that removal of the atmospheric argon contaminant by the step-heating analysis technique is sufficient to reveal that a recycled component is present at the scale of the whole ocean basin. Our data imply that atmospheric rare gases are recycled to the mantle, although in amounts weak enough not to compromise completely the isotopic signature of the degassed mantle component (*26*). Conversely, our study also supports the notion that the radiogenic lead-bearing material present in the mantle is recycled (*20*). Therefore, argon turns out to be a tracer of subduction by providing a quasi-atmospheric signature to recycled matter. Other isotopic tracers such as Pb or Sr do not retain a clear signature of their passage at the surface of Earth; for example, the buildup of ^{206}Pb in recycled sediments started well before subduction, in the crust that generated the sediments. These results could lead to a way to better quantify the amount of material recycled to the mantle and the age of recycling.

References and Notes

1. F. P. Fanale, *Chem. Geol.* **8**, 79 (1971).
2. M. Ozima, *Geochim. Cosmochim. Acta* **39**, 1127 (1975).
3. C. J. Allègre, T. Staudacher, P. Sarda, M. D. Kurz, *Nature* **303**, 762 (1983).
4. C. J. Allègre, T. Staudacher, P. Sarda, *Earth Planet. Sci. Lett.* **81**, 127 (1986–87).
5. J. Kunz, T. Staudacher, C. J. Allègre, *Science* **280**, 877 (1998).
6. M. D. Kurz, W. J. Jenkins, J.-G. Schilling, S. R. Hart, *Earth Planet. Sci. Lett.* **58**, 1 (1982).
7. D. W. Graham *et al.*, *ibid.* **110**, 133 (1992).
8. J. Dymond and L. Hogan, *ibid.* **38**, 117 (1978).
9. P. Sarda, T. Staudacher, C. J. Allègre, *ibid.* **72**, 357 (1985).
10. D. E. Fisher, *Nature* **256**, 113 (1975).
11. T. Staudacher and C. J. Allègre, *Earth Planet. Sci. Lett.* **60**, 389 (1982).
12. T. Staudacher *et al.*, *ibid.* **96**, 119 (1989).
13. M. Moreira, T. Staudacher, P. Sarda, J.-G. Schilling, C. J. Allègre, *ibid.* **133**, 367 (1995).
14. H. Hiyagon, M. Ozima, B. Marty, S. Zashu, H. Sakai, *Geochim. Cosmochim. Acta* **56**, 1301 (1992).
15. K. A. Farley and R. J. Poreda, *Earth Planet. Sci. Lett.* **114**, 325 (1993).
16. M. Moreira, J. Kunz, C. Allègre, *Science* **279**, 1178 (1998).
17. Argon and Pb data, with sample depths and locations, can be found at *Science* Online (www.sciencemag.org).
18. This model predicts that no $^{40}Ar/^{36}Ar$ ratio higher than ~3000 should ever be measured in Atlantic samples with $^{206}Pb/^{204}Pb$ ratios higher than 19.5.
19. P. Schiano, J.-L. Birck, C. J. Allègre, *Earth Planet. Sci. Lett.* **150**, 363 (1997).
20. W. M. White and A. W. Hofmann, *Nature* **296**, 821 (1982).
21. C. J. Allègre, B. Hamelin, A. Provost, B. Dupré, *Earth Planet. Sci. Lett.* **81**, 319 (1986/87).
22. A. W. Hofmann, *Nature* **385**, 219 (1997).
23. C. J. Allègre and D. Turcotte, *ibid.* **323**, 123 (1986).
24. D. Fontignie and J.-G. Schilling, *Earth Planet. Sci. Lett.* **142**, 209 (1996).
25. For example, sample AII107-7/10-1g is situated in a relatively low position in the correlation. On the basis of Pb-Nd-Sr systematics (*24, 33*), this sample reflects the influence of Gough and Tristan plumes.
26. T. Staudacher and C. J. Allègre, *Earth Planet. Sci. Lett.* **89**, 173 (1988).
27. C. Chauvel, A. W. Hofmann, P. Vidal, *ibid.* **110**, 99 (1992).
28. K. P. Jochum, A. W. Hofmann, E. Ito, H. M. Seufert, W. M. White, *Nature* **306**, 431 (1983).
29. S. Sun and W. F. McDonough, in *Magmatism in the Ocean Basins*, A. D. Saunders and M. J. Norry, Eds. (Blackwell, Oxford, 1989), vol. 42, pp. 313–345.
30. N. Machado, J. N. Ludden, C. Brooks, G. Thompson, *Nature* **295**, 226 (1982).
31. L. Dosso, H. Bougault, J.-L. Joron, *Earth Planet. Sci. Lett.* **120**, 443 (1993).
32. B. Hamelin, B. Dupré, C. J. Allègre, *ibid.* **67**, 340 (1984).
33. B. B. Hanan, R. H. Kingsley, J.-G. Schilling, *Nature* **322**, 137 (1986).
34. J. Douglass, J.-G. Schilling, D. Fontignie, *J. Geophys. Res.*, in press.
35. L. Dosso, unpublished data.
36. J.-G. Schilling, B. B. Hanan, B. McCully, R. H. Kinglsey, S. Fontignie, *J. Geophys. Res.* **99**, 12005 (1994).

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Electrical Conductivity in the Precambrian Lithosphere of Western Canada

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The subcrustal lithosphere underlying the southern Archean Churchill Province (ACP) in western Canada is at least one order of magnitude more electrically conductive than the lithosphere beneath adjacent Paleoproterozoic crust. The measured electrical properties of the lithosphere underlying most of the Paleoproterozoic crust can be explained by the conductivity of olivine. Mantle xenolith and geological mapping evidence indicate that the lithosphere beneath the southern ACP was substantially modified as a result of being trapped between two nearly synchronous Paleoproterozoic subduction zones. Tectonically induced metasomatism thus may have enhanced the subcrustal lithosphere conductivity of the southern ACP.

Petrographic, geochemical, and isotopic data indicate chemical heterogeneity in the subcontinental mantle (*1*) that is thought to result from depletion (melt extraction) and enrichment (metasomatic) events (*2*) over time. Physical samples of these mantle processes are sparsely and irregularly distributed, hampering tectonic interpretations. Upper mantle structure is more systematically revealed in global seismic tomography studies that suggest high-velocity keels (*3*) beneath Archean shields that, together with petrological data, imply an FeO poor, but olivine and orthopyroxene rich, mineralogy (*4*). How these keels have influenced, or been modified by, tectonic activity is an area of active research.

Laurentia is the Precambrian core of North America and consists of a cluster of Archean and Proterozoic provinces sutured together by extensive orogenic activity around 1900 to 1750 million years ago (Ma) (*5*) (Fig. 1). Geologic evidence of ancient convergent continental plate margins, such as fold and thrust belts and magmatic arcs, are preserved within the Proterozoic orogenic belts that surround the Archean Churchill Province (ACP) (*5*). Seismic reflection, geological, and geochemical data suggest that this Archean crust was uplifted and then reworked as a result of being trapped between two converging Paleoproterozoic orogenies (*6, 7*). As part of the LITHOPROBE Alberta Basement Transect, a magnetotelluric survey consisting of seven profiles was conducted over an area of ~550,000 km^2, covering the southern ACP and adjacent Proterozoic crust to the northwest (Fig. 1). Electromagnetic (EM) fields were recorded in the period range of 4 to 20,000 s to probe beneath the overlying veneer of conductive Phanerozoic sediments (Fig. 2, top panel). For periods of 30 to 3000 s, the EM data are dominated by the response of a number of continuous, subparallel, electrically thin yet conductive bodies between 3- and 10-km depth (top panel of Fig. 2, near sites 12 and 15). These conductors are interpreted (*8*) to represent euxinic shales, originally deposited in a Proterozoic foreland basin (*9*) and subsequently imbricated and metamorphosed at ~1850 Ma. The deeper conductors seen in the top panel of Fig. 2 are unresolvable as individual bodies and may represent mid-crustal anisotropy.

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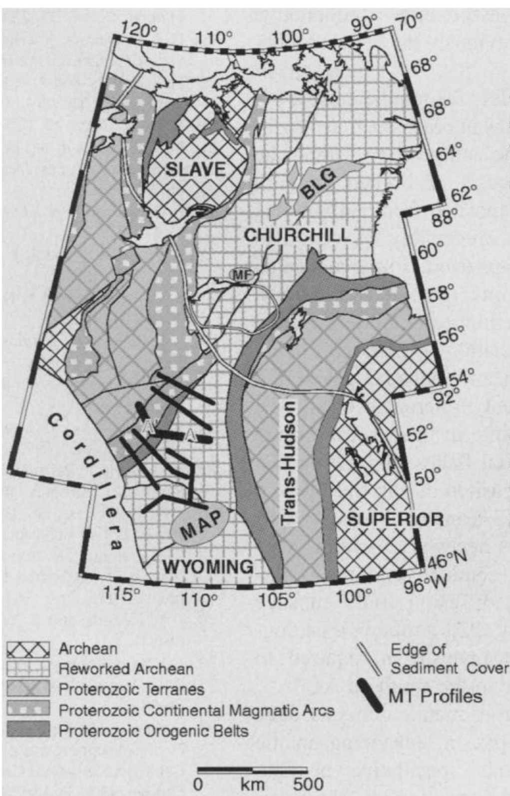
These electromagnetic data demonstrate near complete decoupling into two independent modes over virtually the entire range of recorded periods (*8*, *10*). Such decoupling is consistent with a planar EM source field (*11*) and a two-dimensional (2D) crustal conductivity distribution, in this case striking approximately northeast. We inverted the data to construct 2D models of the conductivity structure. Data from a 200-km profile in the southeast corner of the survey area show no azimuthal dependence (*10*), allowing undistorted 1D estimates of the lithospheric conductivity structure beneath the Archean crust in this one region. Elsewhere, currents flowing parallel to geologic strike [the transverse electric (TE) mode] are affected by the presence of the highly conductive bodies in the upper crust. These bodies must be electrically thin and elongated because they do not affect currents flowing perpendicular to their geologic strike [the transverse magnetic (TM) mode]. As a consequence of the fortuitous occurrence of elongated thin conductors, these TM mode data offer a rare view of the subcontinental mantle unimpeded by the response of crustal structures (compare top and bottom panels in Fig. 2). The 2D inversion results illustrate the extent of TE and TM mode decoupling and the partitioning of the crustal conductor response solely into the TE mode, and consequently demonstrate the two dimensionality of these EM data. Equivalent models were obtained from inversions of TM mode data from each of five different profiles (Fig. 1). Distortion of the observed data by the response of 3D conductivity structures within the crust is unlikely given the complete decoupling into 2D modes shown in Fig. 2.

Two-dimensional conductivity models derived from inverting all the TM mode data (without static distortion corrections (*8*)) along each traverse show that the lithosphere beneath the Archean surface rocks is more conductive than that underlying the Proterozoic terranes (Fig. 2, bottom panel). This contrast in electrical properties is resolved on all profiles, being constrained by observation stations separated by 12 to 15 km, a distance much smaller than the observed length scale of mantle conductivity variations (>60 km). The inversion process intentionally recovers the smoothest model that fits the data, in harmony with the expected resolution capabilities of diffusive EM fields at these periods. Fine geometrical information about the conductivity distribution (for example, contact dips) is, therefore, intrinsically unresolvable with these data, as is the conductivity deeper than 250 km. The trend to increased conductivity with depth is consistent with thermally activated solid-state conduction in mantle minerals. The modeled conductivity of the lithosphere underlying the Proterozoic crust (~0.001 S/m at 150 km) is comparable with that inferred beneath the stable shield of the Archean Superior Province (*12*) and with laboratory studies on olivine (*13*). However, the conductivity beneath the southern ACP crust (~0.01 S/m at 150 km) is one order of magnitude larger than allowed by a dry, olivine-rich mantle.

The spatial correlation of mantle conductivity with crustal age is a first-order constraint that may be used to assess the role of tectonic processes in modifying the mineralogy of the mantle. At subsolidus temperatures, the electrical properties of both the mineralogy (dominantly ferromagnesian olivine) and interconnected phases of minor constituents determine mantle conductivity. Laboratory measurements on dry San Carlos olivine samples at mantle temperatures indicate that thermally activated electric current flows by small polaron hopping, primarily between holes created by the substitution of Fe^{2+} by Fe^{3+} (*14*). If the lithosphere is to be chemically buoyant and refractory to melting, the implausibly iron-rich composition (perhaps Fo_{40}) required to explain the inferred conductivity seems untenable. Increased oxygen fugacity (f_{O_2}) can enhance olivine conductivity by augmenting the Fe^{3+} concentrations, but is



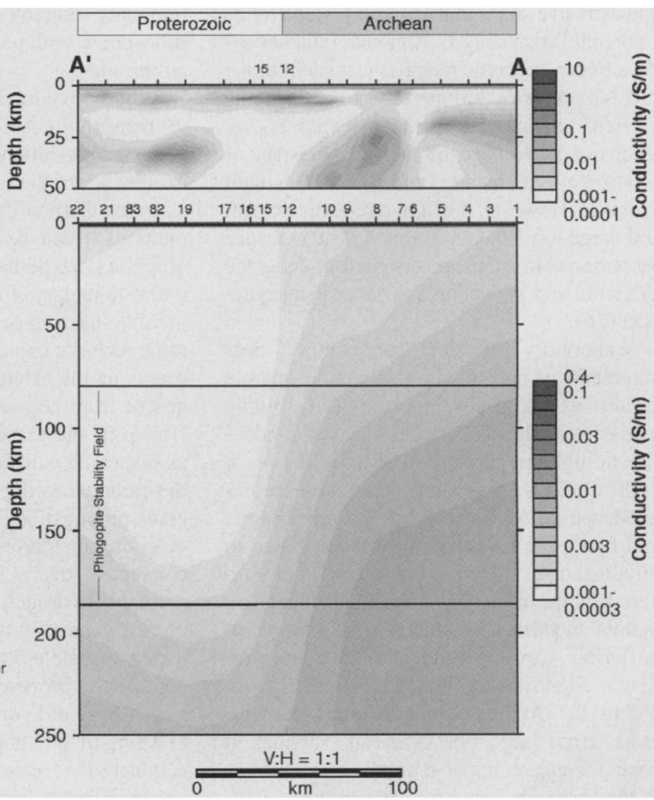


Fig. 1 (left). Tectonic map of western Laurentia ignoring the Phanerozoic sedimentary cover [modified from (*5*)]. Major Precambrian features under Phanerozoic cover are inferred from potential field data and drill results. Dark lines indicate the MT measurement profiles with A-A′ indicating the position of the profile shown in Fig. 2. Potassic to ultrapotassic suites: BLG, Proterozoic Baker Lake Group (*21*, *28*); MAP, Cenozoic Montana Alkalic Province (*22*); MF, Proterozoic Martin Formation (*23*). The area intruded by minette dikes extends at least 250 km around the indicated BLG. **Fig. 2 (right).** Electrical conductivity models derived from TE+TM mode data inversion (top) and from only TM mode data inversion (bottom) along line A-A′ (Fig. 1). Station numbers appear at the top of each section. Note the difference between the two contour scales. Phlogopite stability field is from (*30*).

limited by the restricted range of estimated mantle oxidation states (*15*). It seems unlikely that bulk mantle composition, thermodynamic state, or even fluids can explain the observed conductivity beneath the southern ACP and the spatial correlation with the upper crustal provinces.

An important characteristic of the Wyoming and Churchill Provinces lithosphere is the evidence for mantle metasomatism. Although spatially and temporally separated, multiple exposures of widespread potassic to ultrapotassic dykes and extrusive suites having a similar chemistry are known within the Archean Churchill [Baker Lake Group (BLG) and Martin Formation (MF)] and Wyoming Provinces [Montana Alkalic Province (MAP)] (Fig. 1) (*16–18*). Ultrapotassic magma petrogenesis is thought (*19*) to depend fundamentally on the existence of hydrous mineral veins (for example, phlogopite) within mantle peridotite (*20*). The extreme trace element and isotopic compositions of the ultrapotassic magmas require derivation, at least in part, from metasomatized upper mantle that was isolated from mixing since at least 1800 Ma (*21–24*). In this regard, it is significant that the conductivity anomaly (Fig. 2) falls within the stability field of phlogopite (*25*). Direct evidence of hydrous modal metasomatism is found in glimmerite (dominantly phlogopite veins) in xenoliths recovered from Eocene minettes of the MAP just south of the EM survey area (*17*, *24*). Glimmerite nodules are also described from Proterozoic dykes and extrusive suites in the Keewatin area of the Churchill Province (*23*). Although minettes expose Eocene potassic magmas just south of the EM survey area, sedimentary cover and the inherent limitations on xenolith exposures restrict our knowledge of the lateral extent of metasomatized mantle under the Churchill Province. However, the light rare-earth element and large-ion lithophile enrichment evidence for widespread mantle metasomatism under the Churchill and Wyoming Provinces is unequivocal (*16*).

Laboratory electrical conductivity measurements of hydrous minerals under mantle conditions are rare. In one study (*26*), biotite gneiss from the KTB drill hole was conductive at high temperature, reaching 0.1 S/m at 1000°C. These data show little pressure dependence up to 40 MPa but are anisotropic, and hence the conductivity was attributed to phyllosilicates. More work is required to understand the effect of hydrous minerals on mantle electrical conductivity (in terms of buffering capacity and defect concentrations). Significantly though, EM data from within the Archean Superior Province (remote from any post-Archean subduction zones) indicate upper-mantle conductivities in the range observed for dry olivine (*12*). A conductive mantle is thus not characteristic of all Archean cratons, supporting the notion that enhanced conductivity may be related to the Paleoproterozoic enrichment history characteristic of the southern ACP lithosphere.

Our preference is to associate electrical conductivity with the process of modal metasomatism, perhaps related to the inward shallow subduction on opposing margins of the ACP. Although the exact processes or mineralogy required to produce the conductivity anomaly remains uncertain, we suggest a model of Proterozoic geochemical modification as a consequence of shallow subduction perhaps followed by convective or gravitational removal (or both) of tectonically thickened lithospheric mantle. Evidence for this model is found in the peak metamorphism in the exposed ACP that occurred from 1815 to 1796 Ma (*6*) but somewhat later in the lower crust of the southern ACP (*27*). The southern ACP underwent penetrative deformation during the Proterozoic including crustal-scale thrust imbrication and shortening and may have behaved as a weak plate trapped between two inward-facing subduction zones. The age of the oceanic lithosphere and presence of buoyant continental crust in the Trans-Hudson orogen (*7*) suggest relatively low-angle subduction zones. This strongly coupled subduction system might have thickened the ACP lithosphere enough to allow a portion of it to be removed, gravitationally or convectively. Consequent heating would induce small degrees of partial melting that further enriched the overlying lithospheric remnants, thereby associating a conductive lithosphere with previously thickened Archean terranes.

Alternative models for mantle conductivity beneath the Archean crust, such as graphite or exotic olivine composition, cannot be excluded on the basis of limited xenolith samples. Carbon deposited from carbonatitic melts (*28*) can be irreversibly converted to graphite (*29*), perhaps even as interconnected grain boundary films (*30*). South African graphite-bearing peridotite xenoliths have the same tectonic association as diamonds, being found in the Archean Kaapvaal craton but absent from adjacent Proterozoic belts (*31*). However, the graphite in these rocks occurs as dispersed euhedral flakes, suggesting that the carbon was deposited during fluid-driven crack propagation (*31*) and not by the wetting of grain boundaries necessary to form interconnected (that is, conductive) films. Alternatively, hydrogen diffusion could enhance olivine conductivity (*32*), although a geologically plausible mechanism is required to confine the process to the southern ACP.

The role of hydrous mantle minerals, such as veins of phlogopite, in enhancing mantle conductivity remains speculative pending comprehensive laboratory studies. However, the essential observational evidence remains; a well-resolved, enhanced electrical conductivity distribution is unequivocally correlated with the metasomatized lithosphere of the southern ACP. The EM data thus add important independent information to the body of evidence suggesting that the Churchill Province lithosphere was extensively and pervasively reworked during the Paleoproterozoic. If the ~1700 Ma (*27*) metamorphic data from the lower crust reflects convective thinning, the chemical and geophysical data suggest that a significant fraction of the Churchill lithosphere remained attached to the crust.

References and Notes

1. S. R. Carter *et al.*, *Science* **202**, 743 (1978).
2. D. R. Nelson, M. T. McCulloch, S.-S. Sun, *Geochim. Cosmochim. Acta*, **50**, 231 (1986).
3. S. P. Grand, *J. Geophys Res.* **92**, 14065 (1987).
4. D. L. Anderson and J. D. Bass, *Geophys. Res. Lett.* **11**, 637 (1984).
5. P. F. Hoffman, *Annu. Rev. Earth Planet. Sci.* **16**, 543 (1988).
6. G. M. Ross *et al.*, *Geology* **23**, 195 (1995).
7. S. B. Lucas *et al.*, *Geol. Assoc. Can. Mineral. Assoc. Can. Annu. Meet. Prog.* **22**, A93 (1997).
8. D. E. Boerner, R. D. Kurtz, J. A. Craven, S. Rondenay, W. Qian, *Geology* **23**, 297 (1995).
9. D. E. Boerner, R. D. Kurtz, J. A. Craven, *J. Geophys. Res.* **101**, 13775 (1996).
10. D. E. Boerner *et al.*, *Can. J. Earth Sci.* **35**, 175 (1998).
11. M. Mareschal, *Geophys. J. R. Astron. Soc.* **67**, 125 (1981).
12. A. Schultz *et al. Geophys. Res. Lett.* **20**, 2941 (1993).
13. S. Constable, T. J. Shankland, A. Duba, *J. Geophys. Res.* **97**, 3397 (1992).
14. L. M. Hirsch, T. J. Shankland, A. G. Duba, *Geophys. J. Int.* **114**, 36 (1993).
15. J. D. Blundy, J. P. Brodholt, B. J. Wood, *Nature* **349**, 321 (1991).
16. T. D. Peterson, S. Esperança, A. N. LeCheminant, *Mineral. Petrol.* **51**, 251 (1994).
17. H. E. O'Brien, A. J. Irving, I. S. McCallum, M. F. Thirlwall, *Geochim. Cosmochim. Acta* **59**, 4539 (1995).
18. H. E. Hendry and P. K. Mazimhaka, *Geol. Assoc. Can. Abstr. Prog.* **13**, A54 (1994).
19. S. Foley, *Lithos* **28**, 235 (1992).
20. M. A. Menzies *et al.*, in *Mantle Metasomatism*, M. A. Menzies *et al.*, Eds. (Academic Press, London, 1987), pp. 313–361.
21. F. Ö. Dudás, R. W. Carlson, D. H. Eggler, *Geology* **15**, 22 (1987).
22. R. W. Carlson and A. J. Irving, *Earth Planet. Sci. Lett.* **126**, 457 (1994).
23. T. D. Peterson and A. N. LeCheminant, *Can. Mineral.* **31**, 801 (1993).
24. R. L. Rudnick, A. J. Irving, T. R. Ireland, *Eos Suppl.* **74**, 320 (1993).
25. D. R. Bell and G. R. Rossman, *Science* **255**, 1391 (1992).
26. M. Laštovièková, G. Losito, A. Trova, *Phys. Earth Planet. Int.* **81**, 315 (1993).
27. W. J. Davis, R. Berman, B. Kjarsgaard, in *1995 Alberta Basement Transects Workshop*, *Lithoprobe Report #47*, G. M. Ross, Ed. (Lithoprobe Secretariat, University of British Columbia, 1995), pp. 330–335.
28. E. B. Watson, J. M. Brenan, D. R. Baker, in *Continental Mantle*, M. A. Menzies, Ed. (Clarendon, Oxford, 1990), pp. 111–125.
29. J. D. Pasteris and B. Wopenka, *Can. Mineral.* **29**, 1 (1991).
30. M. Mareschal *et al.*, *Nature* **375**, 134 (1995).
31. D. G. Pearson *et al.*, *Contrib. Mineral Petrol.* **115**, 449 (1994).
32. S. Karato, *Nature* **347**, 272 (1990).

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