tinguished from a "boring" gapped state by the fractionalized spin-$\frac{1}{2}$ at each end. Other known examples of such SPT states include the time-reversal invariant topological insulators and superconductors discovered in recent years (*3–5*).

Chen *et al.* propose a generic classification scheme of SPT states in general dimensions by using the mathematical tool of group cohomology. Heuristically, cohomology studies how many ways exist to thread magnetic fluxes into a manifold. To see its relation to spin fractionalization, consider a spin vector rotating in the x-y plane (see the figure, panel B). If we think of the tip of the spin vector as a charged particle, a full rotation of the spin around the z axis corresponds to the particle moving around the equator ring by a full cycle. If we then thread a half quanta of magnetic flux through the ring, the wavefunction changes sign as the particle goes around the ring, known as the Aharonov-Bohm effect. Possible values of the fluxes, that is, the cohomology, determine the possible distinct topological states. In generic cases, the cohomology should be that of the symmetry group (*1*) instead of the trajectory of the spin, and the discussion above should only be taken as a heuristic picture.

The group cohomology approach has been previously applied to classifying one-dimensional (1D) topological states (*6–8*). The most important progress of Chen *et al.* is the generalization to higher dimensions, which can also be understood in the Aharonov-Bohm effect picture. For example, for a 2D lattice model (see the figure, panel C), there is a line of spins along its edge. Therefore, the end points of these spins form a string in space, instead of a single point in the case of the boundary of one dimension. The time evolution of the string is a surface, which is the analog of the particle orbit in the 1D case. One can then define a flux threaded into the surface, which is a monopole point instead of a flux line. If the string moves around the monopole point, it obtains an Aharonov-Bohm phase that fractionalizes the string. Such magnetic fluxes observed by strings, or higher-dimensional membranes, are characterized by higher cohomology groups of the symmetry group. Chen *et al.* describe the topological states classified by such group cohomology in generic dimensions by presenting exact solvable prototype lattice models for each class, with explicitly defined actions and ground-state wave functions.

Chen *et al.*'s approach is powerful because it describes a large class of new topological states in general dimensions, which is a major expansion of our knowledge on SPT states in interacting many-body systems. Many interesting questions follow: Because the prototype models proposed are discrete lattice models, is there a continuous field theory description for each topological class? Because this approach has been recently generalized to fermion systems (*9*), can it include the free fermion topological insulators and superconductors? And what materials can realize the proposed models?

From the quantum Hall effect to topological insulators, the interplay between symmetry and topology keeps providing us pleasant surprises. The understanding of SPT states suggests that what we have learned so far is only the tip of the iceberg. Besides predicting novel materials, better understanding of symmetry and topology may also shed new light on the understanding of some of the deepest mysteries of our universe, such as the electron spin.

References and Notes

1. X. Chen, Z.-C. Gu, Z.-X. Liu, X.-G. Wen, *Science* **338**, 1604 (2012).
2. F. D. M. Haldane, *Phys. Lett. A* **93**, 464 (1983).
3. M. Z. Hasan, C. L. Kane, *Rev. Mod. Phys.* **82**, 3045 (2010).
4. J. E. Moore, *Nature* **464**, 194 (2010).
5. X.-L. Qi, S.-C. Zhang, *Rev. Mod. Phys.* **83**, 1057 (2011).
6. L. Fidkowski, A. Kitaev, *Phys. Rev. B* **83**, 075103 (2011).
7. A. M. Turner, F. Pollmann, E. Berg, *Phys. Rev. B* **83**, 075102 (2011).
8. X. Chen, Z.-C. Gu, X.-G. Wen, *Phys. Rev. B* **83**, 035107 (2011).
9. Z.-C. Gu, X.-G. Wen, arXiv:1201.2648 (2012).

Acknowledgments: Supported by NSF grant DMR-1151786.

10.1126/science.1232394

GEOCHEMISTRY

Modeling the Formation of Porphyry-Copper Ores

Dynamic changes in the permeability of Earth's crust are needed to account for the formation of porphyry-copper ores from magmatic fluids.

Steven E. Ingebritsen

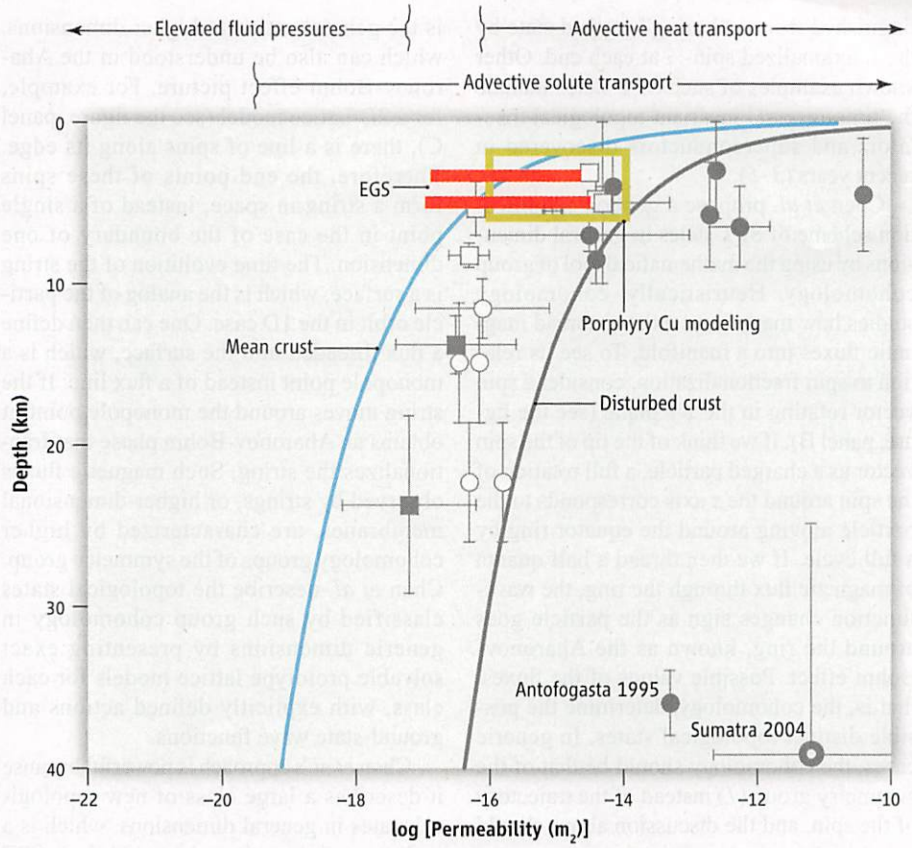
Porphyry-copper ore systems, the source of much of the world's copper and molybdenum, form when metal-bearing fluids are expelled from shallow, degassing magmas. On page 1613 of this issue, Weis *et al.* (*1*) demonstrate that self-organizing processes focus metal deposition. Specifically, their simulation studies indicate that ores develop as consequences of dynamic variations in rock permeability driven by injection of volatile species from rising magmas. Scenarios with a static permeability structure could not reproduce key field observations, whereas dynamic permeability responses to magmatic-fluid injection localized a metal-precipitation front where enrichment by a factor of 10^3 could be achieved [for an overview of their numerical-simulation model CSMP++, see (*2*)].

Dynamic variations in crustal permeability are likely a key to the genesis of many ore deposits, and are also of great interest in the context of enhanced gas and oil production ("fracking"), enhanced geothermal systems (EGSs), geologic carbon sequestration, and both natural and induced seismicity. The permeability of Earth's crust largely governs important geologic processes such as the advective transport of heat and solutes and the generation of elevated fluid pressures by processes such as physical compaction and mineral dehydration. For an isotropic material, permeability k is defined by Darcy's law, which relates the fluid discharge per unit area q to the gradient of hydraulic head h as $q = (kg\rho/\mu)\nabla h$, where ρ is fluid density, μ is fluid viscosity, and g is gravity. Although the permeabilities of common geologic media vary by approximately 16 orders of magnitude, k can sometimes be characterized at the crustal scale in a manner that provides useful insight (see the figure) (*3–5*).

Hydrogeologists and petroleum engineers traditionally treat permeability as a static material property that exerts control on fluid flow, but many economic geologists, geophysicists, and metamorphic petrologists have long recognized that permeability

---

U.S. Geological Survey, Menlo Park, CA 94025, USA. E-mail: seingebr@usgs.gov



How permeable is the crust? Estimates of "mean crust" permeability *k* shown here are based on hydrothermal modeling and the progress of metamorphic reactions (*4*), but on geologically short time scales, *k* may greatly exceed these values (*5*). The power-law fit to these high-*k* data [not including the recently published Sumatra datum (*11*)] is labeled "disturbed crust." The evidence includes rapid migration of seismic hypocenters (solid circles), enhanced rates of metamorphic reaction in major fault or shear zones (open circles), recent studies suggesting much more rapid metamorphism than had been canonically assumed (solid squares), and anthropogenically induced seismicity (open squares); error bars depict the full permissible range for a plotted locality and are not Gaussian errors. Red lines indicate *k* values before and after EGS reservoir stimulation at Soultz (upper line) (*12*) and Basel (lower line) (*13*), and the green rectangle is the *k*-depth range invoked in modeling by Weis *et al.* of the formation of porphyry-copper ores. Arrows above the graph indicate approximate ranges of *k* over which certain geologically important processes are likely.

can respond to dewatering and fluid production [see, for example, (*5*, *6*) and references therein]. This dynamic view of crustal permeability is consistent with indications that during prograde metamorphism (in which volatiles are lost), fluid pressure is nearly in balance with the lithostatic load of the overburden (*7*); sufficiently overpressured fluids cannot be contained in the crust and create the permeability necessary to escape. The permeability of the brittle upper crust may also be dynamically self-adjusting (*8*, *9*).

Weis *et al.* implemented these concepts by using permeability ranges similar to those actually observed in EGSs at similar depths (see the figure). EGS technology aims to enhance heat extraction by fracturing rock with insufficient natural permeability. The bulk permeability of ~1 km^3 of rock increased by a factor of 100 or more in EGS experiments that injected water at rates of tens of kilograms per second, rates similar to those invoked by Weis *et al.* for volatile injection.

A debatable assumption by Weis *et al.* is that permeability is negligibly low between 350° and 400°C, a temperature range associated with the brittle-to-ductile transition (BDT). The argument that a certain permeability is required for volatile release applies both above and below the BDT, and "mean crust" permeabilities on the order of 10^{-19} to 10^{-18} m^2 have been inferred to midcrustal depths on that basis (see the figure). The BDT depends on mineralogy and strain rate as well as temperature [e.g., (*10*)], and in the Weis *et al.* study, it occurs at shallow depths (a few kilometers) because the crust is locally heated by igneous intrusion (typically the BDT occurs at 10 to 15 km depth). The most extreme examples of inferred high permeabilities at great depth come from subduction zones, which are cooled by subducting crust. For instance, a recent reanalysis of the 2004 magnitude 9.2 Sumatra-Andaman earthquake attributes certain aftershock sequences to the migration of aqueous fluids along splay faults, and infers permeabilities on the order of 10^{-12} to 10^{-10} m^2 at depths of 25 to 55 km (*11*). These values are comparable to permeabilities of young, unaltered volcanic rocks in the near surface.

The figure compares data that represent the mean permeability of the tectonically active continental crust (*4*), continental crust disturbed by various transient processes (*5*), selected EGS experience (*12*, *13*), and the porphyry-copper simulations. The higher permeability values must be ephemeral in the context of geologic time; for instance, such high values would imply that heat transport in the continental crust is dominated by advection rather than conduction (see the figure), which is demonstrably not the case. However, as in the porphyry-copper study, ephemeral episodes of higher permeability can lead to localized heat and mass transport and may be linked to certain kinds of seismicity.

The innovative study by Weis *et al.* represents a happy marriage of the Earth science disciplines of hydrogeology and economic geology (the latter being that branch of the Earth sciences concerned with the genesis of ore deposits). The number of economic geologists has declined to <2% of total U.S. geoscience faculty (*14*); for practical and strategic issues related to mineral supply, a resurgence of this discipline is needed.

References and Notes

1. P. Weis, T. Driesner, C. A. Heinrich, *Science* **338**, 1613 (2012); 10.1126/science.1225009.
2. http://csmp.ese.imperial.ac.uk/wiki
3. T. Gleeson *et al.*, *Geophys. Res. Lett.* **38**, L02401 (2011).
4. C. E. Manning, S. E. Ingebritsen, *Rev. Geophys.* **37**, 127 (1999).
5. S. E. Ingebritsen, C. E. Manning, *Geofluids* **10**, 193 (2010).
6. M. Manga *et al.*, *Rev. Geophys.* **50**, RG2004 (2012).
7. W. S. Fyfe, N. J. Price, A. B. Thompson, *Fluids in the Earth's Crust* (Elsevier Scientific, New York, 1978).
8. J. Townend, M. D. Zoback, *Geology* **28**, 399 (2000).
9. S. A. Rojstaczer, S. E. Ingebritsen, D. O. Hayba, *Geofluids* **8**, 128 (2008).
10. F. Simpson, *Geofluids* **1**, 123 (2001).
11. F. Waldhauser, D. P. Schaff, T. Diehl, E. R. Engdahl, *Geology* **40**, 243 (2012).
12. K. F. Evans, A. Genter, J. Sausse, *J. Geophys. Res.* **110**, B04203 (2005).
13. M. O. Häring, U. Schanz, F. Ladner, B. C. Dyer, *Geothermics* **37**, 469 (2008).
14. M. Hitzman, J. Dilles, M. Barton, M. Boland, *GSA Today* **19**, 26 (2009).

Acknowledgments: Thanks to B. Bekins, S. Hurwitz, and J. Lowenstern for helpful comments on an earlier version of this manuscript.

10.1126/science.1231706