

Neolithic archaeology are two sites dating to the Pre-Pottery Neolithic A (PPNA, ~11,700 to 10,500 B.P.). As on the mainland, the PPNA in Cyprus includes villages but does not yet contain morphologically domesticated plants and animals. These sites essentially erase the chronological gap between the Akrotiri Phase and the Neolithic. One site, Ayia Varvara *Asprokremnos*, is a small interior locality (18), the other, *Klimonas* (see the figure, panel C), a more substantial coastal settlement where plants were apparently cultivated but not domesticated (19).

The Neolithic transformation initially occurred in the Near East, but then spread to adjacent areas. This transmission is often thought to have been through Anatolia, but the new research also suggests maritime routes, with the Cypriot evidence indicating a substantial level of mainland interaction.

Genetic data also point to linkages between northern European Neolithic populations and modern groups that include Cypriots (20).

The past 20 years have revolutionized our understanding of the early occupation of the Mediterranean islands. Future research should include developing better chronological controls, conducting rigorous surveys, excavations, and analyses, searching for sites within an intact stratigraphy, and asking questions related to why early humans set forth to these islands. Such studies will continue to change our conceptions of early seafaring and the reasons behind it and of the ever widening influence of the Neolithic Revolution.

References

1. J. Cherry, *J. Medit. Arch.* **3**, 145 (1990).
2. P. Hiscock, *Archaeology of Ancient Australia* (Routledge, London, New York, 2008).
3. A. Brumm *et al.*, *Nature* **464**, 748 (2010).

4. C. Broodbank, *J. Med. Arch.* **19**, 199 (2006).
5. N. Laskaris, *et al.*, *J. Arch. Sci.* **38**, 2475 (2011).
6. C. Perlès, *Recherche* **10**, 82 (1979).
7. T. Strasser *et al.*, *Hesperia* **79**, 145 (2010).
8. G. Ferentinos *et al.*, *J. Arch. Sci.* **39**, 2167 (2012).
9. A. Simmons, *Faunal Extinctions in an Island Society: Pygmy Hippopotamus Hunters of Cyprus* (Kluwer Academic/Plenum, New York, 1999).
10. A. Simmons, R. Mandel, *World Archaeol.* **39**, 475 (2007).
11. A. Ammerman *et al.*, *Rep. Dept. Antiq., Cyprus* **2008**, 1 (2008).
12. N. Efstratiou, D. Kiriakou, *Anaskamma* **5**, 53 (2011).
13. T. Strasser, *Newsletter of the American School of Classical Studies at Athens* **66**, 11 (2012).
14. B. Knapp, *J. World Prehist.* **23**, 79 (2010).
15. E. Peltenburg *et al.*, *Antiquity* **74**, 844 (2000).
16. J. Guilaine, F. Briois, J.-D. Vigne, Eds., *Shillourokambos. Un Établissement Néolithique Pre-Céramique à Chypre. Les Fouilles du Secteur 1* (Erance, Athens, 2011).
17. A. Simmons, *J. Field Archaeol.* **37**, 86 (2012).
18. S. Manning, *et al.*, *Antiquity* **84**, 693 (2010).
19. J.-D. Vigne *et al.*, *Proc. Natl. Acad. Sci. U.S.A.* **109**, 8445 (2012).
20. P. Skoglund *et al.*, *Science* **336**, 466 (2012).

10.1126/science.1228880

PLANETARY SCIENCE

A Vitrage of Asteroid Magnetism

Benjamin P. Weiss

In the early solar system, some protoplanets experienced large-scale melting, leading to the formation of a metallic core overlain by a rocky mantle. This differentiated structure has persisted to the present day in large bodies such as Earth. In Earth's core, vigorous churning of molten metallic liquid generates the geomagnetic field in a process known as the dynamo (1). Although we have no samples of Earth's core, many smaller protoplanets were catastrophically shattered over the intervening eons, producing the present-day asteroid belt and providing us with meteorite samples from their deep interiors. These samples provide a natural cross section of asteroid interiors, with stony meteorites thought to have formed at shallow depths and iron meteorites in the core. Intermediate in composition between these two types are the pallasites, spectacular mixtures of translucent, gem-quality olivine crystals and iron-nickel metal that, when backlit, take on the quality of a medieval stained-glass window (vitrage) (see the first figure). The origin of pallasites and the nature of their parent body (2) have perplexed meteoriticists since the first, eponymous meteor-

ite Pallas was described in 1794 (3). On page 939 of this issue, Tarduno *et al.* (4) suggest that the pallasite parent body was the product of a near-catastrophic impact of a molten body onto a differentiated protoplanet with an active core dynamo.

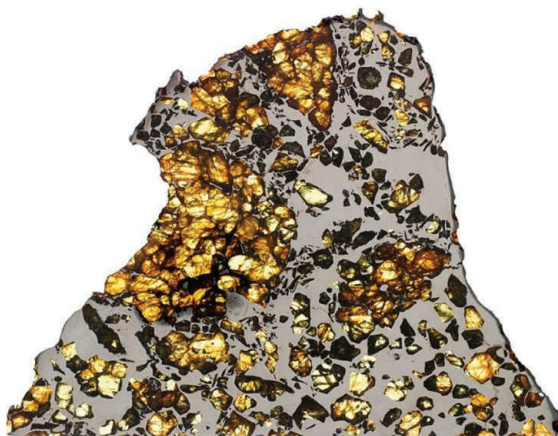
Starting with the earliest visions of meteorite parent body interiors (5), it has been widely assumed that pallasites originated from a gradational boundary layer between the metallic core and overlying rocky mantle (6) (see the second figure). Nevertheless, it

A group of stony-iron meteorites record an ancient magnetic field that may reveal an origin far from the asteroidal core.

was soon recognized that olivine's relatively low density makes such a mixture buoyantly unstable (7). Furthermore, the diverse rates at which various pallasites cooled may be inconsistent with formation deep below an insulating mantle and anchored to a thermally conducting metallic core (8). These findings motivated alternative proposals that pallasites formed as the result of an impact onto a differentiated planetesimal that structurally scrambled the body by mixing molten core and solid mantle materials (8).

Tarduno *et al.* add a fascinating new twist to this debate with their discovery of remanent magnetization in two pallasites. When a rock cools in the presence of a magnetic field, it can acquire remanent magnetization whose intensity is proportional to the field. This magnetization can then persist for billions of years, long after the paleofield has dissipated. In this way, rocks from planetary bodies record the presence of past dynamo activity.

Because of their small size, asteroidal cores have long since solidified and therefore cannot be generating mag-



Pallasite vitrage. Photograph of the pallasite Esquel showing translucent olivine crystals suspended in metal.

Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA 02139, USA. E-mail: bpweiss@mit.edu

netic fields today. Until recently it had been unclear whether asteroids could ever have generated magnetic fields—even when their cores were molten—given that the feasibility of the dynamo process generally increases with core size. However, studies of several stony meteorite groups indicate that core dynamos probably operated in at least several early asteroids (9, 10), thus making asteroids the smallest objects known to have generated magnetic fields.

Meteoriticists have wondered whether iron or pallasite meteorites might record a core dynamo due to their assumed close proximity to the field-generating region of these bodies. However, these meteorites have stubbornly defied magnetic investigations since they were first attempted in 1959 (11). A chief difficulty has been that chunks of intergrown iron crystals typically have poor magnetic recording properties (12). Furthermore, because metallic cores should be mostly isothermal (because of their high thermal conductivity), by the time that core metal cools to temperatures sufficiently low that it could become permanently magnetized, any dynamo may have long since decayed away (13).

Tarduno *et al.* sidestep the first problem by analyzing extracted olivine crystals, which have far better magnetic recording properties than the surrounding metal. These pallasites record substantial magnetic fields, with intensities ranging up to nearly twice that of Earth today. Assuming that these fields were directly produced by an ancient dynamo in the pallasite parent body core, Tarduno *et al.* argue that the body could not have been too big (otherwise, the pallasites would have to come from near the surface, where they would be shattered or destroyed by meteoroid impacts) nor too small (or else they would have cooled faster than observed). They also argue that the pallasites could not have formed at the core-mantle boundary because of the aforementioned requirement that they must cool down before the cessation of dynamo activity. Rather, formation in the outer ~40 km of a protoplanet ~200 km in radius with a core 100 km in radius matches the combined constraints. As a result, they propose that pallasite metal did not come from the interior core of the protoplanet but rather from that of a differentiated foreign impacting body (see the second figure).

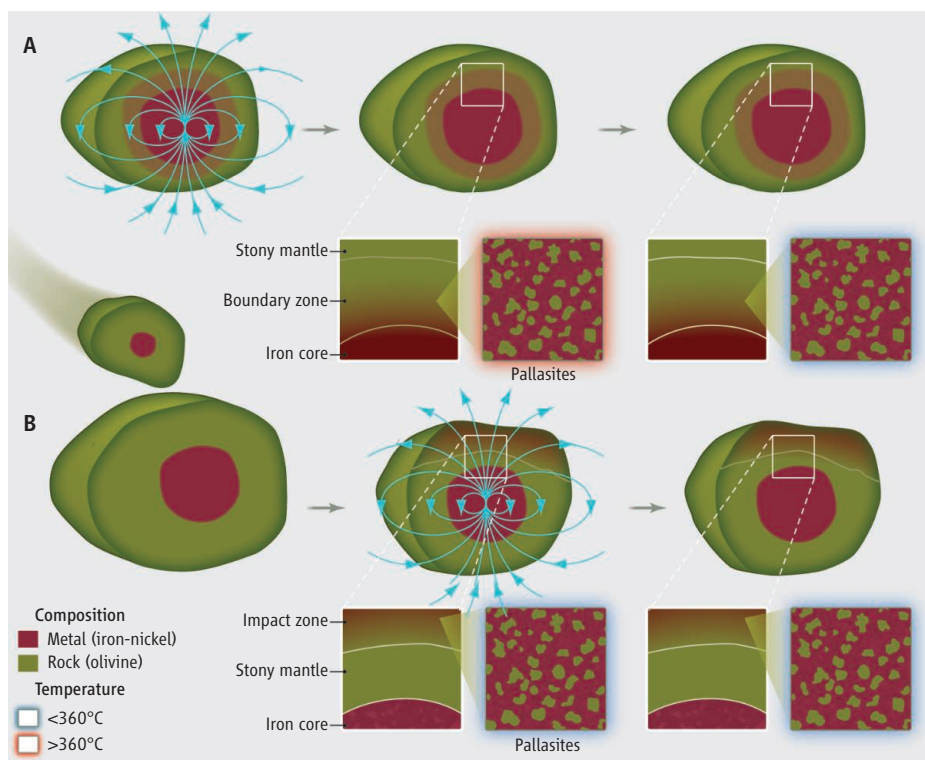
These paleomagnetic measurements are an important new data set with far-reaching implications for the origin of pallasites. A caveat is that it is unknown whether the field that magnetized these pallasites was that of an active dynamo or rather from remanent magnetization in surrounding rocks. For example, surface fields in some locations on Mars today are as strong as Earth's field even though Mars does not have an active dynamo (14). If this were true for the pallasite parent body, an earlier dynamo would still be indicated (because it would likely be required to have produced the magnetization in the surrounding rocks), but the pallasites' magnetism would not rule out an origin at the core-mantle boundary.

Among the terrestrial planets, only Earth and Mercury today have active dynamos. The pallasite parent protoplanet now becomes at least the fourth asteroid-sized body known to have generated a core dynamo, even though the magnetization of only a few meteorite groups has yet been analyzed in detail. This suggests that planetary dynamos may have at one time been common. One can imagine that the early solar system, which contained perhaps thousands of protoplanets larger than 100 km in diameter (15), once brimmed with swarms of little magnetospheres.

References and Notes

1. D. J. Stevenson, *Space Sci. Rev.* **152**, 651 (2010).
2. Most pallasites are classified as part of the "main group" whose members have similar chemical and isotopic compositions and are therefore thought to originate from a single body.
3. E. F. F. Chladni, *Über den Ursprung der von Pallas gefundenen und anderer ihr ähnlicher Eisenmassen und über einige damit in Verbindung stehende Naturerscheinungen* (Johann Friedrich Hartknoch, Riga, 1794).
4. J. A. Tarduno *et al.*, *Science* **338**, 939 (2012).
5. A. Boissé, *Recherches sur l'Histoire, la Nature et l'Origine des Aërolithes* (Cramaux, Mémoires de la Société des Lettres, Sciences et des Arts de l'Aveyron, 1847).
6. J. S. Boesenberg, J. S. Delaney, R. H. Hewins, *Geochim. Cosmochim. Acta* **89**, 134 (2012).
7. R. A. Fish, G. G. Goles, E. Anders, *Astrophys. J.* **132**, 243 (1960).
8. J. Yang, J. I. Goldstein, E. R. D. Scott, *Geochim. Cosmochim. Acta* **74**, 4471 (2010).
9. R. R. Fu *et al.*, *Science* **338**, 238 (2012).
10. B. P. Weiss, J. Gattacceca, S. Stanley, P. Rochette, U. R. Christensen, *Space Sci. Rev.* **152**, 341 (2010).
11. J. F. Lovering, *Am. J. Sci.* **257**, 271 (1959).
12. A. Brecher, L. Albright, *J. Geomag. Geoelectr.* **29**, 379 (1977).
13. C. S. Cissowski, in *Geomagnetism*, J. A. Jacobs, Ed. (Academic Press, London, 1987), vol. 2, pp. 525–560.
14. M. H. Acuña, G. Kletetschka, J. E. P. Connerney, in *The Martian Surface: Composition, Mineralogy, and Physical Properties*, J. F. Bell, Ed. (Cambridge Univ. Press, Cambridge, 2008), pp. 242–262.
15. A. Morbidelli, W. F. Bottke, D. Nesvorný, H. F. Levison, *Icarus* **204**, 558 (2009).

Acknowledgment: I thank T. F. Peterson and the NASA Origins of Solar Systems program for support.



Pallasite production. Two models for the main-group pallasite parent body. (A) Pallasites formed in a gradational boundary layer between the metallic core and silicate mantle. The pallasites would not record an active dynamo field because they could not have cooled sufficiently to become permanently magnetized until after the dynamo had decayed. (B) Pallasites formed near the planetary surface as a result of metal injected into a protoplanet from the molten core of an impactor (4). They cooled while a dynamo was still active, thereby acquiring remanent magnetization.