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MINIMUM CONTINENTAL VELOCITIES WITH RESPECT TO THE POLE SINCE THE ARCHEAN

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ABSTRACT

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Paleomagnetic apparent polar wander paths provide a method for estimating minimum plate velocities which can be extended much further into the geologic past than can be estimated based on sea-floor magnetic anomalies. Minimum velocities can be determined from the rate of change of latitude as derived relative to a fixed pole. Such latitudinal velocities have been determined for the center of mass of the North American, Baltic, Siberian and African shields since the Archean. The results indicate that plate velocities in the past have at times easily exceeded those for present-day continents, and that they often were equivalent to present-day oceanic velocities, although there are peaks and troughs through time. North American velocities are significantly greater prior to one billion years ago than those of Siberia or Baltica.

INTRODUCTION

In order to place constraints on kinematic plate parameters, such as viscosity of the upper mantle, estimates of plate velocities are valuable. Relative velocities have been resolved by dating oceanic magnetic anomaly patterns (Larson and Pitman, 1972). This method fails, however, prior to 180 m.y. because no older anomalies have been observed.

Paleomagnetism offers an alternative estimate of minimum velocities since the Archean. By measuring the remanent magnetizations in rocks it is possible, with certain assumptions, to determine the positions of the magnetic poles relative to a continental block through geologic time by determining the declination and inclination of the earth's magnetic field. The time sequence of paleomagnetic poles yields the apparent polar wander path (APWP). Assuming the magnetic pole to be fixed, this path can be translated into the corresponding motion of a site on the continental plate.

Since the first apparent polar wander paths were constructed in the late

1950's, new techniques in dating and demagnetizing the rock samples have vastly refined the paths. Moreover, data are considered reliable today only if based on sufficient samples and if they satisfy rigorous tests to determine the nature (stability and time of origin) of the magnetizations.

The apparent polar wander paths for the Phanerozoic of North America and Africa are fairly well defined; those for Baltica and Siberia are slightly less so. The Precambrian paths for all continents are relatively poorly defined.

The relative velocities determined from magnetic anomalies consist of two components: longitudinal and latitudinal. Due to the axially symmetric nature of the dipole field, paleomagnetic data can only yield the latitudinal component of the velocity vector. Yet this produces a minimum constraint for velocity through geologic time.

The latitudinal method and a minimum motion rigid body rotation method were used by Gordon et al. (1979) to estimate the minimum rms velocities of North America, Gondwanaland and Eurasia since the Devonian. In this paper, we extend the use of the latitudinal method to the Archean for an estimation of minimum velocities using the apparent polar wander paths for North America, Africa, Baltica and Siberia for the center of mass of each plate. We will discuss the minimum velocities and show that velocities of the continents since the Archean have at times easily exceeded those for continents at present, and often equaled the relatively high velocities of the present oceanic plates.

METHODOLOGY

For a selected reference site S_1 of present latitude λ_1, and longitude θ_1, and a specified pole (λ_2, θ_2), we can describe the position of the site in a paleocoordinate system as defined by the position of the pole. Thus the paleolatitude λ, is defined by the following equation which results from spherical trigonometry:

$$\lambda = \sin^{-1}[\sin \lambda_1 \sin \lambda_2 + \cos \lambda_1 \cos \lambda_2 \cos(\theta_2 - \theta_1)]$$

and the colatitude p is determined from the following relation:

$$\cos p = \sin \lambda$$

We recall that the paleolongitude cannot be constrained by paleomagnetism, so that the paleosite is best restricted to move along a meridian.

If we have two consecutive paleopoles P_1 and P_2, we can compute the corresponding latitudes λ' and λ''. These are unique values for any given pole and site S_1. Thus, since we have assumed the pole to be fixed, the motion bringing P_2 into coincidence with P_1 results in the corresponding motion of site S_1 along a meridian over a fixed distance equal to the difference between λ' and λ''. The rate of change of latitude yields a minimum estimate of the velocity of that site.

Gordon et al. (1979) point out that the magnitude and direction of the latitudinal component of the velocity vector depend on the location of the site with respect to the absolute angular velocity vector. This results in differing tangential components of this vector throughout the plate. They developed a new method to determine a greater minimum rms velocity by finding the angular velocity vector which produced the minimum rms velocity subject to the constraints of the apparent polar wander path and the requirement that the velocity field be consistent with a rigid body rotation. This method produces an estimate of minimum velocities which ranges from less than a few percent to more than 20% greater than the latitudinal method.

We have, instead, computed the minimum velocities for the center of mass of each plate. This eliminates the problem of the varying velocities for each site in a plate and the computational problems inherent in performing an integration over the plate for each pair of poles in order to compute each velocity, while at the same time the geometry of the continental outlines may changes as successive orogenic belts and displaced terranes are welded onto the continental nuclei. The center of gravity was determined from the cratonic parts of the continents during the Cambrian, assuming a thin plate of homogeneous density. This was assumed to be representative of the center of gravity throughout Precambrian and younger time. The coordinates of these centers are 54.9°N, 94.3°W for North America, 10.2°N, 23.0°E for Africa, 56.3°N, 33.7°E for Baltica and 63.3°N, 89.8°E for Siberia.

It is clear that the minimum velocities of the continental centers of gravity so obtained are not necessarily the truly lowest velocities for that continent, since in certain cases points can be found on a rigid continental surface that move slower than its center of gravity. The method of Gordon et al. (1979) takes this fact into account. However, for ease of computation and conception and because the geometrical shapes of the continents change with time, we prefer the calculation of the minimum velocities for a fixed point (the center of gravity). For this point, we note that the velocities calculated with our method are indeed the minimum velocities.

APPARENT POLAR WANDER PATHS

Sets of north pole positions defining the APWP's used in this study are given in Tables I—IV for North America, Gondwana, Baltica and Siberia. Other continents were not considered because of their poorly defined APWP's, insufficient data length, or poor dating.

The APWP for North America is predominantly from Irving (1979), with a few exceptions. Two alternate paths with respect to the Hadrynian Loop (Morris and Roy, 1977) are utilized to connect the poles for the period between 600 and 1000 m.y. ago. The shorter Grenville Loop was calibrated by Berger et al. (1979). It is preferred because it yields more reasonable lower velocities of about 5 cm/yr rather than the 20 cm/yr necessary if the path of Morris and Roy (1977) or Irving (1979) is used. In choosing the shorter path, we have, of course, reversed the polarity of Irving's poles prior

TABLE I

Northpoles for North America

Age	(m.y.)	Pole	Source	Age	(m.y.)	Pole	Source
M	20	87, 167	I	Cu	290	40, 122	I
O/M	25	87, 162	I	Cu	300	39, 126	I
O	30	86, 166	I	Dl	350	47, 120	I
E	40	83, 164	I	Su	400	32, 102	F
E	50	81, 177	I	Ou	450	34, 120	I
Pa	60	77, 187	I	Ꞓu	500	06, 158	VFW
Ku	70	72, 190	I	Ꞓl	570	07, 159	E&B
Ku	75	72, 194	I	EoꞒ	600	25, 155	I
Ku	80	69, 193	I		820	21, 171	BYD
Ku	90	67, 187	I		910	−12, 163	BYD
K	100	69, 188	I		980	−36, 143	BYD
Kl	110	68, 185	I		1050	−15, 188	I
Kl	120	64, 191	I		1100	00, 185	I
Kl	125	68, 179	I		1150	40, 185	I
Kl	130	67, 170	I		1200	35, 230	I
K/Ju	140	70, 161	I		1250	05, 185	I
Ju	150	74, 134	I		1300	10, 205	I
Ju	160	76, 135	I		1350	−15, 190	I
Jm	170	78, 122	I		1400	−20, 220	I
Jm	175	78, 110	I		1450	00, 210	I
Jl	180	73, 103	I		1650	−48, 085	I
Jl	190	72, 095	I		1700	−10, 110	I
Tru	200	68, 093	I		1750	22, 167	I
Tru	210	61, 100	I		1800	30, 115	I
Trm	220	56, 100	I		1850	−05, 095	I
Trl	225	56, 102	I		1900	−15, 093	I
Tr/P	230	55, 104	I		2000	−25, 080	I
Pu	240	54, 107	I		2100	−40, 060	I
Pu	250	43, 123	I		2200	−70, 050	I
Pl	260	42, 124	I		2300	−70, 320	I
Pl	270	42, 120	I		2600	−45, 240	I
Pl	275	43, 121	I		2800	15, 205	I
P/C	280	44, 122	I				

The following sources were used: I = Irving (1979); VFW = Van der Voo et al. (1976); E&B = Elston and Bressler (1977); BYD = Berger et al. (1979).

to 1000 m.y. ago. The Phanerozoic path for Africa is from Van der Voo and French (1974) and French (1976). The Precambrian paths are those of McElhinny and Embleton (1976) and Piper (1976). The APWP for Baltica was compiled from McElhinny (1973), Van der Voo and French (1974), French (1976), and the Precambrian path of Poorter (1975). The Siberian APWP is from McElhinny (1973) and French (1976). In all cases, the APWP has been constructed so as to minimize its length.

The differences in quality and data length should be noted when judging the results of this study. North America's APWP is the most refined with 66

TABLE II

North poles for Africa

Age	(m.y.)	Pole	Source	Age	(m.y.)	Pole	Source
E/Pa	55	75, 212	V&F		743	72, 068	P
Ku	80	62, 231	V&F		813	29, 113	M&E
Kl	120	54, 253	V&F		878	−20, 114	M&E
Ju	150	42, 242	V&F		990	−40, 137	P
Jl	185	62, 263	V&F		1020	−53, 156	P
Tru	205	66, 236	V&F		1115	−62, 195	P
Trl	230	48, 237	V&F		1140	−66, 220	P
Pu	240	36, 235	V&F		1210	−06, 168	P
Pl	265	26, 235	V&F		1310	−08, 223	P
Cu	300	35, 238	F		1750	−51, 218	P
Cl	330	38, 202	F		1880	−07, 160	P
Du	350	11, 199	F		1950	−23, 216	P
Dl	380	−16, 206	F		2070	−03, 255	P
Ol/m	480	−47, 203	F		2200	54, 243	P
Ꞓu	510	−48, 242	F		2250	42, 194	P
Ꞓm	530	−79, 179	F		2300	71, 173	P
Ꞓl	560	−30, 129	F		2340	35, 104	P
PꞒ/Ꞓl	610	−26, 139	M&E		2520	22, 062	P
	650	05, 186	M&E		2630	−33, 041	P
	700	85, 228	M&E				

The following sources were used: V&F = Van der Voo and French (1974), F = French (1976), M&E = McElhinny and Embleton (1976), P = Piper (1976).

TABLE III

Northpoles for Baltica

Age	(m.y.)	Pole	Source	Age	(m.y.)	Pole	Source
M/Pl	10	83, 177	M	Ou	445	14, 180	M
M	20	77, 153	M	Ol	475	36, 142	M
O/E	30	75, 151	M	Ꞓm	525	08, 189	F
Ku	80	72, 200	V&F	Ꞓl	570	63, 142	P*
Kl	125	73, 222	V&F		700	02, 240	P*
Tru	200	68, 137	V&F		850	−27, 236	P*
Trm	215	46, 155	M		935	−34, 208	P*
Trl	225	44, 151	M		950	−36, 227	P*
Pl	250	44, 160	M		1120	−03, 207	P*
Pl	270	46, 162	M		1330	02, 158	P*
Cu	290	37, 168	M		1400	07, 164	P*
Cl	315	30, 163	F		1569	23, 176	P*
Dm	370	30, 161	F		1650	31, 174	P*
Dl	390	19, 160	M		2000	45, 228	P*
S	410	06, 134	F				

The following sources were used: M = McElhinny (1973); V&F = Van der Voo and French (1974); F = French (1976); P* = Poorter (1975).

TABLE IV

Northpoles for Siberia

Age	(m.y.)	Pole	Source	Age	(m.y.)	Pole	Source
M	10	64, 245	M	Ol	470	−34, 132	F
M	20	68, 223	M	Єu	510	−37, 125	F
O/E	35	57, 152	M	Єm	530	−43, 157	F
Ku	80	71, 175	M	Єl	560	−36, 179	F
Kl	120	64, 177	M	PЄ/Є	590	−24, 176	M
Trl/m	210	47, 146	M	PЄu	620	−22, 141	M
Trl	225	45, 151	M		750	−40, 118	M
P	250	33, 147	M		835	−37, 077	M
Cm/u	300	47, 125	M		925	−17, 089	M
Cl	330	43, 139	F		950	10, 142	M
Du	350	36, 141	F		1075	25, 115	M
Dl	380	15, 106	F		1270	20, 103	M
Sl	430	−08, 103	F		1500	25, 026	M
Om/u	450	−22, 130	F				

The following sources were used: M = McElhinny (1973); F = French (1976).

points, which begin at 2.6 b.y. ago. Africa's path comprises 39 points and begins at 2.6 b.y. ago. Baltica's path is less certain with 29 points extending to 2.0 b.y. Siberia has the poorest path with 27 points extending only to 1.5 b.y. Our method treats the data sets as if they were of equal quality.

Other restrictions are imposed by the velocity uncertainties which arise from the errors in the location of the pole (α_{95} or A_{95}) and errors in dating or calibrating the APWP. The errors resulting from the uncertainties in the location of one pole can be computed from the α_{95}:

$$d\lambda = \alpha_{95}(1 + \sin^2\lambda)/2$$

where $d\lambda$ is the error in the latitude and:

$$dm = \alpha_{95}(\cos\lambda/\cos I)$$

where dm is the error in the paleoazimuth and I is the mean inclination. The errors in latitude resulting from the mean poles are given by the A_{95}, so that $dp = A_{95}$.

Errors in the apparent polar wander paths for the Phanerozoic rarely exceed 10° of arc length, while the Precambrian paths generally have errors between 10° and 15°. The corresponding uncertainties in the velocities are on the order of 1—2 cm/yr, when intervals of 50 m.y. are considered. For shorter intervals the calculational uncertainties are correspondingly larger, but since for the Phanerozoic the APWP's are often sufficiently well defined to enable us to use an unsmoothed APWP (as given in Tables I—IV and explained below) and then calculate the cumulative velocity per 50 m.y., the errors per 50 m.y. would be larger only in the measure by which the unsmoothed path deviates from a great circle.

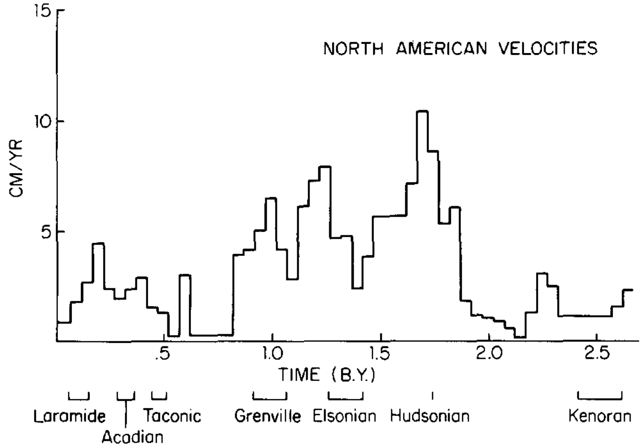

Fig. 1. Latitudinal plate velocities for North America's center of mass (54.9°N, 94.3°W). Major orogenies and events are indicated. Note that the peak at 200 m.y. correlates with the Nevadan-Sonoma orogenies. All velocities are given with respect to the pole.

The uncertainties introduced by dating error are more difficult to determine because the poles often have errors in the estimation of their ages of 50 m.y. or more. Those rocks which are radiometrically dated can have errors of up to ±200 m.y. in the Precambrian, although Phanerozoic radiometric dates are usually considered to be fairly accurate. The effect of dating errors on our results can easily be seen from the velocity versus time graphs (Figs. 1—4). For example, if the graph had the following sequence: low velocity, high velocity, low velocity, and the estimate of the age of one of

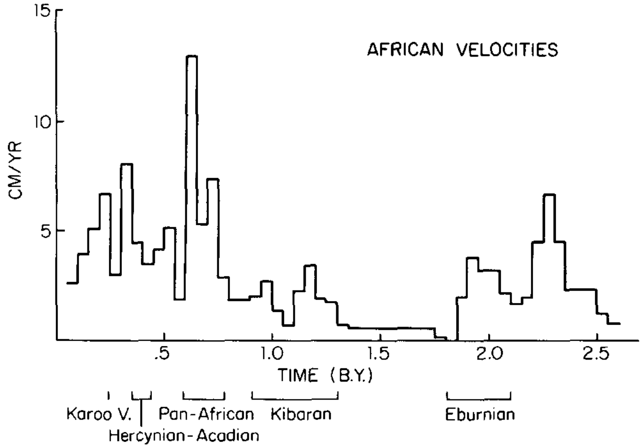

Fig. 2. Latitudinal plate velocities for Africa's center of mass (10.2°N, 23.0°E). The peak at 620 m.y. correlates with the Katangan orogeny, incorporated in the Pan-African.

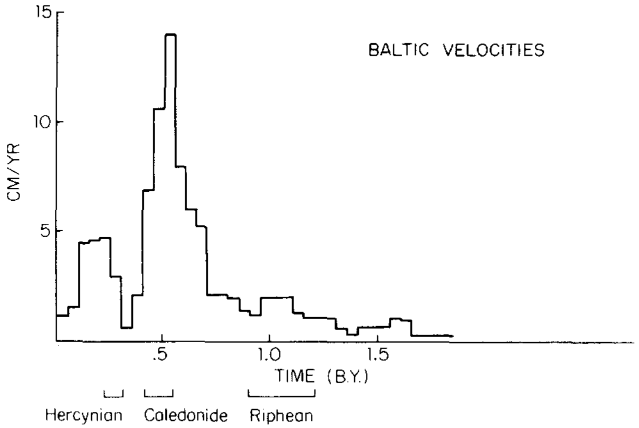

Fig. 3. Baltica's latitudinal plate velocities (For 56.3°N, 33.7°E).

the poles was too young, then the peak would either be higher, or the sequence would be more smoothed. In other words, errors in age (when considered alone and independently from pole position errors) may change the individual velocity values for successive intervals of 50 m.y., but the area under the curve (Figs. 1—4) would not change at all.

Even though the errors for any particular velocity estimate are sometimes very high (greater than a few cm/yr), there is little point in putting error bars on our data because of the interdependent nature of the dating and pole position uncertainties; we must resign ourselves to the fact that this is the best estimate we have until better dating techniques and more refined APWP's

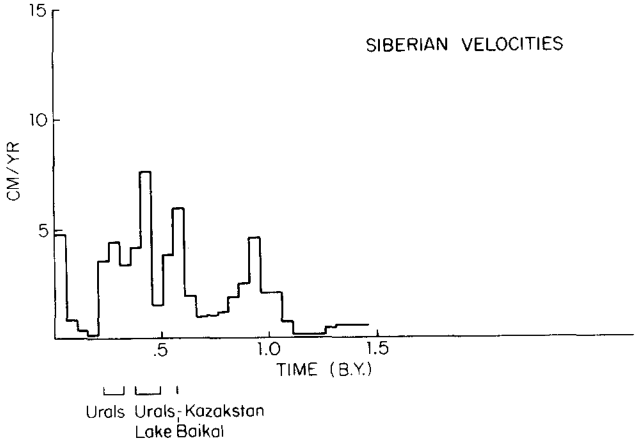

Fig. 4. Siberia's latitudinal plate velocities (For 63.3°N, 89.8°E). Two phases of formation of the Urals correspond to peaks. Also, in the lower Paleozoic events occurred in Kazakhstan and near Lake Baikal.

are developed. We feel that the generally observed *trends* in the velocities will not be significantly altered in the future.

RESULTS

We have computed the minimum velocities for the centers of mass for North America, Africa, Baltica, and Siberia. In order to determine trends through time we have performed linear regressions on the data. The minimum velocity estimates for the four continents since the Archean are given in Figs. 1—4. The raw data were unevenly spaced so a 50 m.y. average was applied along the APWP. Unsmoothed APWP's as defined by the tables, were used and the signs of the changes in paleolatitude were taken into account, before averaging the velocities for 50 m.y. intervals. From Figs. 1—4, a number of conclusions can be drawn. Velocities with respect to the pole have fluctuated rather rapidly throughout geologic time since the Archean. The periods of rapid motion are interrupted by apparently static periods in the Precambrian as well as the Phanerozoic. The minimum velocities of the four continents that we analyzed have at times been significantly higher in the past, often reaching peaks of 6 cm/yr or more, whereas recent *total* velocities for continents rarely exceed 3 cm/yr. In fact, minimum velocities in the past have often been equal to estimates of absolute velocities for present-day oceanic plates. There have also been periods of very low velocity throughout time.

From the figures it is easy to draw the conclusion that each continent has its own velocity signature. North America has highest latitudinal velocities in the middle and late Proterozoic, while Baltica has prominent velocities in latest Precambrian and the lower Paleozoic. Africa has numerous peaks, but the most prominent are in the late Precambrian to lower Paleozoic and a smaller peak in the early Proterozoic. There is a significant apparent low between 1.4 and 2.0 b.y. ago. The velocity signature of Siberia also indicates high velocities in the late Precambrian and early Paleozoic, and has very low apparent velocities from 1.1 to 1.5 b.y., not unlike Baltica. Some segments of the APWP's require velocities which easily exceed 10 cm/yr. Some of these high narrow peaks are probably not real, but are likely due to errors inherent in the data. Since our analysis yields minimum velocities, however, it is possible that continental velocities have, at times, been very high (greater than 6 cm/yr). Rapid jumps in (relative) velocities have been indicated by marine geophysical studies for the Mesozoic and Cenozoic; the work by Gordon et al. (1979) suggests that they may also have occurred in the more remote past, so that shifts from 1 cm/yr to 5 cm/yr over a period 20—50 m.y. could have been common. Our analysis lacks detail on such a time scale, and yields only the longer-term trends of plate velocity. The mean minimum velocity for all the continents is about 2.8 cm/yr.

Linear regression of the center of mass velocities has been performed, but as can be seen at a glance in the Figs. 1—4, this is not a very meaningful exercise. If anything, an increase in minimum velocity with respect to the pole towards the present-day is suggested but it is not statistically significant. The slope for North America is negative but almost negligible, while the negative slopes of the other shields are more prominent. Again, it is essential when interpreting the data to recall the varying quality of the data and the data lengths. The two shields with the highest (negative) slopes have data of poorer quality and shorter data length than Africa or North America. It is quite possible that both Baltica and Siberia had higher velocities in the early Proterozoic which would significantly alter the slope; at present the only conclusion that can be inferred is that the velocity versus time graphs have insignificant negative slopes of roughly —0.001 cm/yr/m.y.

DISCUSSION

Despite uncertainties in the data we can produce respectable estimates of minimum plate velocities since the Archean, and therefore, we can place severe restrictions on plate parameters since that time.

High velocities and rotation rates in the past may reflect changes in the thermal regime of the upper mantle and asthenosphere, or they may be the result of the thinner lithosphere and smaller (?) plate dimensions in the past. It is interesting, then, to note that there is good correlation between the peaks in minimum velocity and orogenic events. This is best exemplified by the three major peaks in the North American velocity diagram. They occur during the Hudsonian, Elsonian, and Grenville times. Only the Kenoran orogeny does not correlate to a peak, but the results in this interval are based on only two poles and there are peaks on either side. The Appalachian orogeny corresponds to a smaller peak.

The Baltic Shield's high velocity peaks correspond to the Caledonian and Riphean (Grenville) orogenies. The Karelide orogeny does not correspond to a peak, but the velocity for that time is derived from only one pole which spans 350 m.y. For Africa, the peaks corresponding to the Eburnian and Kibaran orogenies are small, but they stand out against the almost negligible velocities on either side. Peaks also correspond to the Pan-African and Hercynian-Acadian. The two phases of formation of the Urals, the events in Kazakhstan and Lake Baikal correlate with the peaks on the Siberian latitudinal velocity diagram. All of the continents show that orogenies correspond to high latitudinal velocities, indicating a possible relationship to thermal events.

Gordon et al. (1979) hypothesized that continental plates move rapidly when a large fraction of their boundary is attached to subducting slabs. Since there is more subduction going on at these times, and since we have high heat flow resulting from frictional heating of the upper surface of the downgoing slab (which is a function of the shear stress and plate velocity), partial melting and mass transfer occurs, so that we find an increase in plutonism and metamorphism. Therefore, we expect to find a positive correlation between high velocities and orogenies.

CONCLUSIONS

We have seen that the minimum velocities of the continents since the Archean have at times been much higher than the velocities of the continents today, and have also been equivalent to the relatively rapid velocities of the present oceanic plates, although there are peaks and troughs in time. Velocities may have fluctuated over relatively short intervals (10—50 m.y.), but our analysis lacks the detail to give other than long-term trends. On that scale, periods of rapid motion are separated by apparently static periods. The trend of the latitudinal velocities is toward marginally higher velocities toward the present. Orogenies seem to occur at periods of peak velocity. Because we see the same type of velocity signature (peaks and troughs) in the Proterozoic as we see in the Phanerozoic (as derived relative to a fixed pole), we infer that the same mechanisms for plate motions active in the Phanerozoic have been operative at least since the middle Proterozoic.

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