different intrinsic latencies. The consequence is that the RyRs in a cluster open and close randomly, generating a relatively slow, damped, and irregular local Ca flux. The Marx *et al.* (*1*) coordinated-gating hypothesis suggests that adjacent RyRs are mechanically linked and that the linked RyRs function (open and close) in a coordinated fashion. The consequence is that RyR clusters operate as functional units and generate large, fast local Ca release events. Thus, concerted RyR gating would speed the SR Ca release process, starting with the most "eager" RyR in the cluster. Concerted RyR gating might also occur in cardiac muscle. Because there are fewer DHPRs per RyR in cardiac cells (*6*), concerted RyR gating may prove to be even more crucial in heart than in skeletal muscle.

Small, localized intracellular Ca release events called Ca sparks have been measured by using fluorescent Ca indicators in skeletal, cardiac, and smooth muscle cells (*7–9*). The Ca spark is generally considered to be the elementary unit of SR Ca release. Although there is not complete agreement, it is likely that the Ca spark (particularly in cardiac muscle) arises from the opening of several RyRs rather than from the opening of a single RyR channel. The concerted RyR gating hypothesis may explain the apparent stereotypical amplitude and duration of the Ca spark. It implies that local RyR clusters operate as all-or-none Ca release units (all channels in a cluster open or closed together). Thus, a Ca spark would represent the brief, simultaneous, concerted opening of all RyRs in a cluster. Global cellular Ca signaling would be the result of RyR group dynamics. For example, in skeletal muscle the all-or-none twitch may result from all RyR clusters firing simultaneously. The graded nature of cardiac Ca-induced Ca release (*10*) may simply represent Ca influx–dependent recruitment of additional RyR clusters to generate the global Ca signal.

FKBP coordianates the gating of the RyR multimer, which is the fundamental SR Ca release channel and individual foot structure (*11*). The new work suggests that FKBP may also help in the cooperative gating of multiple RyRs (although it does not appear to be the glue that sticks them together). Interestingly, targeted knockout of the mouse FKBP12 gene produces a severe cardiomyopathy (and altered cardiac RyR gating), while skeletal muscle can still function (*12*).

This report of the coordinated gating of multiple RyR channels will stimulate new investigation to further define how the remarkable "molecular dance" of the RyR "feet" allows precise control of our muscles.

References

1. S. O. Marx, K. Ondrias, A. R. Marks, *Science* **281**, 818 (1998).
2. B. A. Block *et al.*, *J. Cell Biol.* **107**, 2587 (1988).
3. T. Wagenknecht *et al.*, *Biophys. J.* **70**, 1709 (1996).
4. E. Ríos and M. D. Stern, *Annu. Rev. Biophys. Biomol. Struct.* **26**, 47 (1997).
5. G. R. Ferrier and S. E. Howlett, *J. Physiol.* **484**, 107 (1995).
6. D. M. Bers and V. M. Stiffel, *Am. J. Physiol.* **264**, C1587 (1993).
7. H. Cheng *et al.*, *Science* **262**, 740 (1993).
8. A. Tsugorka, E. Ríos, L. A. Blatter, *ibid.* **269**, 1723 (1995).
9. M. T. Nelson *et al.*, *ibid.* **270**, 633 (1995).
10. A. Fabiato, *J. Gen. Physiol.* **85**, 247 (1985).
11. A. B. Brillantes *et al.*, *Cell* **77**, 513 (1994).
12. W. Shou *et al.*, *Nature* **391**, 489 (1998).

PERSPECTIVES: PALEOMAGNETISM

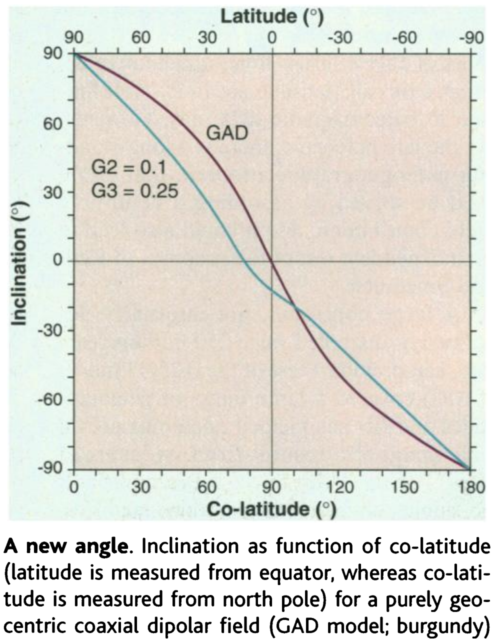
A Complex Field

Rob Van der Voo

Our knowledge of ancient locations of continental blocks is based in part on paleomagnetic data—the direction of the magnetic field in rock samples. Assuming that Earth's magnetic field is a dipole, a formula can be used to determine paleolatitude from the inclination of the rock's magnetic field. However, this formula is only appropriate if the long-term field was purely dipolar and early paleomagnetic publications always stated the premise explicitly. In the past several decades, a purely dipolar field, on average, has been tacitly assumed by paleomagnetists, even though it has become common knowledge that small nondipole contributions were probably long lasting (*1*). These quadrupole and octupole fields are thought to have been mostly zonal (that is, having symmetry about the rotation axis) and were estimated to cause paleolatitude errors of typically some 5° and were therefore not of great concern.

The blissfully ignorant are about to be rudely awakened, however, because of an analysis by Kent and Smethurst (*2*) that reveals a shallow bias in paleomagnetic inclinations older than about 250 million years (the Paleozoic and Precambrian eras). Such an analysis had been carried out in 1976 (*3*), but since that time the database has more than quadrupled, and this time the Precambrian data have also been included. The premise for the analysis is that spatially random sampling of observed inclinations for a given time window produces a frequency distribution that can be compared with the distinctive distributions theoretically calculated for a pure dipole field or for fields of a more complex nature. Representing each observed inclination by its absolute value $|I|$ takes care of sign changes because of reversals of the magnetic field and allows data from the Northern and Southern Hemispheres to be combined.

Kent and Smethurst conclude that, for the past 250 million years, the frequency distributions of $|I|$ are not demonstrably different from those for a purely dipolar field. However, the shallow bias in $|I|$ for rocks older than 250 million years could well be caused by a considerable octupole contribution with a relative magnitude of some 25% of the ambient dipole field; I will call this the "0.25G3" model, where G3 is the ratio of the octupole and dipole fields. Kent and Smethurst examined and rejected several other possible causes for this bias, such as inclination shallowing in sedimentary rocks, which is the flattening of the magnetic vector as the sediments compact over time. They do allow an alternative explanation that involves a geographic (low-latitude) bias in the ancient locations of the continents; if the polar areas were mostly oceanic, the steep inclinations of higher latitudes would be underrepresented, and the database would con-



A new angle. Inclination as function of co-latitude (latitude is measured from equator, whereas co-latitude is measured from north pole) for a purely geocentric coaxial dipolar field (GAD model; burgundy) and for a model that includes a quadrupole and octupole contribution (blue) [adapted from (*2*)].

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tain predominantly shallow inclinations. These two explanations, long-lasting octupole fields or preferentially equatorial paleolocations of the continents, could each have very important implications for paleogeography, as well as for the generation of the magnetic field and the evolution of Earth's core or alternatively for mantle dynamics and true polar wander (that is, a tumbling of the body of Earth with respect to the rotation axis) (*4*).

The most serious immediate implications arise for paleogeography and for paleomagnetists attempting to reconstruct ancient continental configurations. The figure, adapted from Kent and Smethurst (*2*), shows inclination values as a function of latitude for a purely geocentric axial dipole (GAD) model and the 0.25G3 model with the addition of a small quadrupole field (10% of the dipole, or G2 = 0.1). The magnitude of the octupole field is fairly critical for producing a good fit to the observations, but the magnitude of the quadrupole field (G2) is not, because its effects are antisymmetric about the equator and averaged by the analysis method that combines hemispheres. A paleolatitude calculated with the GAD model could differ by up to about 18° from the real paleolatitude if the field were partly nondipolar in this fashion. And if, coincidentally, two coeval paleomagnetic sites, one with an inclination $I = +40°$ and the other with $I = -50°$, were to be compared, the relative paleolatitude difference estimated with the GAD model might be erroneous by more than 30°. Are there any indications that errors of such magnitude could be present? An affirmative answer would mean, of course, that there is some independent evidence for the paleolatitudes, and there's the rub: For most of Precambrian time, quantitative estimates of paleolatitude are fairly well limited to paleomagnetic data only. However, for the late Paleozoic, there is a long-standing paleogeographic problem that could well be solved by assuming a nondipole field contribution, and it could also lead to an independent test of the proposal of Kent and Smethurst.

A large continent, not internally deformed or disrupted since 250 million years ago, can provide a test of the 0.25G3 model if it (i) covered a large range of paleolatitudes and (ii) has yielded numerous coeval paleomagnetic results from widespread sites. For the Paleozoic (or Precambrian), no single continent existing today qualifies, but a supercontinental assembly such as Pangea provides some clues, granted certain assumptions about how it was configured. This mention of "assumptions" reveals, in fact, the "problem": Paleomagnetists have long been forced to modify the classical Pangea A configuration, if they wanted to keep adhering to the GAD model [for discussion, see (*5*)]. From this modification resulted proposals such as those for Pangea B or C, in which the Gondwana continents are located 3500 km (or more) to the east of their Pangea A location with respect to a fixed North America–Europe continent and some 10° to 30° to the north. However, nonpaleomagnetist paleogeographers have not adopted Pangea B or C, and if the 0.25G3 model is applicable to times in which Pangea existed (~250 million years ago), they may have been right.

Kent and Smethurst include in their paper a discussion of the implications of their 0.25G3 model for the evolution of Earth's core and the generation of the magnetic field. They speculate that growth of the solid inner core may have reached a threshold size for stabilizing the GAD field (*6*) as late as some 250 million years ago. However, their alternative explanation of the shallow bias in $|I|$, namely that continents in the Precambrian and Paleozoic were perhaps preferentially located in lower latitudes, is also of great interest. Anderson (*7*) has suggested that supercontinents induced long-lived geoid highs that could influence Earth's moment of inertia tensor in such a way as to cause true polar wander. This would imply that continental movements were "frustrated" in their attempts to reach polar latitudes, as the latter continuously receded to new locations orthogonal to the bulk of the continental positions. As interest in true polar wander in older geological times has recently been revived (*4*), this alternative will undoubtedly see considerable attention in the coming years.

References

1. M. W. McElhinny, P. L. McFadden, R. T. Merrill, *J. Geophys. Res.* **101**, 25007 (1996).
2. D. V. Kent and M. Smethurst, *Earth Planet. Sci. Lett.*, in press.
3. M. E. Evans, *Nature* **262**, 676 (1976).
4. J. L. Kirschvink, R. L. Ripperdan, D. A. Evans, *Science* **277**, 541 (1997).
5. R. Van der Voo, *Paleomagnetism of the Atlantic, Tethys and Iapetus Oceans* (Cambridge Univ. Press, Cambridge, 1993), pp. 117–121; G. Muttoni, D. V. Kent, J. E. T. Channell, *Earth Planet. Sci. Lett.* **140**, 97 (1996).
6. R. Hollerbach and C. A. Jones, *Nature* **365**, 541 (1993); *Phys. Earth Planet. Inter.* **87**, 171 (1995).
7. D. L. Anderson, *Nature* **297**, 391 (1982).

PERSPECTIVES: QUANTUM COMPUTING

Beyond Factorization and Search

Lov K. Grover

All of the computers manufactured so far are based on the laws of classical physics. About 15 years ago, Feynman, Bennett, Deutsch, and others observed that if a computer could be built around the laws of quantum physics instead of those of classical physics, it would result in an entirely different computational structure (*1*). For a long time, it was not obvious how such a device would differ from a classical computer. Finally in 1994, Shor discovered a quantum mechanical algorithm for factorization (*2*). This aroused a lot of interest—mathematicians had been looking for efficient factoring algorithms for several decades and had not found any. Furthermore, commonly used cryptographic codes, such as RSA (Rivest-Shamir-Adleman), had been designed on the assumption that no such algorithm existed. The idea behind Shor's factorization algorithm was something every solid-state physicist knows, namely that periodic quantum systems have special properties (see figure on next page). Shor's insight was to recall the observation that the factorization problem can be converted into one of estimating the periodicity of a sequence, something that quantum systems are very good at (*2*).

The next step took 2 years. In 1996, I discovered a quantum mechanical algorithm that could rapidly search an unsorted database of N items for a single item satisfying a given condition. This took about $\sqrt{N}$ steps, which was surprising because any classical algorithm, deterministic or probabilistic, will clearly need N tries. The idea behind the quantum search algorithm was that a quantum computer can be in a superposition of states and simultaneously examine multiple items. However, for an observer outside the quantum system to be able to determine which is the satisfying item, a process known as amplitude amplification is carried out. In about $\sqrt{N}$ elementary quantum mechanical operations, the amplitude of the desired item is substantially increased at the expense of other items (*3*). The discovery of this quantum search algorithm stimulated experimentalists to explore various physical systems for which this algorithm could be implemented. Very recently, fast search algorithms have been independently implemented by two research groups (*4*).

On the theoretical side, the obvious question is can the search algorithm be further

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