cavity. Prechondrogenic cells surrounding the interzone form the joint capsule and the tendon attachments to adjacent muscle (*1*).

In their search for molecules directing the formation of long bones in the chick embryo, Hartmann and Tabin (*4*) realized that the pattern of Wnt14 expression implicated this signaling molecule in the segmentation of mesenchyme condensations. Wnt14 is expressed both in interzone cells located at the position of future joints, and in neighboring nonchondrogenic cells. Intriguingly, in the fully formed chick limb, Wnt14 is still expressed in joint synovial membrane and connective tissue. These observations prompted the authors to overexpress the *Wnt14* gene in prechondrogenic cells of distal mesenchyme in the chick limb bud.

Overexpression of *Wnt14* resulted in the formation of abnormal cartilage elements or the absence of cartilage altogether. This suggests that Wnt14 may instruct prechondrogenic cells to differentiate into something other than cartilage. Prechondrogenic cells overexpressing Wnt14 appeared to be morphologically similar to interzone cells—they produced large amounts of type III collagen (an essential component of joints) but very little chondromucin (found in cartilage) (*1*). This result implicates Wnt14 in the induction of joint formation (although true joints were not formed, possibly because of the variable amounts of Wnt14 produced in this rather artificial system).

A pivotal part for Wnt14 in joint development was substantiated by data from micromass cultures, which were prepared from embryonic chick limb (stage 22 to 23). Overexpression of Wnt14 in micromass cultures did not prevent the formation of pre-cartilage aggregates but did inhibit the differentiation of these aggregates into cartilage nodules. The presence of interzone-specific markers—such as Gdf5, autotaxin, and chordin—confirmed that Wnt14 was instructing prechondrogenic cells to become interzone cells. Thus, Wnt14 initiates joint formation, probably acting upstream of Gdf5, autotaxin, and chordin.

The investigators noticed that whenever Wnt14 induced the formation of an interzone in one place, interzone formation at a nearby location was blocked. Therefore, Wnt14 may also be essential for the correct spacing of joints and, in turn, for the formation of the correct number of bones in the limb skeleton. The capacity to form joints may be an intrinsic property of all prechondrogenic cells in mesenchyme condensations. External guidance cues may direct prechondrogenic cells in the proximal region of mesenchyme to form an interzone. Release of inhibitory molecules by interzone cells would then prevent the formation of a second interzone too close to the first. The second interzone would then be formed only by prechondrogenic cells that were sufficiently far away to be unaffected by the inhibitory factors. This sequence of events may be correct: Interzone cells produce chordin, an inhibitor of bone morphogenetic proteins (BMPs), whereas cells surrounding mesenchyme condensations produce BMPs, which are known to promote joint formation. Although robust evidence is still lacking, it is intriguing that treatment of chick limb buds with noggin (another BMP inhibitor) reduces the number of phalanges (*7*).

In any case, if the formation of one joint is necessary to determine the position of the next, induction of the first interzone still needs to be explained. The first joint forms at the initial branching point of the mesenchyme condensation (*6*). From an evolutionary perspective, it is logical that joint formation should be linked to the segmentation of bone primordia—the branching of one bone into two is of no benefit if it is not accompanied by introduction of an articulation. There is little doubt that joint formation is intimately linked to the spatiotemporal organization of mesenchyme condensations. Wnt14 may well turn out to be a key player in both bone segmentation and joint formation.

Finally, the continued production of Wnt14 by cells in the synovial membranes and capsules of mature joints supports the notion that Wnt signaling is involved in the maintenance of adult synovial joints. Messenger RNA transcripts for some Wnt molecules and their target genes are up-regulated in the synovial joint cells of patients with rheumatoid arthritis (*8*). Engineering mice with mutations in different Wnts should reveal whether the Wnt signaling pathway is necessary for the maintenance of joint integrity. If it is, then members of the Wnt family may provide new therapeutic targets for treating synovial joint diseases.

References

1. P. H. Francis-West *et al.*, *Cell Tissue Res.* **296**, 111 (1999); E. E. Storm, D. M. Kingsley, *Development* **122**, 3969 (1996); N. M. Wolfman *et al.*, *J. Clin. Invest.* **100**, 321 (1997).
2. E. E. Storm *et al.*, *Nature* **368**, 639 (1994).
3. A. Polinkovsky *et al.*, *Nature Genet.* **17**, 18 (1997).
4. C. Hartmann, C. J. Tabin, *Cell* **104**, 341 (2001).
5. J. R. Hinchliffe, D. R. Johnson, *The Development of the Vertebrate Limb* (Clarendon, Oxford, 1980).
6. N. H. Shubin, P. Alberch, *Evol. Biol.* **20**, 319 (1986).
7. R. D. Dahn, J. F. Fallon, *Science* **289**, 438 (2000).
8. M. Sen *et al.*, *Proc. Natl. Acad. Sci. U.S.A.* **97**, 2791 (2000).

PERSPECTIVES: GEOPHYSICS

When the Compass Stopped Reversing Its Poles

Subir K. Banerjee

Earth's magnetic field reverses a few times every million years at random intervals, as a result of positive feedbacks to magnetohydrodynamic instabilities within the liquid iron core (*1*). Occasionally, however, the dynamo mechanism in Earth's liquid iron core stops its dance of random dipole field reversals and for 30 to 50 million years maintains either "normal" polarity (like today) or the reversed state (in which a compass would point south). At least two such superchron periods are known in the recent geological past. Between 118 and 83 million years ago (Ma) (the Cretaceous superchron), the field maintained constant normal polarity, and it remained reversed from 312 to 262 Ma. Why did the random dipolar reversal suddenly stop, and what made the stochastic dance start again?

To answer this question, we require accurate data of geomagnetic field behavior during a superchron, so as to devise and test models of geomagnetic dynamo behavior that could cause it. On page 1779 of this issue, Tarduno *et al.* (*2*) report the latest in a series of innovative attempts to accurately determine the magnitude of the magnetic field at Earth's surface and the virtual dipole moment (VDM) at Earth's center that is responsible for it before, during, and after the Cretaceous superchron (*3*–*5*). Unlike low values found by previous authors, however, Tarduno *et al.* find that during the superchron, the time-averaged VDM was 12×10^{22} A/m^2—twice as high as the average for the past 160 Ma (*4*) and 50% higher than today.

Obtaining a truly accurate datum that is not contaminated by local effects unrelated to the global dipole field is a real tour de force. Tarduno *et al.* used a multistep polishing and etching method to extract 149 single crystals of plagioclase feldspar from eight independent lava flows that erupted at different times between 113 and 115 Ma. Other researchers have previously performed paleomagnetic and rock magnetic studies at the

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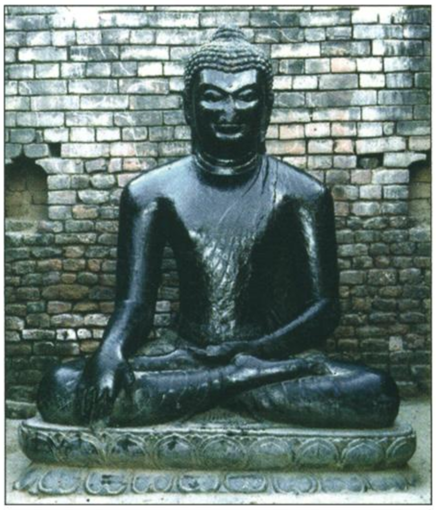
same site, the Rajmahal volcanic field near the Bihar/West Bengal state boundary in eastern India. But unlike previous investigators, Tarduno *et al.* concentrated on measuring the weak (~10^{-11} A/m^2) but geologically stable magnetic moment from millimeter-sized single crystals of plagioclase, rather than whole rocks. The reason was simple: Although whole rocks ~2.5 cm in size may have more easily measurable magnetic moments, laboratory reheating inevitably causes some degree of chemical alteration, compromising the reliability of the measurement. Tarduno *et al.* show that whole rock samples contain clay minerals formed since crystallization by weathering at Earth's surface. These rapidly break down during laboratory reheating and produce new, very effective carriers of magnetic remanence (the magnetization that remains after the removal of an external field). This excess magnetite conspires to produce a remanent magnetization of the same magnitude as observed today in nature (the natural remanent magnetization, NRM) but in a weaker field than the original geomagnetic paleointensity. In contrast, the tiny (100- to 350-nanometer diameter) magnetite inclusions sealed inside the plagioclase crystals are safe from chemical change and thus yield the true paleointensity during the Cretaceous superchron. This leads to the deduced high value for the VDM.



A site of more than scientific interest. This Buddha sculpture is at the famous Buddhist school at Nalanda, near the Rajmahal volcanic field.

CREDIT: FREDERICK ASHER/VISUAL ARTS CENTER, DEPARTMENT OF ART HISTORY, UNIVERSITY OF MINNESOTA

Of the 149 single crystals of plagioclase that were studied, 56 satisfied rigorous reproducibility tests. The latter come from eight lava flows that erupted at different times within 0.1 to 1 Ma. The average value from all the flows and all the 56 crystals with reproducible data can thus be taken to represent the true dipolar field during Cretaceous superchron. The averaging process removes potential sources of error in VDM magnitude due to the highly variable (in space and time) nondipole components of the total geomagnetic field. These have shorter than 10,000-year periodicities and hence cancel out when data are averaged over 0.1 to 1 Ma.

The fact that it represents a reliable time average distinguishes Tarduno *et al.*'s VDM value from those deduced with an earlier, equally innovative method that targeted submarine basaltic glasses found in ocean sediments (*6*). The magnetite carriers of NRM are again protected from chemical change in the laboratory by their natural glass armor. However, unlike the layered stratigraphy of the Rajmahal volcanic lavas, individual submarine glass samples cannot be shown to be from sources that erupted over a sufficiently long time interval to cancel out nondipole contributions. This may explain why studies based on submarine basaltic glasses (*4*, *5*) have yielded equivocal answers as to whether the VDM was unusually high or low during the Cretaceous superchron.

One may argue that compared with the 35-Ma length of the superchron, we have so few reliable VDM values that the jury is still out. But there is some conceptual and model support for the high value of Tarduno *et al.* The late Allan Cox suggested (*7*) that during times of high dipole field strength, nondipoles cannot randomly drive the total field to reversal and furthermore (*8*) that even though core reversals may be stochastic, their frequency may be set and reset in intervals of ~100 Ma by processes in the core-mantle boundary. And in a recent three-dimensional numerical modeling study by Glatzmaier *et al.* (*9*), the field did not reverse when the imposed core-mantle boundary heat flux pattern was in phase with the convected flux from the liquid core. This led to very high dipole field values.

The tales of Panchatantra, a Buddhist book of fables, were written within a few hundred kilometers of the volcanic field of Rajmahal. It tells the well-known story of five blind men in complete disagreement about the shape and size of an elephant that they could all touch (but at different spots on the elephant). We need many more "seeing eyes" to explain why superchrons occur, but we are one step closer to knowing what characterized them.

References

1. R. T. Merrill *et al.*, *The Magnetic Field of the Earth* (Academic Press, San Diego, CA, 1996).
2. J. A. Tarduno, R. D. Cottrell, A. V. Smirnov, *Science* **291**, 1779 (2001).
3. M. Perrin, V. Shcherbakov, *J. Geomagn. Geoelectr.* **49**, 601 (1997).
4. M. T. Juarez *et al.*, *Nature* **394**, 878 (1998).
5. P. Selkin, L. Tauxe, *Philos. Trans. R. Soc. London Ser. A* **358**, 1065 (2000).
6. T. Pick, L. J. Tauxe, *J. Geophys. Res.* **98**, 17949 (1993).
7. A. J. Cox, *J. Geophys. Res.* **73**, 3247 (1968).
8. ______, *Rev. Geophys. Space Phys.* **13**, 35 (1975).
9. G. A. Glatzmaier *et al.*, *Nature* **401**, 885 (1999).

PERSPECTIVES: COSMOLOGY

Probing the Early Universe with the SZ Effect

Marshall Joy and John E. Carlstrom

The cosmic microwave background radiation (CMBR) we observe today provides a window to an early stage in our universe's evolution, when the expanding universe had cooled to the point that free electrons and ionized nuclei recombined to form atoms. Before recombination, scattering between photons and free electrons was frequent, and the distance that light could penetrate was small; afterward, with free electrons out of circulation, the universe became largely transparent to light. Small variations in the CMBR intensity trace small perturbations in the primordial matter density, which have been amplified by gravitational forces to form the magnificent, complex structures that make up the present-day universe.

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In certain massive objects, however, interactions between CMBR photons and free electrons continue to play an important cosmological role. The largest gravitationally collapsed structures in the universe are clusters of galaxies with masses up to 100,000 times greater than the mass of our galaxy, the Milky Way. At optical wavelengths, clusters are beautiful objects consisting of thousands of galaxies, each containing billions of stars, all bound together by a strong gravitational field. The galaxies and stars, however, only account for a few percent of the total mass. Most of the normal (baryonic) matter resides in the hot (~100 million K) gas that permeates the galaxy cluster. When CMBR photons interact with the free electrons in