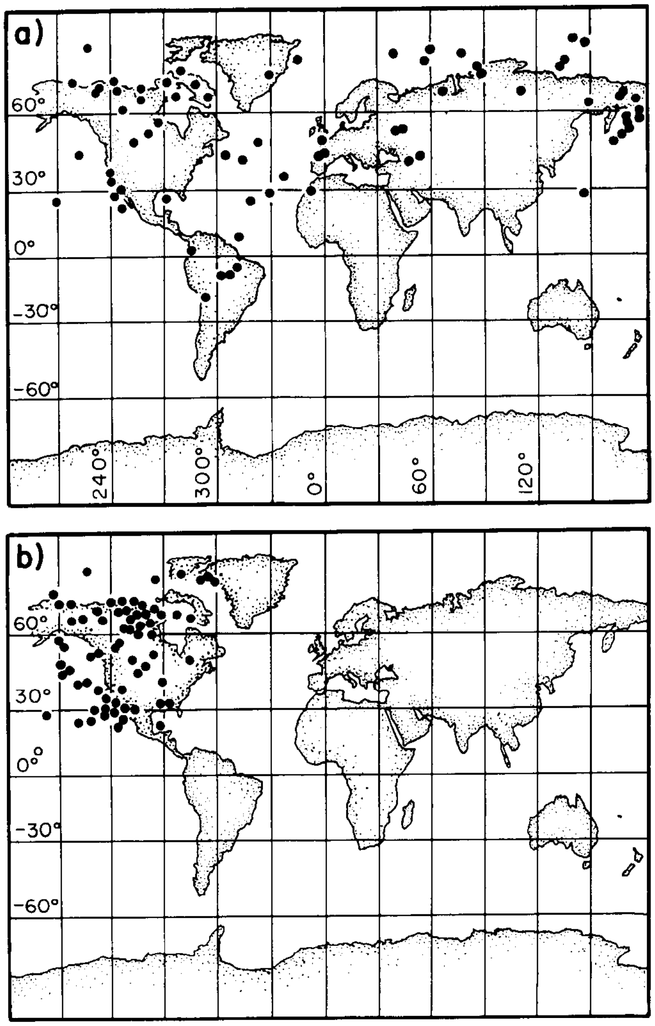

Fig. 3. a) Individual late Carboniferous through Early Jurassic paleomagnetic north poles from each of the Gondwana continents with each pole plotted in the reference frame fixed relative to the present location of its continent. b) Individual late Carboniferous through Early Jurassic paleomagnetic north poles from each of the Gondwana continents rotated into the West African reference frame using the reconstruction of Lottes and Rowley [25]. From Van der Voo [46].

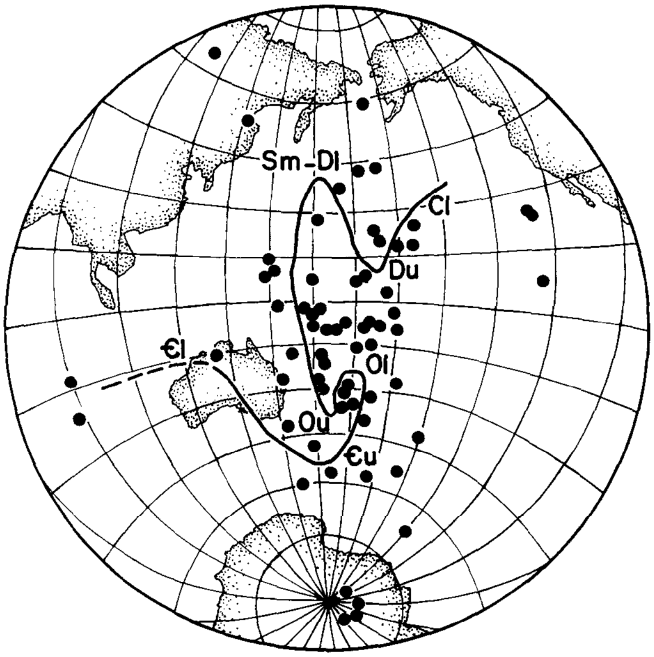

Fig. 4. Individual Cambrian through early Carboniferous paleomagnetic north poles from each of the Gondwana continents reconstructed into the West African reference frame using the reconstruction of Lottes and Rowley [25]. Also shown is the best estimate of the apparent polar wander path. From Van der Voo [46].

anomalies caused by the alternating polarity of seafloor magnetization recorded as the seafloor spreads away from mid-ocean ridges.

Most of the information about Pacific APW during Cretaceous time comes from seamount poles [43, 43, 9, 19, 33, 34, 35, 36, 20]. Most of these poles have been determined using a linear least-squares analysis and by assuming that the seamount is uniformly magnetized. R. Parker and colleagues have demonstrated that the observed anomalies over seamounts are inconsistent with uniform magnetization and have developed promising alternative methods for analyzing seamount magnetism [e.g., 29, 30], which have replaced uniform-magnetization approaches as the method of choice. The results from these new methods have provided bounds on how the magnetization is really distributed, but the pole positions are on average not very different from those from the uniform magnetization approach [e.g., 20]. In early work on seamount magnetism, seamounts lying close to one another were assumed to be of about the same age, and their poles were averaged together. This work indicated that seamount poles had large dispersions, with two-dimensional angular standard deviations of 6° to 11° [19]. Later work, building on more precise age dates, indicates that the dispersions are somewhat smaller, with two-dimensional angular standard deviations of 5° to 8° [11, 14, 34, 36]. The many seamount poles now available, in large part due to the work of W. Sager, renders the random error on averages of seamount poles small.

The main weakness of seamount poles for determining the Pacific APW path is that so few of them are precisely dated that they are not very useful in problems requiring a fine age resolution, which is critical, for example, for study over intervals of rapid APW. A

Table 4. Mean Palepoles for Siberia

Age or Interval	Pole	N	K	A_{95}	Ref.
Tl (45)	70, 162	4	39	11	1
Tl (59)	62, 146	5	46	9	1
Ku (88)	64, 151	4	108	7	1
Kl (121)	70, 167	5	234	4	1
Ju/Kl (142)	70, 150	6	42	9	1
Ju (151)	69, 131	5	49	9	1
Jm (173)	65, 132	6	29	11	1
Jl (195) *	63, 110	4	21	21	1
Tru/Jl (207)	56, 129	6	48	8	1
Tru (222)	55, 138	6	38	9	1
Trm (238)	52, 150	7	58	7	2
Trl (245)	52, 156	9	113	4	2
Pu (253)	42, 161	6	61	7	2
Pl (268)	38, 159	5	48	9	2
Cu/Pl (288)	34, 158	5	31	11	2
Devonian (360–408)	28, 151	7	65	8	3
Silurian (408–438)	-4, 121	8	-	19	4
M. Ordovician (458–478)	-22, 130	11	-	4	4
E. Ordovician (479–505)	-40, 132	12	-	7	4
L. Cambrian (505–523)	-36, 127	14	141	3	3
M. Cambrian (523–540)	-44, 157	4	61	12	3
E. Cambrian (540–575)	-35, 188	4	16	24	3

Mean north paleopoles for Siberia are given in the (Eur-)Asian reference frame [46]. The mean paleopoles were determined from individual poles that are listed in Van der Voo [46] and meet 3 or more of 7 criteria. Abbreviations and conventions are as in Table 1. References: 1 = Khramov [21 and pers. comm., 1990], with running mean averages in 20-Myr windows of all data from the U.S.S.R. part of Eurasia; 2 = Khramov [21 and pers. comm., 1990] with running mean averages in 20-Myr windows of the data from the Siberian Platform only; 3 = from McElhinny [27, table 20], conventional Fisher averages; 4 = Tarling [42, table 9.3], conventional Fisher averages.

* Calculated without running mean average, for the time of the peak of the polar wander path cusp (see also the discussion of North American paleopoles).

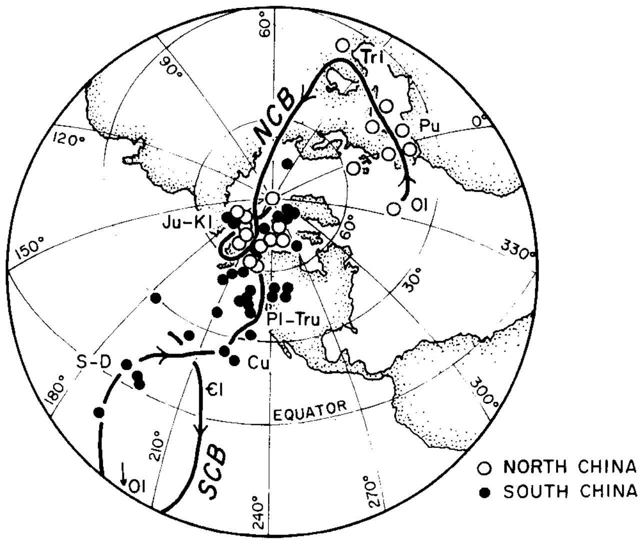

Fig. 5. Individual paleomagnetic north poles from South and North China, as well as best estimates of their paths of apparent polar wander. From Van der Voo [46].

lesser problem, which is undiminished by estimating poles for more seamounts, is that seamount poles must have a small poorly known bias or systematic error due to an induced magnetization or to a mainly Brunhes-age overprint. In a laboratory-based paleomagnetic study the former would be eliminated by making measurements in magnetic field-free space whereas the latter would be removed by alternating-field cleaning, thermal cleaning, or both. A final limitation to seamount poles is that it is unlikely that many, if any, useful poles can be obtained for time intervals when the geomagnetic field was reversing frequently because a seamount is unlikely to form entirely during a single short polarity interval. Consequently, few useful seamount poles have been obtained for the past 75 Ma when the interval between reversals was short, although many useful seamount poles have been obtained for mid- to Late Cretaceous time when the interval between reversals was long [see, Ogg, this volume].

Drill-core data also provide much useful information (see, for example, the review of deep sea drilling results by Cox and Gordon [6] and the many paleomagnetic results presented by Hammond et al. [18] and Epp et al. [7]). The most useful data are from igneous rocks recovered by deep-sea drilling and for sedimentary rocks recovered by piston cores. Paleomagnetic inclinations from sedimentary rocks recovered by deep-sea drilling are shallowly biased and are not of much use for the determination of accurate poles [16, 41]. The main weaknesses of unbiased drill core data are that the data are sparse and that the cores are azimuthally unoriented and therefore inclinations but not declinations are obtained. Results from widely separated sites can be combined to obtain unique pole positions, but the resulting poles are always much more narrowly

Table 5. Mean Paleopoles for the North and South China Blocks

Age Interval	South China Block				North China Block			
	Pole	N	K	A_{95}	Pole	N	K	A_{95}
Ku (67–97)	84, 213	2			80, 170	1		
Kl (98–144)	76, 201	2			77, 213	2		
Ju, uJm (145–176)					71, 224	7	102	6
Tru, uTrm (216–232)	45, 224	1						
Trl/m, Trl (233–245)	46, 215	8	26	11	42, 26	2		
Pu (246–266)	47, 232	12	30	8	46, 3	5	73	9
Cu/Pl, Cu (282–308)	22, 225	1						
Dm, Dl (379–397)	-9, 190	1						
Su, Sm (415–429)	5, 195	1						
Ol/m, Ol (468–505)	-39, 236	1			43, 333	1		
€l (543–575)	37, 206	4	4	53				

Mean north paleopoles for North and South China continents are given in their own reference frames [46]. The mean paleopoles were determined from individual poles that are listed in Van der Voo [46] and meet 3 or more of 7 criteria. Abbreviations and conventions are as in Table 1.

bounded in latitude than in longitude. Equatorial sediment facies have also provided useful information [45, 40, 12].

The fourth source of information comes from the shapes and amplitudes of marine magnetic anomalies. Pioneering studies of Larson and Chase [22] and of Cande [5, 37] provided useful constraints on Pacific APW. Cande's work, however, also showed a limitation caused by a systematic difference between the anomaly shape observed and that expected from simple crustal magnetization models that assume vertical boundaries between crust magnetized in opposite directions. This difference is referred to as anomalous skewness and has been observed in many studies. If no correction is made for anomalous skewness, the apparent effective inclination of the remanent magnetization of the seafloor is systematically in error. Recently, Petronotis et al. [31] have developed a method for estimating paleomagnetic poles with compact confidence limits from analysis of the shapes of Pacific plate anomalies despite the complication of anomalous skewness. Insofar as this approach proves successful, the skewness approach has many attractions: (1) There are typically one hundred or more magnetic profiles that cross each Tertiary and Late Cretaceous anomaly on the Pacific plate. (2) The available sites are widely distributed; on the Pacific plate, for example, some crossings of Tertiary and Late Cretaceous anomalies are separated by distances exceeding 10,000 km. (3) The age of the anomalies is (by definition) exactly correlated with the reversal time scale and in a useful and important sense the age of magnetization is exactly known. (4) Insofar as induced magnetizations, viscous magnetizations, and overprinted remanent magnetizations are widespread and well approximated by an infinite sheet, they produce no measurable influence on the observed magnetic anomalies or the inferred direction of magnetization.

Pioneering studies of seamount magnetism and of anomaly skewness showed that the Pacific plate has moved northward by 30°–35° since middle Early Cretaceous time (~125 Ma; Figure 6) [e.g., 44, 9, 22]. Additional studies showed that nearly all the northward motion has occurred since 80–85 Ma (Figure 6) with mid- and Early Cretaceous APW moving along a nearly constant line of latitude corresponding to a clockwise rotation of the Pacific plate with indeterminate east-west motion [11, 14]. Later work indicates that the Pacific plate mainly rotated clockwise from about late Middle Jurassic time (~155 Ma) to about mid-Cretaceous time possibly superposed on modest southward motion during Late Jurassic and part of Early Cretaceous time (Figure

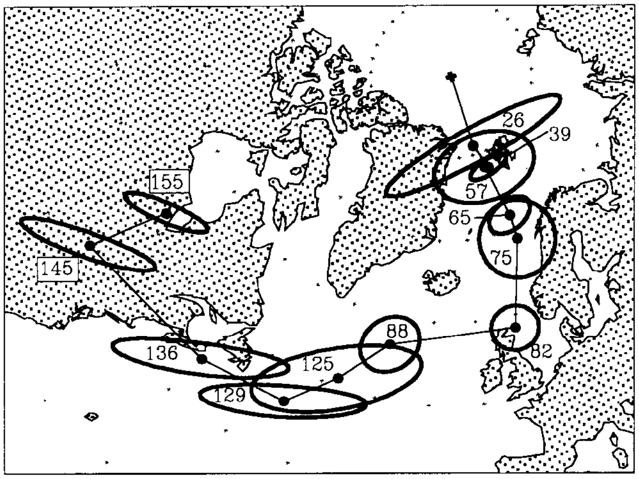

Fig. 6. Observed paleomagnetic north poles for the Pacific plate. Solid squares and surrounding open ellipses are the Pacific plate paleomagnetic poles and 95% confidence limits (Table 6). Stereographic projection.

Table 6. Pacific Plate Apparent Polar Wander Path

Age (Ma)	Pole	Major Semi-Axis	Minor Semi-Axis	Az	Ref
26	81.1, 2.4	12.3	2.1	80	1
39	78.0, 7.1	4.5	1.6	80	2
57	78.2, 4.8	6.4	4.1	93	3
65	71.6, 7.9	2.9	1.8	75	4
75	68.6, 7.2	4.7	4.7	--	5
82	58.4, 359.0	2.9	2.7	91	6
88	56.6, 330.7	3.8	3.1	41	6
125	50.9, 322.6	10.0	3.6	60	7
129	46.0, 315.6	9.4	1.8	67	8
136	44.9, 300.8	9.9	1.8	57	8
145	42.7, 276.5	7.6	1.3	45	8
155	51.9, 277.4	5.1	1.1	49	8

Mean north paleopoles for the Pacific plate. Ages are given in millions of years before present (Ma). Each 95% confidence limit is an ellipse, which is specified by the length in great circle degrees of the major semi-axis and of the minor semi-axis, and by the azimuth ("Az") in degrees clockwise from north of the major semi-axis. Sources and references ("Ref") are as follows: (1) Acton and Gordon [3], (2) Calculated by Acton and Gordon [3] from the data of Sager [35], (3) Petronotis et al. [32], (4) Acton and Gordon [1], (5) Calculated from three poles (dated as being from chron 33n) from the data of Sager and Pringle [36], (6) Sager and Pringle [36], (7) Petronotis et al. [31], and (8) Larson and Sager [23] (using their calculations with non-zero, adjustable anomalous skewness).

6) [23, 24].

Work building on the results of Cande [5] showed that much (~15°) of the post-mid-Cretaceous northward motion occurred between 80–85 Ma and ~65 Ma [13, 33], whereas paleomagnetic results from piston cores [18, 7] showed substantial (~10°) northward motion during the past 25–30 millions years. These results indicate that little APW occurred between ~65 and 25 Ma and later results, especially those of Sager [34], have started to fill in the details. Recently, Petronotis et al. [32] have determined a 57 Ma pole (Figure 6, Table 6) that indicates rapid APW continued after 65 Ma until 57 Ma, but that only insignificant APW occurred between 57 and 39 Ma. An important application of Pacific APW is to test the plate motion circuit used to estimate the motion of the Pacific plate relative to the continents [2].

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