Geophysics

Wandering why

Richard G. Gordon

True polar wander is the slow, secular shift of the entire solid Earth, relative to its rotation axis, in response to Earth's changing distribution of mass. In recent years the emphasis of dynamical models for true polar wander has turned from deglaciation, which is responsible for much of the wander this century, to the processes that drive polar wandering over millions of years[1,2]. Now, Steinberger and O'Connell (page 169 of this issue[3]) have produced an actualistic model that makes predictions of true polar wander over the past 65 million years (Myr), and they agree strikingly well with the wander observed from palaeomagnetism and plate reconstructions relative to hotspots[4].

Eight decades of observations from the International Latitude Service indicate, and two decades of space geodetic observations verify, that the solid Earth is moving relative to its rotation axis at a rate of about 10 cm yr^{-1}, or 1° Myr^{-1} (ref. 5). Estimates of true polar wander over millions of years are very uncertain and indicate a net drift of about 10° over Cenozoic time (the past 65 Myr), giving an average rate of drift of about 0.15° Myr^{-1}, but with drift as fast as about 0.5° Myr^{-1} occurring in the past 10 Myr or so (ref. 6).

True polar wander is a consequence of the changing location of Earth's maximum principal axis of non-hydrostatic moment of inertia (that is, where the maximum principal axis would be on a non-rotating Earth). The diurnal rotation causes a bulge at the Equator and a flattening of the Poles resulting in the equatorial radius exceeding the polar radius by about 21 km. Without the diurnal rotation this difference would shrink dramatically, and the average equatorial radius would exceed the average polar radius by about only 100 m. Here the tail wags the dog — as the 100-m non-hydrostatic departures from sphericity migrate with time, the 21-km hydrostatic bulge gradually follows.

Over millions of years, surface features are unlikely to significantly perturb Earth's non-hydrostatic shape and moment of inertia. Nearly everywhere, the lateral mass anomalies implied by the topographic highs and lows of Earth's surface are cancelled out at depths of less than about 100 km, because the crust and upper mantle lack the strength to sustain appreciable shear stress on vertical planes. The lack of correlation between the geoid and nearly all surface topographic features (except deep-sea trenches) is direct evidence for this shallow compensation. Probably the most important source of the mass anomalies responsible for the departures of the non-hydrostatic figure from sphericity are the cold, dense, subducting slabs delivered into the mantle at deep-sea trenches[2]. Their changing geometry indicates that the non-hydrostatic figure evolves with a characteristic time of about 50 Myr (ref. 7).

By how long does the 21-km bulge lag behind the 100-m bulge? Interpretations in the 1960s favoured the idea that Earth's mantle was viscous enough to cause a very long time lag. The tiny non-hydrostatic bulge was believed to have been inherited from tens or hundreds of millions of years before, when Earth's diurnal rotation was much faster than it is now (the Earth has gradually been decelerating over its history because of tidal frictional dissipation of its rotational energy). In 1969, Goldreich and Toomre[8] showed that the tiny departures from sphericity of the non-hydrostatic figure of the Earth are as expected if the hydrostatic bulge tracks them in a geologically negligible amount of time. Work in the early 1990s revived the hypothesis of a slow response of the bulge[1], but the most recent results — those of Richards *et al.*[2], published earlier this year, and of Steinberger and O'Connell[3] — show that the hydrostatic bulge adjusts quickly.

Steinberger and O'Connell show, for example, that the rotation axis would lag the inertia axis by less than 1° assuming a reasonable upper limit to the viscosity of the lower mantle. Simulations indicate that rapid and large-amplitude polar wander, with occasional swings of about 90°, is to be expected on an Earth-like planet[8]. But the palaeomagnetic and plate-reconstruction record indicate that the swings over the past 100 Myr are much smaller than this, no more than 10°. The absence of large swings might imply that the viscosity of the lower mantle is high enough to slow true polar wander, but both Richards *et al.* and Steinberger and O'Connell find instead that the migrations of the axis of maximum non-hydrostatic moment of inertia have been small. Richards *et al.* explain the smallness of true polar wander over the past 100 Myr by the slow rate of change of the large-scale pattern of plate-tectonic motions and associated geometry of subducting slabs during the past 200 Myr.

So how do the two studies differ? Whereas Richards *et al.*[2] calculate the changing non-hydrostatic moment of inertia due to the evolving geometry of subducting slabs of oceanic lithosphere, Steinberger and O'Connell[3] take a complementary approach. They start with the present distribution of density anomalies estimated from anomalies in the velocity of seismic-wave propagation and an empirical relation between density and velocity. They trace these anomalies backwards in time in a modelled flow that is driven by buoyancy anomalies and is consistent

NATURE

100 YEARS AGO

English weather is as fruitful a subject for composition as it is a theme for conversation. Like many other people, Mr. C. A. Whitmore, M. P., is a devoted student of our meteorology, so that what he writes about in the May number of the *National Review* is worth reading. Weather fallacies have been exposed times without number, but they are so deeply rooted in the minds of the unscientific that it may be doubted whether they will ever be completely eradicated. Mr. Whitmore throws doubt upon the popular impression that the changes of the moon synchronise with marked changes of weather. The few facts he states as to weather and lunar phases since the beginning of summer, ought to convince people that their faith in the influence of the moon is misplaced. Another very common idea is that a heavy dew at night presages a fine day on the morrow, whereas it only indicates that the sky is clear and conditions are favourable for the deposition of dew. At certain times of the year a heavy dew is a sign of unstable rather than of stable weather. A luxuriant crop of berries in the autumn is said to forebode a severe winter; but the people who believe this, forget, or do not know, that the berries tell of conditions which have passed rather than of those to come.

From *Nature* 6 May 1897.

50 YEARS AGO

There is a large gap in our knowledge which must be bridged before we can take decisive steps from present aircraft subsonic speeds to supersonic speeds. ... Normally one would expect to get a large part of this information from wind tunnels, and although the capabilities of existing wind tunnels will be used to the limit, nobody knows how to design or to use a practicable wind tunnel at or about the speed of sound. ... This is the main reason for going into the air, and a series of experiments has been planned to use flying model aircraft launched from a great height from another aircraft and powered by rockets.

From *Nature* 10 May 1947.

Many more abstracts like these can be found in *A Bedside Nature: Genius and Eccentricity in Science, 1869–1953*, a 266-page book edited by Walter Gratzer. Contact David Plant (e-mail: subscriptions@nature.com).

with the sources and sinks imposed by the motion between the surface tectonic plates.

The two approaches give predicted paths of true polar wander that are broadly similar, especially in giving similar 10° amplitudes of true polar wander over the past 65 Myr. But they differ in direction, with the path calculated by Steinberger and O'Connell[3] being in excellent agreement with the observed path of true polar wander and the path of Richards *et al.*[2] being in only fair agreement. Whereas the latter reflects the changing density distribution due to the evolving geometry of subducting slabs, the former implicitly captures all sources of the changing density distribution. The difference in the two calculated paths could possibly be due to inaccuracies in the modelled history of subduction, but it may it be telling us something important about other smaller yet significant sources of evolving mantle density structure. Possibilities to be considered by geodynamicists include upwelling mantle plumes, and downwelling cold mantle at locations other than subduction zones (for example by convective destabilization of mantle lithosphere beneath horizontally shortened continental plateaux).

The plate reconstructionists also have work to do. Models of the history of subduction can be no better than the plate reconstructions on which they are based, and debates about many features of circum-Pacific plate motion are still far from settled. (Unfortunately, the nature of some pre-Cenozoic features may never be known because of subduction of the sea floor that records the older plate motions.) Moreover, published uncertainties on paths of true polar wander include the uncertainties in the palaeomagnetic data but neglect those, possibly larger, uncertainties in the reconstructions of the plates relative to the hotspots. So it is necessary to incorporate these uncertainties to ascertain whether the differences between the observed path of true polar wander and that calculated by Richards *et al.*[2] are significant before giving too much weight to the difference.

Palaeomagnetism has contributions to make as well. First, better palaeomagnetic data for the Pacific plate and the surrounding continents is likely to be the ultimate arbiter between the distinctly different plate reconstructions that have been proposed for the Pacific Ocean basin. Moreover, estimated paths of true polar wander are based entirely on data from the continents and, to be really convincing, also require data from the Pacific. Second, the observed path of true polar wander is a highly smoothed version of a possibly undersampled signal. Palaeomagnetic data of higher accuracy and age resolution would place a more stringent bound on viscosity of the lower mantle than is now possible.

Palaeomagnetically observed true polar wander is similar in direction to true polar wander observed this century. This agreement would be expected if the long-term wander was much faster than that caused by deglaciation. Such is not the case, however, and the agreement is mainly a coincidence[9]. Although the 0.6° Myr^{-1} along 40° W of true polar wander over the past 10 Myr is much faster than the average rate over many tens of millions of years[6], it is still slower than true polar wander this century, which is about 1.1° Myr^{-1} along 70° W (ref. 5). Steinberger and O'Connell's model predicts an even slower rate for the long-term wander, about 0.4° Myr^{-1} along 24° W over the past 1 Myr. This predicted rate, if accurate, can be subtracted from the historically observed wander to obtain an estimate of the wander due to deglaciation of 0.9° Myr^{-1} towards 90° W, which is still faster, perhaps much faster, than the long-term rate of wander. □

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Protein transport

A fusion of new ideas

Jason B. Bock and Richard H. Scheller

Eukaryotic cells rely on a series of membrane-bound organelles to compartmentalize biochemical reactions and to regulate the secretion and localization of proteins. Although each organelle has a unique molecular composition, giving it a distinct functional identity, membranes and proteins are continuously shuttled between compartments. This process is mediated by transport vesicles that bud from the membranes of donor compartments and then fuse with acceptor membranes (Fig. 1). ▶

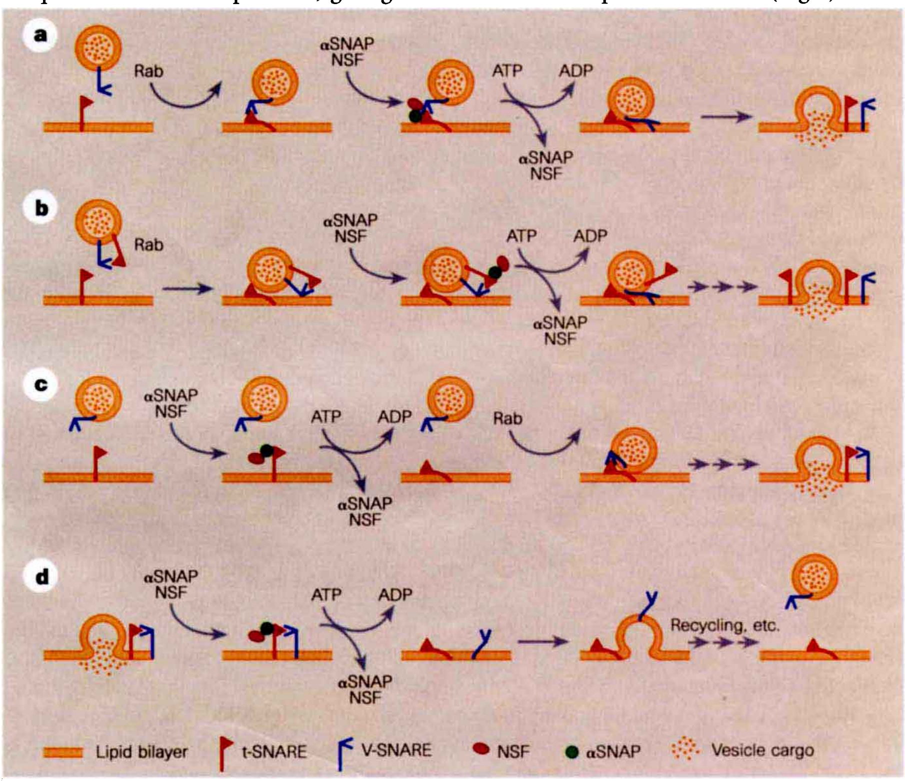

Figure 1 a, **The low-molecular-weight Rab-family GTPases are involved in vesicle target recognition, followed by the action of α-SNAP and NSF on a v- and t-SNARE complex. NSF-mediated SNARE rearrangement leads to membrane fusion, and Nichols *et al.*[1] have shown that v- and t-SNARES are required on opposing membranes for vacuole fusion in yeast.** b, **The v- and t-SNAREs were originally thought to be localized to vesicle and target membranes, respectively, but a fraction of the t-SNAREs are also found on vesicles. This allows potentially physiologically important v- and t-SNARE pairing to occur on the same membrane.** c, **α-SNAP and NSF act on the t-SNARE alone, altering its conformation to allow Rab-mediated vesicle targeting. A series of undefined steps leads to membrane fusion.** d, **After membrane fusion, α-SNAP and NSF act to untangle the SNARE proteins, which are then segregated to vesicle and acceptor membrane compartments for another round of docking.**