The role of latitude in mobilism debates

Edward Irving*

Pacific Geoscience Centre, North Saanich, BC, Canada V8L 4B2

This contribution is part of the special series of Inaugural Articles by members of the National Academy of Sciences elected on April 28, 1998.

Contributed by Edward Irving, November 2, 2004

In the early 1920s, the continental displacement theory of Wegener, latitude studies of Köppen and Wegener, and Argand's ideas on mountain building led to the first mobilistic paleogeography. In the 1930s and 1940s, many factors caused its general abandonment. Mobilism was revived in the 1950s and 1960s by measurements of long-term displacement of crustal blocks relative to each other (tectonic displacement) and to Earth's geographic pole (latitudinal displacement). Also, short-term or current displacements can now be measured. I briefly outline the categories of tectonic and current displacement and focus on latitudinal displacement. Integration of tectonic and latitudinal displacement in the early 1970s completed the new mobilistic paleogeography, in which the transformation of rock magnetization directions into paleopoles and latitudes and the finite rotation of spherical plates about pivot points play complementary roles; this new synthesis now provides a quantitative basis for studying long-term evolution of Earth's surface features and climate, the changing environments in which life evolves.

paleogeography | paleomagnetism | plate tectonics | Pangea | magnolias

> Ideas do not spring full-blown from a single brain. There has to be wandering along bypaths, mid-night readings, and sustained effort.
> L. Eiseley (1)

When Darwin's *On the Origin of Species* (2) was published (1859) little was known about how life responded to movements of continents and climate changes. Darwin was interested in these questions; in his notes (3) he reminded himself to "speculate on land being grouped towards centres near equator in former periods and then splitting off." In 1600 Gilbert (4) proposed a link between the inclination of the geomagnetic field and latitude, which, in a modern formulation, we now use to determine ancient latitude and thus to examine the distinction that Darwin made between the latitude change of landmasses and their relative (tectonic) motion.

In the 20th century there were two opposing schools of thought, "fixist" and "mobilist" (5). Until the late 1960s, the dominant belief was a form of fixism (permanentism), which held that, although shallow seas may have sometimes flooded lowlands, continents and deep oceans remained where they are, and latitudes did not change. By mobilism, I mean large, lateral motions of segments (or blocks) of Earth's crust relative to each other and to the rotation axis. Mobilism is an overarching concept, embracing continental drift, long-term latitude-related climate change, seafloor spreading, and plate tectonics. Support for mobilism in any form was rare until the late 1950s, uncommon until the mid-1960s, and almost unanimous by the later 1970s (Fig. 1*d*). Fixism did not collapse because it was poorly argued; at the time it was regarded by most workers as persuasive, but its supporters could not have imagined the discoveries that brought about its demise.

The timescales of crustal motions range from minutes during earthquakes to >10 million years (Myr) during continental drift and seafloor spreading. Motions fall into three categories: long-term motions of crustal blocks relative to each other [tectonic motions (T)] and to the geographic pole [latitudinal motions (L)] and current motions (C) of either sort (Fig. 1). Much of our present understanding depends on agreement among measurements of motion in these three categories. There are already many accounts of the development of tectonics (e.g., ref. 20 and references therein) and a few of the early failure of geodetic measurements to detect current motions (34, 35), although not of their remarkable success in recent decades. Here I briefly summarize the major innovations of categories T and C. To explain how the general paleogeographic frame (category L) came to be established is my main purpose.

Advent of Mobilism

Mobilism, in a globally and physically testable form, was introduced between 1912 and 1924 in four main installments. In his 1912 papers (6, 7) and the first edition (1915) of his *Origin of Continents and Oceans* (8), Wegener gave "a genetic interpretation of the principal features of the Earth's surface" (T1 in Fig. 1*a*). He imagined continents floating on a denser substrate, through which they ploughed, impelled by tidal and rotational forces. He placed his mechanism at the center of his theory, which was dangerous, because little was then known about Earth's interior. Wegener was an atmospheric physicist who pioneered high-altitude observations (see note by K. Wegener in ref. 10) and seems to have carried the ethos of his main research deep into Earth, where behavior cannot be directly observed and problems need to be tackled differently.

In his third edition (9), Wegener assembled continents into Pangea (T2 in Fig. 1*a* and identified hereafter as Pangea A1). He closed the Atlantic, Antarctic, and Indian Oceans and placed Africa immediately south of Europe and South America south of North America (Fig. 2*a*). His grid was arbitrary (with Africa fixed). He drew no paleogeographical latitudes.

In the third installment, Köppen and Wegener (24) used the distribution of climate-sensitive deposits to construct latitudes (L1 in Fig. 1*b*). This, the first mobilist paleogeographic synthesis, comprised a dozen maps (three are given in Fig. 2) from the Devonian to the present. Pangea A1 was situated mainly in the southern hemisphere from the Devonian through Jurassic periods [350–150 Myr ago (Ma)]. It broke up in the Cretaceous (100 Ma), and the fragments drifted northward.

In the fourth installment, Argand (5) proposed that the Cenozoic (<65 Ma) Alpine–Himalayan mountains were caused by collisions between northern and southern continents (T3 in Fig. 1*a*). By analogy, he speculated that the Paleozoic (450–300 Ma) Appalachian mountains are the site of a former ocean (his "Proto-Atlantic") whose margins moved first away and then toward each other; preMesozoic drift hides in older mountain belts, a prescient thought soon forgotten.

Beginning in 1912 (6), Wegener examined geodetic measurements of current motions of continents, and his last edition opens with a discussion of them (10). Although to no avail, he thought

---

Abbreviations: GAD, geocentric axial dipole; APW, apparent polar wander; Myr, million years; Ma, Myr ago.

See accompanying Biography on page 1819.

*To whom correspondence should be addressed at: Geological Survey of Canada, P.O. Box 6000, North Saanich, BC, Canada V8L 4B2. E-mail: tirving@pgc-gsc.nrcan.gc.ca.

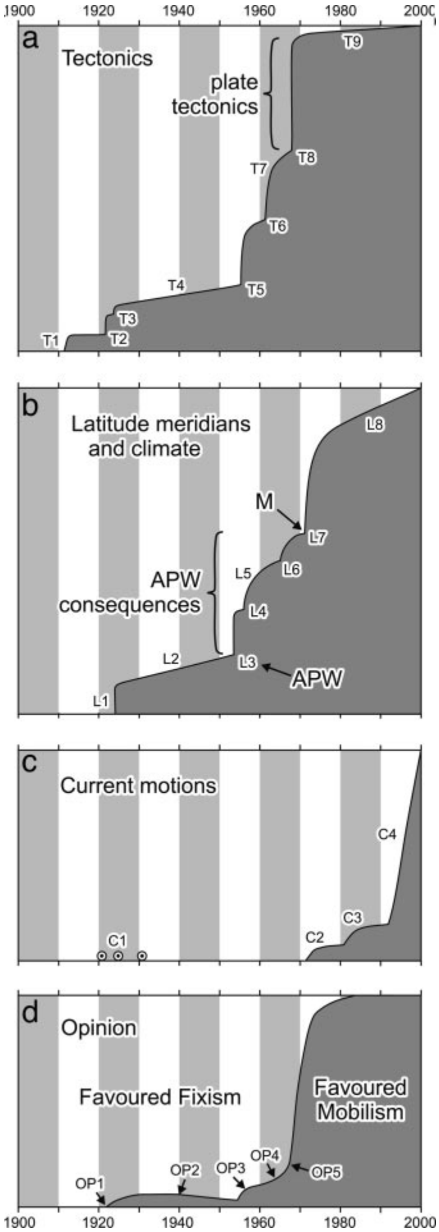

Fig. 1. Three categories of displacements and general opinion are shown. The ordinate shows the subjective measure of increasing understanding, and the upwardly convex segments connect key discoveries and formulations. (*a*) Tectonic displacement. T1, general theory of continental drift introduced in refs. 6 and 7; T2, Pangea A1 and its fragmentation (8–10); T3, mountain-building by continental collision (5); T4, stratigraphic and biogeographic evidence favorable to mobilism accumulates (11); T5, each continent has its own APW path (12–18); T6, seafloor spreading (19); T7, oceanic displacement measurements (compiled in ref. 20); T8, plate tectonics (21–23); and T9, regional plate syntheses. (*b*) Latitudinal displacement. L1, climate indicator proxies for latitude (24); L2, paleoclimatic and biogeographic evidence favorable to mobilism accumulates (11); L3, GAD hypothesis, APW, and latitudes (12–18, 25); L4, regional concordance and global discordance of paleoclimates and paleomagnetic latitudes (17); L5, beginnings of the new paleogeography, applications to paleoclimatology, biogeography, and continental reconstructions (26, 27); L6, very large displacements and rotations in mountain belts (28–31); L7, marriage of APW with plate tectonics (M), beautiful constructs (32, 33); and L8, new paleogeographic synthesis radiates. (*c*) Current displacement. C1, early failures; C2, very long-base interferometry; C3, laser-ranging; and C4, seismic and global positioning system (GPS) campaigns and networks. (*d*) General opinion. OP1, continental drift introduced; OP2, fixism entrenched; OP3, continental paleomagnetism and APW; OP4, oceanic displacements; OP5, plate tectonics.

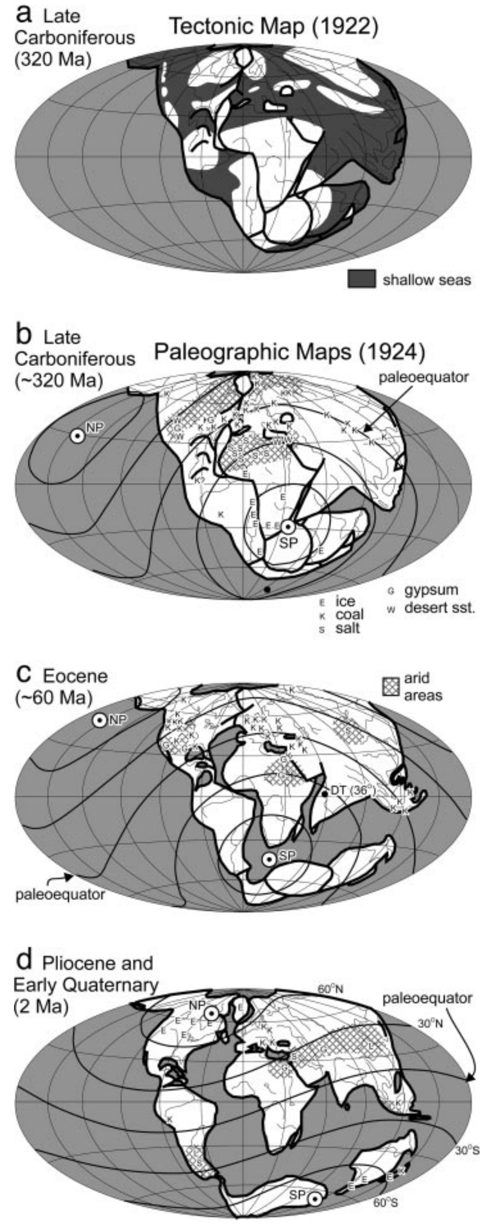

Fig. 2. Tectonic and paleogeographic maps compared. (*a*) Wegener's Pangea A1 with its arbitrary grid (9, 10). (*b*–*d*) Wegener's maps with paleoclimatically determined latitudes superimposed by Köppen and Wegener (24); NP, north geographic pole; SP, south geographic pole; DT, Deccan Traps with paleomagnetically determined latitude (see text); sst., sandstones.

that his theory would eventually gain acceptance through such measurements. It is noteworthy that the first chapter of Darwin's *On the Origin of Species* (2) is titled "Variation under Domestication," evidence vital to his great work. Thus, like Darwin, Wegener believed in the incremental accumulation over long periods of small, currently observable effects, as embodied in Lyell's 19th century doctrine of uniformitarianism.

Rejection of Mobilism

Although ingenious and forward-looking, these early mobilist theories and the paleogeography derived from them did not prosper. Wegener was not a solid Earth scientist, "not an expert, but simply interested in the problem" (W. Jacoby, personal communication) to which he brought wide reading and bold but vulnerable thoughts. For example, Wegener noted that there were European-type earthworms in North America, left there, he thought, as the Atlantic opened; in fact they were brought by Europeans. Jeffreys (36) soon disproved Wegener's mechanism, and so began the relentless citation by all and sundry of the lack of an acceptable mechanism for continental drift, casting a pall over the discussion and eroding mobilism's credibility.

At school (1944), I was taught about continental drift. As a geology undergraduate (circa 1950) I found Wegener's *Origin of Continents and Oceans* imaginative and fun. Jeffreys, however, was a figure of awesome achievement, writing with an air of invincibility. Notwithstanding, as a graduate student (1951–1954), I came to believe that his work on mechanism was unrealistic and that the paramount question was, Could large long-term displacements actually be measured? Others could worry about mechanism; regrettably, they did, and it haunted discussions until the concept was exorcised in the late 1960s by plate tectonics.

In South Africa, South America, and India, drift was commonly accepted. Few Australians and New Zealanders spoke favorably. Europeans generally were unsympathetic. North Americans were solidly against the theory, although they were among the first to give "embryonic expositions of a mobilist position" (34); for example, Taylor (37) argued that the Alpine–Himalayan mountains were produced by movement of continents away from the poles. However, the permanentism of an "intransigent" establishment and the importance falsely attached to the absence of a known mechanism had inoculated North Americans against mobilism, and they responded by discharging in Wegener's direction a fierce polemical barrage. He was, according to Schuchert (quoted in ref. 34), "a stranger to the facts" because he used and reinterpreted the results of others. According to Willis (quoted in ref. 34), his was a theory "run wild." Berry (quoted in ref. 34) called drift "German pseudoscience." More temperate authors condemned him by silence or grudging mention. Fixism permeated the literature, and a generation found difficulty in renouncing its education.

Uncontrolled speculation, of which Wegener was, I believe, unfairly accused, is not helpful. Creativity requires the recognition of a small window of belief that common opinion might be wrong (38). Doubtless, workers of the day believed they were open-minded and that such windows existed, but they themselves rarely opened them, and their negligence, integrated across the community, amounted, by midcentury, to de facto rejection of drift by the majority. Then, in the mid-1950s, much to almost everyone's surprise, an obscure field of geophysics provided evidence of long-term latitudinal displacement of continents, revived the mobilism debate, and inaugurated a new quantitative paleogeography.

New Evidence from Continents: Determining Ancient Latitude, 1950–1963

Under favorable conditions, the remanent magnetization of rocks (paleomagnetism) records the ancient geomagnetic field direction, defined by declination, *D,* and inclination, *I.* Directions are variably dispersed, and in 1951 Fisher (39) devised appropriate statistics. To compare directions from different places, directions were represented by corresponding paleopoles (12–15) (Fig. 3*b*). This deceptively simple idea, combined with Fisher's statistics, quickly became and remains the basis for analyzing the ancient geomagnetic field; together they allowed us to place observations in their correct spherical framework, to summarize them compactly, and to speak about them unambiguously.

In the early 1950s, studies of later Cenozoic (<15 Ma) rocks yielded mean directions of magnetization along the geocentric axial dipole (GAD) field and paleopoles grouped about the present geographical pole from which none differed significantly: the mean of the seven poles in Fig. 3*c* is an insignificant 1° from the geographic pole. Also, lava and sedimentary sequences were found with normal and reversed polarities alternating in stratigraphic sequence (44–47), and a strong case for believing them to record reversals of the geomagnetic field was built (45–47). Thus, in 1953–1954, the central paleomagnetic model was constructed; it held that when short-term (secular) variations are averaged, the geomagnetic field is, to an accuracy of a few degrees, that of a GAD field that occasionally reverses polarity (Fig. 3*a*). In such a field, $D = 0$ everywhere, and $\tan I = 2 \tan \lambda$, with λ being latitude. This model did not come out of the blue; it had been foreshadowed by Gilbert (4) 350 years earlier; the geomagnetic field observed at magnetic observatories over the past few centuries was known to vary roughly about the present GAD field; reversals of polarity had been observed (but not repeatedly in sequence) in several continents (48–51); and theories of origin of the field presupposed a causal relation to Earth's rotation (52–54).

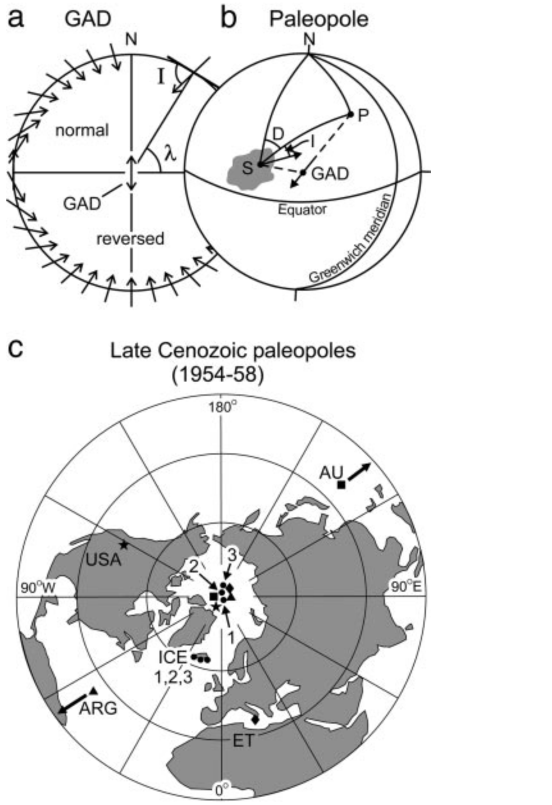

Fig. 3. Geocentric axial dipole field confirmed for later Cenozoic time. (*a*) Time-averaged, occasionally reversing GAD field inclination (I) and latitude (λ). When the field reverses in polarity, the arrows denoting field at the surface also reverse. (*b*) N, the present geographic pole; D, declination of time-averaged field at sampling locality; I, inclination of time-averaged field at sampling locality S. When a continent moves, the field is directed along an oblique axis emergent at paleopole P. The triangle NSP can be solved and P can be determined. D is the total rotation of S relative to the present meridian. The change in latitude is the difference between the distance from S to P and from N to P. (*c*) Key Late Cenozoic paleopoles establishing the GAD hypothesis in the 1950s. Errors ($P = 0.05$) are given in square brackets. (*i*) Iceland lavas (24): ICE 1, ≈10 Ma [10°]; ICE 2, ≈2 Ma [12°]; ICE 3, <5,000 years ago [12°]; (*ii*) Mount Etna lavas (40): ET, 2,400 years ago [7°]; (*iii*) Newer Volcanics, Victoria, Australia (41): AU, <4 Ma [6°]; (*iv*) Neuquen lavas, Argentina (42): ARG, ≈5 Ma [7°]; and (*v*) Columbia River basalts, United States (43): USA, ≈10 Ma [12°]. The mean of these seven poles is latitude 89°N, longitude 118°E, error = 3° ($P = 0.05$), precision $K = 461$ and circular standard deviation (CSD) = 4°.

By early 1954, we in Britain had found that Eocene and older (>50 Ma) rock formations, including weakly magnetized sedimentary rocks, had directions oblique to the present GAD field

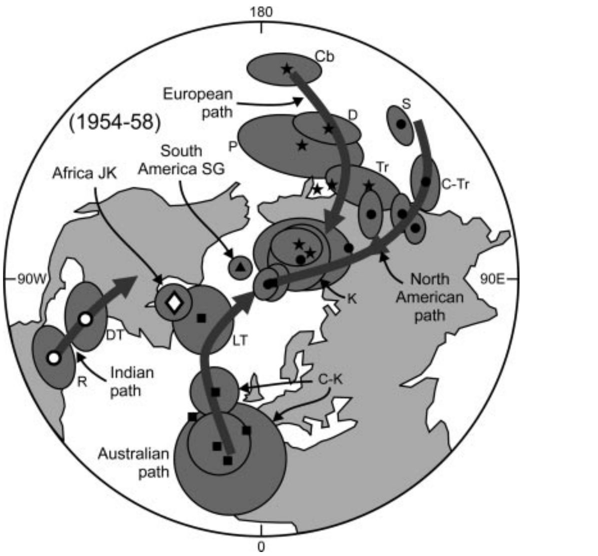

Fig. 4. APW paths in 1958 were mainly Carboniferous and younger. Earlier Paleozoic results from Europe and North America are shown; complex results from Australia are not. Africa: JK, Jurassic Karroo lavas (59, 60). Australia: C–K, Late Carboniferous through Cretaceous; LT, Paleogene (41). Europe: Cb, Cambrian; D, Devonian; P, Permian; Tr, Triassic (12). India: R, Rahajmahal Traps (61); DT, Early Cenozoic Deccan Traps (17, 62). North America: S, Silurian; C–Tr, Carboniferous through Triassic; K, Cretaceous (16). South America: SG, Jurassic Serra Geral volcanics (42).

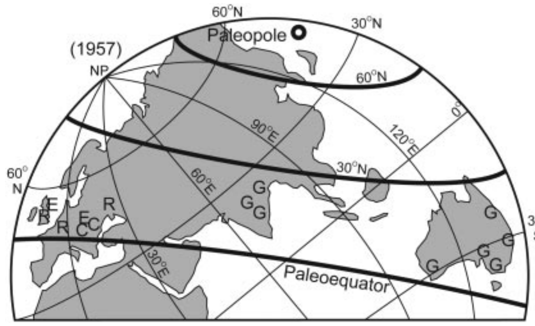

Fig. 5. Contradictions arise when Permian paleolatitudes (dark lines) determined from Europe are extended across fixed continents. NP, north pole of present geographic grid; C, carbonates; R, desert sandstones; E, evaporites; G, glacial strata (26). This figure is reproduced with permission from ref. 17 (copyright 1956, Birkhäuser, Basel).

(44, 55–57). This seminal discovery was made possible by the development of high-sensitivity magnetometers by Blackett (58), by means of which we were able to study a wide range of rocks, studies that led us quickly to continental drift, as the following example shows.

According to Köppen and Wegener (24), India has moved ≈49° of latitude (5,400 km) northward and rotated ≈30° counterclockwise since the beginning of the Cenozoic (Fig. 2*c*). In late 1951 (59), I planned a test, and the Indian Geological Survey sent me oriented samples of the earliest Cenozoic (65 Ma) Deccan Traps from seven localities spread over several hundred kilometers (mean $\lambda = 19°$N). Their mean direction of magnetization was $D = 329°$, $I = -56°$ (error = 10°, $P = 0.05$), 85° oblique to the present GAD field at the collecting locality. Some samples had normal and some had reversed polarity, indicating that magnetizations were stable and spanned secular variation (17, 44). The inclination gave a latitude of 36 ± 10°S, implying northward motion of 55° or 6,000 ± 1,000 km, and the northwest declination signified ≈30° counterclockwise rotation, as Köppen and Wegener (24) predicted. An inexperienced student, I did not publish immediately, and only Fisher (who promoted the project) and I were convinced (59).

In the late summer of 1954, a second seminal discovery was made (12–15) that when oblique directions [which we then had back to the Late Precambrian (≈800 Ma)] were converted into paleopoles they fell in age order on a simple curve, later called "the path of apparent polar wander" (APW path) for Britain. This second discovery led to the first successful geophysical test of continental drift; if continents were fixed (or had drifted) relative to one another, all would have the same (or different) path(s).

Within 2 years we knew that North America's path lay west of Europe's, as if the Atlantic formerly had not existed. Australia's path could hardly have been more different, approaching the present pole from an opposite longitude (Fig. 4). All three of the above continents had moved ≈4,000 km northward since the Mid-Mesozoic, India had moved even further (>6,000 km), and latitude changes for South America and Africa were less, all as Köppen and Wegener (24) had imagined (Fig. 2).

Late Proterozoic and Early to Mid-Paleozoic (800–350 Ma) paleopoles, however, did not conform to this simple picture. European paleopoles fell on a smooth path (12), whereas those from Australia fell on a longer, looped path. It was as if continents had moved relative to one another, not only in the Mesozoic and Cenozoic, as Wegener (9) proposed, but also during the Phanerozoic and Late Precambrian (18).

In the mid-1950s, I began testing the GAD hypothesis through time by calculating paleolatitude variations and comparing them with paleoclimatic evidence (17). Paleolatitude variations for northern Europe calculated from its APW path were consistent with paleoclimatic evidence; for example, low paleolatitudes of the Permian (300–250 Ma) corresponded to deposition of tropical redbeds, evaporites, thick carbonate rocks, and aeolian desert sandstones (Fig. 5). Hence, the APW path recorded motions of the rotation axis relative to northern Europe. However, paleolatitudes calculated from this path for other continents by assuming them to be fixed were inconsistent with the paleoclimatic evidence (L4 in Fig. 1*b*); the low latitudes of central India and eastern Australia, predicted from Europe, contradicted the presence in both places of Permian strata of glacial origin (Fig. 5). Doing the experiment in reverse by measuring Permian paleolatitudes from Australia, I found that they were high (70°S), consistent with glaciations there (18). The same paleoclimatic data could not be right in one context and wrong in another: continental drift was required to remove this palpable contradiction.

By the end of the 1950s, Mesozoic and Cenozoic continental drift had been confirmed, and a new paleogeography began to emerge, based on paleomagnetically determined latitudes and meridians of continents (26), as can be visualized from Fig. 3*b*. The latitude of crustal block S is $\tan \lambda = 0.5 \tan I$. The line connecting S and P is the paleomeridian, and D indicates the block's azimuthal rotation. Studies of paleowind directions (64) and the latitudinal distribution of climate-sensitive rocks and fossils began to reveal the character of past climate zones (65–67).

Our continental work was carried out by small groups in several countries including the Union of Soviet Socialist Republics (68). It was all very new. We had principles to establish, sampling and statistical procedures to work out, instruments to build, expeditions to mount, and data to obtain and analyze. Then we had to explain our results to a public unfamiliar with what we were doing and generally displeased with what they heard. Even as late as the mid-1960s experts declared our results wrong. Anti-drift sentiment softened a little, but there was no general move to mobilism (OP3 in Fig. 1*d*).

New Evidence from Oceans: Seafloor Spreading and Plate Tectonics, 1963–1968

In the early 1960s, displacement measurements began to be made from oceans and their margins. These researches were made by large, well funded groups, on a far grander scale than our continental work (ref. 20 and references therein). In quick succession (T7 in Fig. 1*a*), the worldwide earthquake-marked ocean ridges were recognized, seafloor spreading was proposed (T6 in Fig. 1*a*) and confirmed through dating of the reversal time scale and marine magnetic anomalies, transform faults were recognized, and the sense of motion along transform faults and faults beneath deep ocean trenches were determined from seismology. By 1966, most workers actively involved in ocean geophysics had accepted that the seafloor moved away from ocean ridges and descended beneath trenches. Standing somewhat apart from this marine work and pointing to the future was the quantitative reassembly of the western half of Pangea A1 achieved by imagining continents to be rigid spherical shells rotating about pivot points on Earth's surface (69), a procedure invoked earlier but infrequently used (16, 27).

Meanwhile, mechanism discussions lingered. It was, for example, imagined that up-welling from the deep mantle at ocean ridges drove the seafloor apart, but as ocean ridges became better known, especially those ringing Antarctica and three sides of Africa, this theory could not be true. Mechanism models were set aside, and the practical task of providing kinematic descriptions was undertaken. By means of finite rotations of rigid spherical shells or plates as delineated by earthquakes, observed motions (seafloor spreading rates, continental drift, earthquake slip vectors, and transform fault motions) could be integrated regardless of their cause (21–23, 70). By the mid-1970s, most earth scientists had accepted that, except for currently active mountain belts, these rigid plates, not continents and oceans, are the basic building blocks and that motions between them are concentrated at ocean trenches, ridges, and transform faults (T8). Present oceans are Jurassic or younger (<180 Ma), so, strictly, plate tectonics applies to only 5% of the lifetime of Earth.

The New Paleogeography Matures: Latitudes, Plates, and Mountain Belts

One further step was needed to complete the new paleogeography. Plate tectonic maps, like Wegener's (Fig. 2*a*), are silent on geographic latitude, the main determinant of climate and hence of the distribution of life. However, for over a decade we had been drawing latitudes for continents: plate rotations could bring these together and global geographic grids could be constructed (32, 33). Oceanic displacements, paleopoles, and latitudes were integrated into one global geographical framework (M in Fig. 1*b*). Relative longitude was determined for major continents for the past 180 Myr. See *Supporting Text* and Figs. 10–13, which are published as supporting information on the PNAS web site, for further details.

Fig. 6, dating from the 1980s, shows the good agreement of paleopoles from Early Jurassic rocks of each constituent block of Pangea A1, demonstrating the essential correctness of the reconstruction and that its age is ≈180 Myr. It is difficult to exaggerate the importance of such beautiful constructs; combined with the paleoclimatic evidence, they validate paleomagnetic (notably the GAD model) and plate tectonic methods for the past 180 Myr; they confirm paleomagnetism as the method *par excellence* of estimating paleolatitude.

This marriage of paleomagnetically determined latitudes and plate tectonics (M in Fig. 1*b)* marks the maturing of the new paleogeography (see supporting information). Its importance

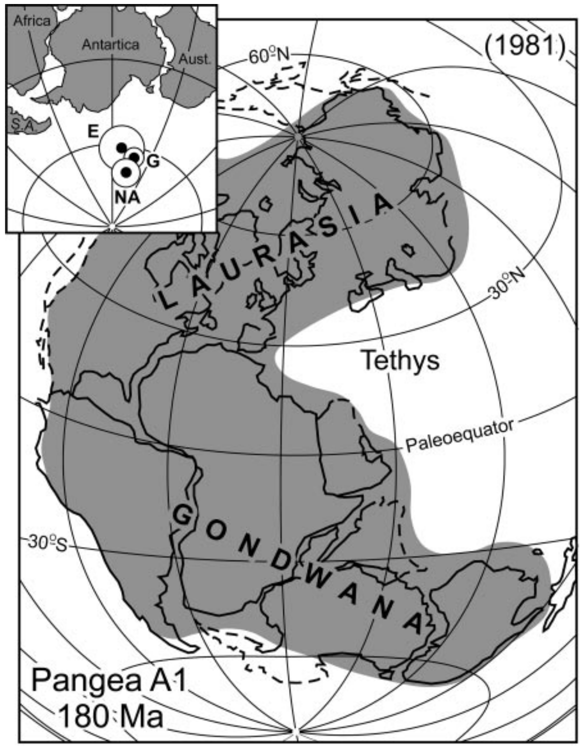

Fig. 6. A beautiful construct integrating plate tectonics and paleomagnetically determined latitude. Early Jurassic geographic grid of the larger map (68, 70) constructed from paleopoles (*Inset*) for major crustal blocks rotated with continents (71). E, Europe; G, Gondwana (data combined from Australia, Africa, South America, and Antarctica); NA, North America.

was quickly realized, and by late 1971 an atlas based on these principles had been compiled (33), and their significance was discussed in 1973 (73). Over the last 30 years, such studies have had a seminal effect on our understanding of long-term climate changes, paleobiogeography, and pre-Jurassic paleogeography. They have also guided our ideas about the tectonics of mountain belts where there are no rigid plates and plate tectonics does not apply; beginning in the late 1950s (28–30) and especially after 1970, paleopoles from mountain belts were found to disagree with coeval paleopoles from adjacent plates, and large displacements and rotations were inferred; most were unanticipated and many remain contentious.

The first example of the consequence of the new paleogeographic synthesis concerns global geography just before the oldest plate tectonic reconstruction, with which, as Fig. 6 shows, Early Jurassic (180 Ma) paleopoles are in good agreement. However, Late Carboniferous through Early Triassic (330–230 Ma) paleopoles are not (74), and latitudes derived from them require Gondwana and Laurasia (Fig. 6) to overlap by as much as 15°, which is absurd. Two explanations have been given. The first (75) proposes a modified Pangea, Pangea A2, which has no Gulf of Mexico (Fig. 7*b*) and which existed from Late Carboniferous through Early Triassic (320–220 Ma). As more data accumulates, Pangea A2 remains tenable only if long-term, nondipole components in the geomagnetic field for this interval are assumed (76). The second solution asserts the accuracy of the GAD model and paleomagnetically determined latitudes. To avoid overlap and minimize motion, Gondwana must be shifted ≈4,000 km east relative to Laurasia, so that northwest Africa is next to Europe and northeast South America to eastern North America (Fig. 7*a*); this assembly is Pangea B (74). Recently it has been proposed that the transformation of Pangea B into Pangea

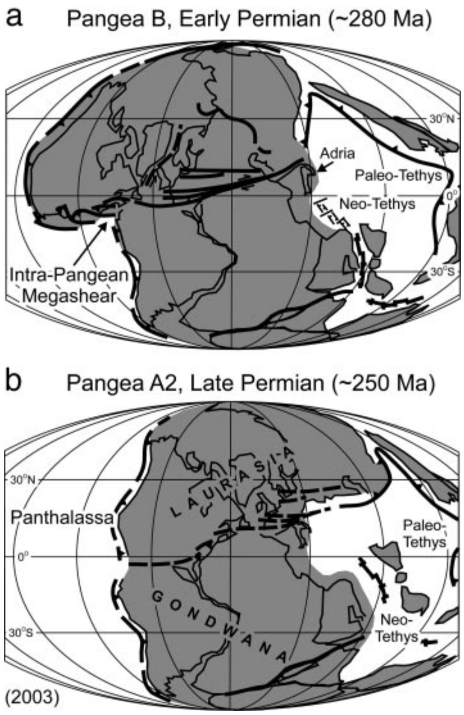

Fig. 7. Intra-Pangean megashear. In this interpretation the transition from Pangea B to Pangea A2 is Permian, and the transition from Pangea A2 to Pangea A1 is Triassic. [Reprinted with permission from ref. 77 (Copyright 2003, Elsevier).]

A2 occurred by rapid dextral shear in the Permian (77) and then more slowly into Wegener's Pangea A1 in the Late Triassic (200 Ma). This scenario implies that Pangea B lasted for ≈50 Myr, whereas Pangea A1 was short-lived, explains the origin of the Varisan Mountain Belt, and raises the possibility of a hitherto unrecognized deformational event just before the greatest of all life extinction at the Paleozoic–Mesozoic boundary.

The second example concerns the disjunctive genus *Magnolia*. Extant species occur only in southeast Asia and the Americas (Fig. 8*c*) yet they share common ancestry. Magnolias are moisture-loving, generally warm-temperate plants. A new taxonomy (summarized with references in ref. 78), based partly on DNA studies, groups them into 17 sections, of which 15 occur only in one or the other place, their recent evolution happening separately. The other two sections occur in both places, as if originating in one and later migrating to the other. North American species of these two sections are the most diverse and basal to the DNA tree, indicating that they are ancestral stock. Fossil evidence confirms this. Ancestral forms (95–80 Myr old) are confined to North America, and fossils of true magnolias older than ≈20 Myr occur in North America, northern Europe, and southern Siberia but are unknown in eastern Asia until later in the Cenozoic; all lived at latitudes 40°N to 60°N (15° higher than today) when warm temperatures extended further north under a greenhouse regime (Fig. 8 *a* and *b*). Apparently, magnolias of the two "older" sections migrated out of North America to northern Europe during the especially warm climate of the Eocene (≈60 Ma) along the Thulean (Iceland-Faroes) land-bridge situated at ≈45°N (TH in Fig. 8*b*). Then they spread across Eurasia to eastern Asia, leaving a fossil trail. There were two other possible routes (DG and BE in Fig. 8*b*), both in very high latitudes (>70°N) with no fossil traces, and so are less likely. Global cooling began ≈33 Ma, and magnolias shifted their range south by ≈15°. During the past few Myr, mountain ranges with congenial, warm-temperate upland habitats formed in tropical

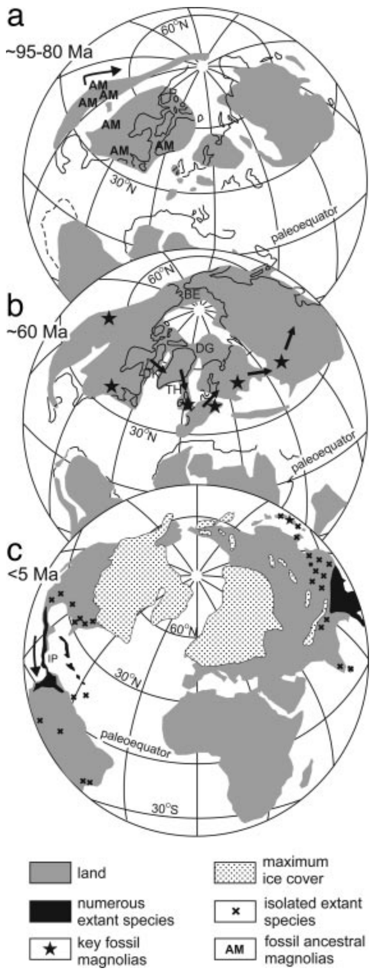

Fig. 8. Distribution of magnolias at three intervals. (*a*) Ancestral magnolia (AM) fossils. (*b*) Proposed eastward migration out of North America during the Eocene supergreenhouse, then later to east Asia, with key fossil localities for the time interval 60–15 Ma indicated by stars. Land-bridges are Beringia (BE), deGeer (DG), and Thulean (TH). (*c*) Disjunctive populations caused by southerly migration in response to global cooling. IP, Isthmus of Panama. [Simplified with permission from ref. 78 (Copyright 2004, American Geophysical Union).]

southeast Asia and the western Americas. Magnolias migrated there, prospered, and diversified into the extant 15 "younger" sections. Concurrently they were driven from their former range in western North America, northern Europe, and central Asia by the cold and dryness of Quaternary ice ages, creating today's separated populations (Fig. 8*c*). Magnolias of our temperate gardens come from the eastern United States, northern China, and Japan, hardy relicts left behind during the southward migrations.

In the past decade, measurements of current motions have had a seminal effect on studies of tectonic processes and their dynamical causes. Most notable is the astonishing agreement observed between measurements of rates made on widely varying timescales, an unfolding story noted here for completeness (Fig. 1*c*).

Comments

Two advances merit special mention: first, the formulation (1954) of the hypothesis that the time-averaged geomagnetic field was an occasionally reversing GAD and the recognition of APW and long-term latitude change that flow from it; and second, the integration (1971–1973) of latitudes and plate tectonics (M in Fig. 1*b*). These advances divide paleomagnetic work into three phases: (*i*) an early chaotic phase that ended in 1954 when Fisher's statistics and APW analysis brought order and predictability; (*ii*) a consolidation phase (1954–1971) that ended when long-term latitude changes (APW) were integrated with plate tectonics to complete the new paleogeographic synthesis; and (*iii*) the present phase (1971 to now) in which this new synthesis has spread across the paleobiological and earth sciences and is now corroborated by studies of current motions. There are comparisons to be made between this geological synthesis and the 1930s synthesis in biology achieved by integrating Darwinian evolution with genetics and, latterly, molecular biology. Remarkably, R. A. Fisher had a hand in both.

APW is a regional phenomenon. It was established (1954) in Britain, but its global implications could not be known until data were obtained from elsewhere, which took about a decade; this and the obstacle of entrenched fixism delayed acceptance of APW and the mobilism it implied (Fig. 1*b*). By contrast, plate tectonics is a global phenomenon requiring global surveys that, once completed, allowed plate tectonics to emerged (1967–1968) quickly and essentially fully formed, commanding quick acceptance (70) (Fig. 1 *a* and *d*).

Cox (79) has remarked on my early (1955–1958) study and acceptance of the GAD model of the time-averaged geomagnetic field and on the success that it brought. I have come to believe that progress is made by devotion to a single, well defined idea not by judging the merits of several ideas simultaneously. Also essential is the ability to spot when such pursuits risk becoming dead-ends. There may be early premonitions and initial ideas may be vague, and headway is made by clarifying them in a form allowing testable predictions; the clarification brought to early paleomagnetic work by representation as paleopoles and APW paths is a good example (L3).

I continue to accept the GAD model and latitudes when competently derived, because its consequences are never dull, and nothing damns it outright. Indeed, support grows (Fig. 9). The paleomagnetic pole relative to the northwestern Canadian Shield (Western Laurentia) between 1,950 and 1,850 Ma is situated ≈70° to the south in today's coordinates, so the region was then situated in latitudes ≈20°. Redbeds containing the oldest recorded sequential reversals (83), carbonates and

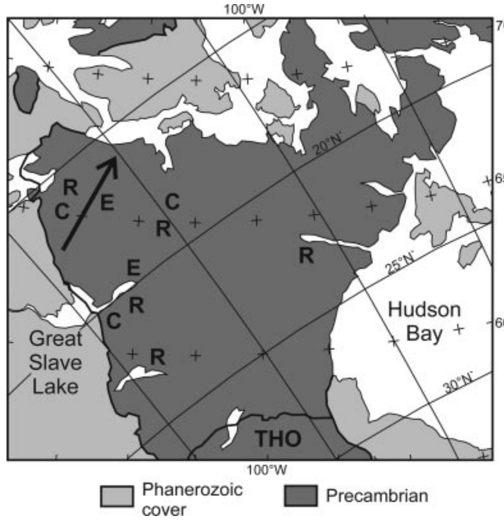

Fig. 9. Precambrian latitudes of western Laurentia 1,950–1,850 Ma (79). The bold arrow indicates inferred wind direction (80, 81). C, carbonate rocks; E, evaporites; R, redbeds with sequential reversals; THO, TransHudson mountain belt.

evaporites, indicate tropical conditions and are consistent with this latitude. Elongation of stromatolite structures was probably caused by wind-driven currents from SW in today's coordinates or from ENE in coordinates of the time, reminiscent of present trade winds at latitude of 15°N; these are northern, not southern, trade winds, and Western Laurentia was then in the northern hemisphere, as it is today (81, 82). Thus the time-averaged geomagnetic field ≈1,900 Ma has every appearance of being an occasionally reversing GAD, just as it has been in the past few Myr.

I thank Lloyd Evans for telling me about Darwin's note; Hank Frankel, Steve Johnston, and Dennis Kent for reviews; Randy Enkin and Hank Frankel for endless discussions; Richard Franklin for drafting figures; and Judith Baker for help with the manuscript. This is publication of the Geological Survey of Canada no. 2004220.

1. Eiseley, L. (1975) *All the Strange Hours: The Excavation of a Life* (Scribner's Sons, New York), p. 186.
2. Darwin, C. (1859) *On the Origin of Species by Means of Natural Selection: or the Preservation of Favoured Races in the Struggle for Life* (John Murray, London).
3. Darwin, C. (1987) *Charles Darwin's Notebooks, 1836–1844: Geology, Transmutation of Species, Metaphysical Enquiries*, eds. Barrett, P. H., Gautrey, P. J., Herbert, S., Kohn, D. & Smith, S. (Cornell Univ. Press, Ithaca, NY).
4. Gilbert, W. (1600) *De Magnete* (Chiswick, London); trans. Mottely, P. F. (1958) (Dover, New York).
5. Argand, E. (1924) *Congr. Geol. Int.* **8,** 171–372; trans. Carrozzi, A. V. (1977) *Tectonics of Asia* (Hafner, New York).
6. Wegener, A. (1912) *Geol. Rundsch.* **3,** 276–292.
7. Wegener, A. (1912) *Petermanns Geogr. Mitt.* **58,** 185–195, 253–256, 305–309; trans. Jacoby, W. R. (2001) *J. Geodynam.* **32,** 29–63.
8. Wegener, A. (1915) *Die Entstehung der Kontinente und Ozeane* (Bornträger, Berlin).
9. Wegener, A. (1922) *Die Entstehung der Kontinente und Ozeane* (Bornträger, Berlin), 3rd Ed.; trans. Skerl, J. G. A. (1924) *The Origin of Continents and Oceans* (Methuen, London).
10. Wegener, A. (1929) *Die Entstehung der Kontinente und Ozeane* (Bornträger, Berlin), 4th Ed.; trans. Biram, J. (1966) *The Origin of Continents and Oceans* (Methuen, London).
11. Du Toit, A. L. (1937) *Our Wandering Continents* (Oliver & Boyd, Edinburgh).
12. Creer, K. M., Irving, E. & Runcorn, S. K. (1954) *J. Geomagn. Geoelectr.* **6,** 163–168.
13. Anonymous (September 9, 1954) *The Times of London*, p. 3.
14. Anonymous (September 27, 1954) *Time*, p. 49.
15. Creer, K. M. (1955) Thesis (Univ. of Cambridge, Cambridge, U.K.).
16. Runcorn, S. K. (1956) *Proc. Geol. Assoc. Can.* **8,** 77–85.
17. Irving, E. (1956) *Geofis. Pura Appl.* **33,** 23–41.
18. Irving, E. & Green, R. (1958) *Geophys. J. R. Astron. Soc.* **1,** 64–72.
19. Hess, H. H. (1962) in *Petrologic Studies: A Volume in Honor of A. F. Buddington*, eds. Engel, A. E. J., James, H. L. & Leonard, B. F. (Geol. Soc. Am., New York) 599–620.
20. Cox, A. (1973) *Plate Tectonics and Geomagnetic Reversals* (Freeman, San Francisco).
21. McKenzie, D. P. & Parker, R. L. (1967) *Nature* **216,** 1276–1280.
22. Morgan, W. J. (1968) *J. Geophys. Res.* **73,** 1959–1982.
23. Le Pichon, X. (1968) *J. Geophys. Res.* **73,** 3661–3697.
24. Köppen, V. & Wegener, A. (1924) *Die Klimate der Geologischen Vorzeit* (Bornträger, Berlin).
25. Hospers, J. (1954) *Nature* **173,** 1183–1184.
26. Irving, E. (1957) *Philos. Mag. Suppl. Adv. Phys.* **6,** 194–218.
27. Creer, K. M., Irving, E., Nairn, A. E. M. & Runcorn, S. K. (1958) *Ann. Geophys.* **14,** 492–501.
28. de Boer, J. (1965) *J. Geophys. Res.* **70,** 931–944.
29. Beck, M. E., Jr., & Noson, L. (1976) *Nature* **235,** 11–13.
30. Irving, E. (1964) *Paleomagnetism* (Wiley, New York).
31. Packer, D. R. & Stone, D. B. (1972) *Nature* **237,** 23–26.
32. McKenzie, D. P. & Sclater, J. D. (1971) *Geophys. J.* **25,** 437–528.
33. Smith, A. G., Briden, J. C. & Drewry, G. E. (1973) *Spec. Pap. Paleontol. (London)* **12,** 1–42.
34. Newman, R. P. (1995) *Earth Science History* **14,** 62–83.
35. Oreskes, N. (1999) *The Rejection of Continental Drift* (Oxford Univ. Press, London).
36. Jeffreys, H. (1924, 1929, 1952, 1959) *The Earth* (Cambridge Univ. Press, Cambridge, U.K.).
37. Taylor, F. B. (1909) *Geol. Soc. Am. Bull.* **21,** 179–226.

38. Feynman, R. P. (1999) *The Pleasure of Finding Things Out* (Perseus, New York).
39. Fisher, R. A. (1953) *Proc. R. Soc. London Ser. A* **217,** 295–305.
40. Chevallier, R. (1925) *Ann. Phys.* **4,** 5–162.
41. Irving, E. & Green, R. (1957) *Nature* **179,** 1064–1065.
42. Creer, K. M. (1958) *Ann. Geophys.* **14,** 373–390.
43. Campbell, C. D. & Runcorn, S. K. (1956) *J. Geophys. Res.* **61,** 449–459.
44. Irving, E. (1954) Thesis (Univ. of Cambridge, Cambridge, U.K.).
45. Hospers, J. (1953) *Proc. K. Ned. Akad. Wet. Ser. B* **56,** 467–476.
46. Hospers, J. (1953) *Proc. K. Ned. Akad. Wet. Ser. B* **56,** 477–491.
47. Hospers, J. (1954) *Proc. K. Ned. Akad. Wet. Ser. B* **57,** 112–121.
48. Bruhnes, B. (1906) *J. Phys. (Paris)* **5,** 705–724.
49. Matuyama, M. (1929) *Proc. Imp. Acad. Japan* **5,** 203–205.
50. Mercanton, P. L. (1931) *C. R. Acad. Sci. Paris* **192,** 978.
51. Mercanton, P. L. (1932) *C. R. Acad. Sci. Paris* **194,** 1371.
52. Elsasser, W. M. (1947) *Rev. Phys.* **72,** 821–833.
53. Bullard, E. C. & Gellman, H. (1954) *Philos. Trans. R. Soc. London A* **247,** 213–278.
54. Runcorn, S. K. (1954) *Trans. Am. Geophys. Union* **35,** 49.
55. Griffiths, D. H. & King, R. F. (1954) *Nature* **173,** 1114–1117.
56. Hospers, J. & Charlesworth, H. A. K. (1954) *Mon. Not. R. Astron. Soc. Geophys. Suppl.* **7,** 32–43.
57. Clegg, J. A., Almond, M. & Stubbs, P. M. S. (1954) *Philos. Mag.* **45,** 583–598.
58. Blackett, P. M. S. (1952) *Philos. Trans. R. Soc. London A* **245,** 309–370.
59. Box, J. F. (1978) *R. A. Fisher, the Life of a Scientist* (Wiley, New York).
60. Nairn, A. E. M. (1956) *Nature* **178,** 935–936.
61. Graham, K. W. T. & Hale, A. L. (1957) *Philos. Mag Suppl. Adv. Phys.* **6,** 149–161.
62. Clegg, J. A., Radakrishnamurty, C. & Sahasrabude, P. W. (1958) *Nature* **181,** 830–831.
63. Clegg, J. A., Deutsch, E. R. & Griffiths, D. W. (1956) *Philos. Mag. Suppl. Adv. Phys.* **1,** 419–431.
64. Opdyke, N. D. & Runcorn, S. K. (1960) *Geol. Soc. Am. Bull.* **71,** 959–972.
65. Blackett, P. M. S. (1961) *Proc. R. Soc. London Ser. A* **263,** 1–30.
66. Briden, J. C. & Irving, E. (1964) in *Problems in Paleoclimatology*, ed. Nairn, A. E. M. (Interscience–Wiley, New York), 200–250.
67. Irving, E. & Brown, D. A. (1964) *Am. J. Sci.* **262,** 689–708.
68. Khramov, A. N. (1958) *Paleomagnetism and Stratigraphic Correlation* (Gostoptechizdat, Leningrad, U.S.S.R.); trans. Lojkine, A. J. (1960) (Australian Natl. Univ., Canberra, Australia).
69. Bullard, E. C., Everitt, J. E. & Smith, A. G. (1965) *Philos. Trans. R. Soc. London* **258,** 41–75.
70. McKenzie, D. P. (2001) in *Plate Tectonics*, ed. Oreskes, N. (Perseus, New York), 169–190.
71. Smith, A. G. & Hallam, A. (1970) *Nature* **225,** 139–144.
72. Morel, P. & Irving, E. (1980) *J. Geomagn. Geoelectr.* **32,** 39–45.
73. Hughes, N. F. (1973) *Spec. Pap. Palaeontol. (London)* **12,** 44–335.
74. Irving, E. (1977) *Nature* **270,** 304–309.
75. Van der Voo, R. & French, R. B. (1974) *Earth–Sci. Rev.* **10,** 99–119.
76. Van der Voo, R. & Torsvik, T. H. (2001) *Earth Planet. Sci. Lett.* **187,** 71–81.
77. Muttoni, G., Kent, D. V., Garzanti, P., Brack, P., Abrahamsen, N. & Geatani, M. (2003) *Earth Planet. Sci. Lett.* **215,** 379–394.
78. Hebda, R. J. & Irving, E. (2004) in *Time Scales of the Paleomagnetic Field*, eds. Channel, J. E. T., Kent, D. V., Lowrie, W. & Meert, J. G. (Am. Geophys. Union, Washington, DC).
79. Cox, A. (1979) *Trans. Am. Geophys. Union* **60,** 620.
80. Irving, E., Baker, J., Hamilton, M. & Wynne, J. P. (2004) *Precambrian Res.* **129,** 251–270.
81. Hildebrand, R. S. (1988) *Geology* **16,** 1089–1091.
82. Hoffman, R. F. & Grotzinger, J. P. (1993) *Geology* **21,** 195–198.
83. Bingham, D. K. & Evans, M. E. (1976) *Can. J. Earth Sci.* **13,** 365–576.