# THERMAL THICKNESS OF CRATONIC LITHOSPHERE: A GLOBAL STUDY

**Irina M. Artemieva* and Walter D. Mooney**

*U.S. Geological Survey, 345 Middlefield Rd., Menlo Park, CA 94025 ,*
*Fax: 1-650-329 5163; irina@andreas.wr.usgs.gov; mooney@usgs.gov*

** Now at Dept. of Earth Sciences, Uppsala University, Villavagen 16, S-75236, Uppsala, Sweden. Fax: 46-18-50 11 10. Email: iartem@geofys.uu.se*

**Abstract**

The thermal thickness of Precambrian lithosphere is calculated and compared with estimates from seismic tomography and xenolith data. We present the maps of the lateral temperature distribution at depths 50, 100 and 150 km and the map of the thermal thickness of the lithosphere. We find that the thickness of continental lithosphere generally decreases with age, from >200 km beneath Archean cratons, to 200±50 km in early Proterozoic lithosphere, and to 140±50 km in middle and late Proterozoic cratons. The Ar-ePt lithosphere is found to have two typical thicknesses, 200-220 km and 300-350 km. In general, thin (~ 220 km) Ar-ePt roots are found in the southern hemisphere (South Africa, Western Australia, South America and India) and thicker (>300 km) roots are found in the northern hemisphere (Baltic Shield, Siberian Platform, West Africa, and possibly the Canadian Shield). We find that Ar-ePt mantle lithosphere is 1.5% less dense (chemically depleted) than the underlying asthenosphere, while mPt-lPt sub-crustal lithosphere should be depleted by ~ 0.6-0.7 %. Our results suggest three contrasting stages of lithosphere formation at the ages: >2.5 Ga, 2.5-1.8 Ga, and <1.8 Ga, which apparently reflect secular changes in mantle temperature.

**Introduction and Method**

Seismic tomography shows that the continental lithosphere of many Archean (>2.5 Ga.) shields commonly exceeds 200-300 km, whereas the lithosphere of post-Archean (<2.5 Ga.) crust is only 100-200 km thick (e.g., Ekström et al., 1997; Polet and Anderson, 1995; Grand, 1994; Zhang and Tanimoto, 1993). In contrast, studies of pressure-temperature (P-T) relations for mantle xenoliths suggest only about 200-220 km thickness for the Archean lithosphere in South Africa, eastern Siberia, the Baltic Shield, and North America (e.g., Boyd, 1984; Boyd et al., 1985; Rudnick et al., 1998; Rudnick and Nyblade, 1999; Kopylova et al., 1999; Kukkonen and Peltonen, 1999).

In this study we estimate the thermal thickness of the Precambrian lithosphere and compare it to the lithospheric thickness as estimated from global and regional seismic tomography and from P-T data derived from lithospheric xenoliths. We calculate the temperature distribution in the stable continental lithosphere from the solution of the steady-state thermal conductivity equation. This study is facilitated by global databases for heat flow (Pollack et al., 1993), updated for more recent data, and crustal structure (Mooney et al., 1998). We use consistent assumptions for depth distributions of thermal parameters. This approach permits quantitative comparison of lithospheric geotherms and lithospheric thermal thickness in different cratons. We consider eight of the nine

Precambrian cratons: the East-European (including Baltic and Ukrainian shields), Siberian, Indian, Australian, African, South American, North American, and Cathaysian cratons.

**Data**

Most of the heat flow data were derived from the global compilation of Pollack et al. (1993) (with ~300 data points for Ar and ~1000 points for Pt crust). These data were supplemented by ~250 new data points for stable continental crust. All heat-flow data were analyzed, as far as possible, for potential regional perturbations; paleoclimatic corrections to surface heat flow data were made using standard procedures.

Seismic data from the global crustal database of the U.S. Geological Survey were used to distinguish crustal layers in order to constrain typical models of the depth distribution of thermal parameters. About 500 models of the depth distribution of heat-producing elements (HPEs), used to calculate continental geotherms, were based on laboratory studies of heat production in near-surface rocks, data on seismic velocities in the crust, and direct HPE measurements in exposed upper-middle Precambrian crust (Nicolaysen et al., 1981; Ashwal et al., 1987; Fountain et al., 1987; Weaver and Tarney, 1984; Pinet and Jaupart, 1987). For the crystalline upper crust we assumed an exponential decrease in heat production with depth (Lachenbruch, 1970), with a variable thickness D (5 to 15 km). The average calculated values of the total heat production in Archean and post-Archean crust were compared with published estimates derived from petrologic models for Precambrian crustal composition that are constrained mainly by crustal xenoliths (McLennan and Taylor, 1996; Rudnick and Fountain, 1995; Rudnick et al., 1998; Shaw et al., 1986; Weaver and Tarney, 1984). Summary of the thermal properties of the Precambrian crust and lithosphere assumed in the present study is given in the Table.

| Layer | Depth range (km) | $V_p$ (km/s) | Thermal conductivity (W/m/K) | Heat production ($\mu W/m^3$) |
|---|---|---|---|---|
| Sedimentary cover | 0-10 | 3.0-5.6 | 0.5-4.0 | 0.7-1.3 |
| Upper crust | 0-25 | 5.6-6.0<br>6.0-6.5 | 2.5-3.0<br>2.6-2.8 | 0.4-6.7<br>0.4-0.5 |
| Middle crust | 20-40 | 6.5-7.0 | 2.0-2.5 | 0.2-0.4 |
| Lower crust | 30-50 | 7.0-7.5 | 2.0 | 0.1 |
| Lithospheric mantle | >35-50 | >7.9<br>>8.3 | 4.0<br>4.0 | 0.01<br>0.004 |

**Results**

Geotherms

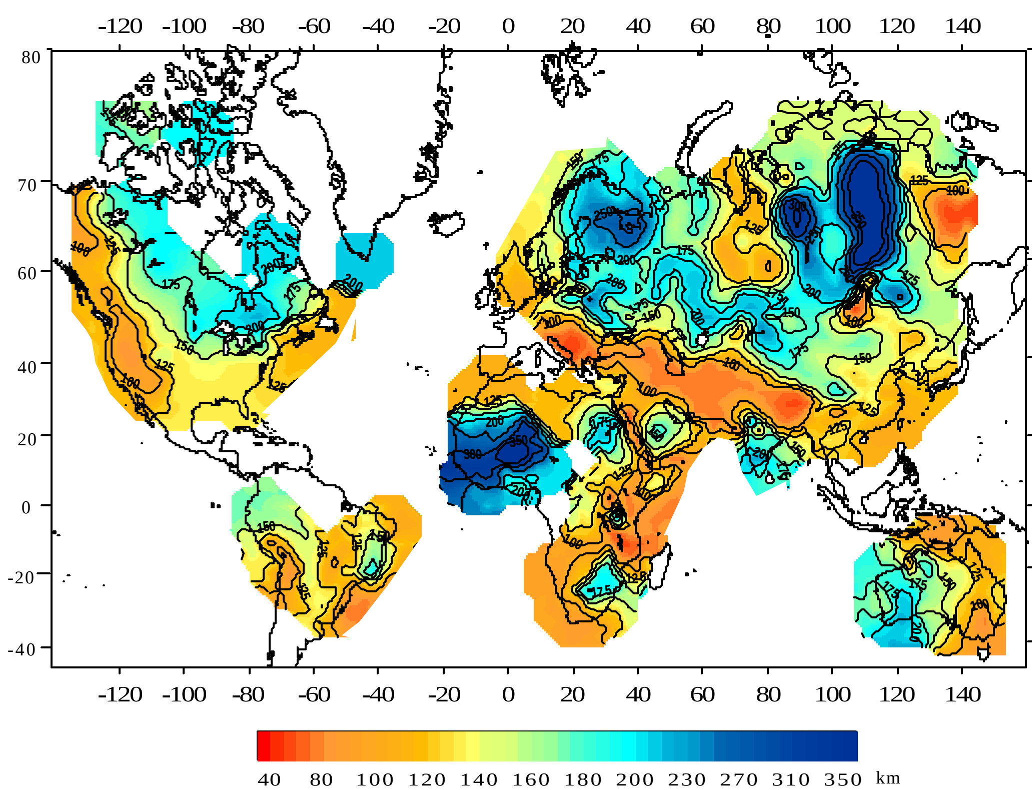
We present the maps of lithospheric temperature for Precambrian cratons and adjacent regions for depths of 50, 100 and 150 km. Unlike previous studies, we used consistent model assumptions for all Precambrian cratons, which permits meaningful comparisons. Estimates of the thermal state of the lithosphere in tectonically active regions (such as the North American Cordillera, the Andes, the East African Rift, Tibet, the Himalayas, the Baikal Rift Zone, the Carpathians and the Caucasus) are not based on our steady-state modeling, but on petrologic and non-steady state geothermal constraints available for these regions. In accord with these publications, temperatures at 50 km depth were assumed to be in the range 900 to 1100$^{o}$C and the lithosphere thermal thickness to be 60 to 80 km.

Temperatures at 50 km depth vary widely from about 300$^{o}$C in cold Archean regions, through about 600$^{o}$C in middle and late Proterozoic blocks, to more than 1000$^{o}$C in tectonically active regions. Typical temperatures at the Moho were estimated to be 300-500$^{o}$C in Archean cratons (where the crust is usually about 30 to 45 km thick, but occasionally exceeds 45 km) and 500-800$^{o}$C in middle and late Proterozoic regions (where crustal thickness is typically 40 to 55 km, and averages about 45 km).

The calculated temperature distributions at depths of 100 and 150 km agree well with results from seismic tomography, both globally (e.g., Nataf and Ricard, 1996; Ekström et al., 1997; Van Heijst and Woodhouse, 1997) and regionally for Australia (Van der Hilst et al., 1998), North America (Van der Lee and Nolet, 1997), Eurasia (Ritzwoller and Levshin, 1998) and Africa (Ritsema and van Heijst, 2000). The thermal and seismic results are in particularly good agreement for Australia where data quality is very good. The agreement for West Africa is very encouraging in view of the fact that the heat flow data are sparse there. Both the seismic and thermal estimates indicate that the Sino-Korean craton is underlain by warm mantle and lacks a lithospheric root.

Lithospheric thermal thickness

The thickness of the thermal lithosphere, here defined as a conductive layer above a mantle adiabat of 1300$^{o}$C, was calculated for all of the Precambrian cratons (Figure). We find two typical thicknesses of the Archean lithosphere, one about 200-220 km, the other about 350 km. This result is supported by mantle convection models that suggest the existence of two equilibrium thicknesses of the thermal boundary layer above the



convecting mantle: 220 and 350 km (Doin et al., 1997). The wide range of lithospheric thermal thicknesses for Archean regions (from 160 to 350 km), which is not observed for regions of any other age, is supported by global seismic tomography studies that show the base of the high-velocity zone can vary from 100 to 400 km (Zhang and Tanimoto, 1993; Grand, 1994; Ekström et al, 1997; Polet and Anderson, 1995).

The first group of Archean cratons with relatively thin lithospheric roots includes South Africa, Western Australia, the Indian Shield, Cathaysian Craton, and the Saõ Francisco Craton in South America. It is possible that the Congo and Antarctic Cratons, which were adjacent to the above cratons during the existence of the ancient supercontinents, belong to this group as well.

The second group of cratons with lithospheric roots exceeding 300 km includes the Siberian Platform, West Africa, and the Baltic Shield. A lack of heat flow data does not permit us to draw any conclusions for some portions of the central and especially northern Canadian Shield, nor for the Amazon Craton, where heat flow data are entirely absent. However, seismic tomography data (e.g., Polet and Anderson, 1995) provide strong evidence that the Canadian Shield belongs to the group of Archean cratons with thick lithospheric roots. A recent comparative study of Precambrian South Africa and the Canadian Shield (Jaupart and Mareschal, 1999) also supports the idea that these two regions have different deep thermal regimes.

Compared to Archean lithosphere, the thickness of middle and late Proterozoic lithosphere appears to be more uniform. The calculated thickness ranges from 110-130 km (the Sino-Korean Craton, Northern Australia and the mobile belts around the Kaapvaal and Zimbabwe Cratons) to 150-170 km in mid-Proterozoic blocks of the Baltic and Indian Shields and in Western Australia. Exceptionally thick (≥ 200 km) Proterozoic lithosphere, similar to that of typical Archean lithosphere, was found only for the Grenville Province and the Trans-Hudson Orogen of the Canadian Shield.

Density of the roots

Isostasy requires that cold, thick lithosphere be chemically depleted (Jordon, 1975; Boyd, 1989). Using the temperatures at the base of the crust and typical lithosphere thicknesses from this study, we now estimate the density contrast between the asthenosphere and the lithospheric mantle for northern and southern Archean lithosphere. The calculations follow the approach of Lachenbruch and Morgan (1990) and are based on the assumption that isostatic balance is achieved locally at the base of the lithosphere.

Our isostatic calculations suggest that all Archean cratons (i.e., in both the northern and southern hemispheres) have a composition that is 1.5% less dense (depleted) than the underlying asthenosphere. The equality of lithospheric depletion estimated for all Archean and early Proterozoic cratons is a consequence of systematic variations in crustal thickness of the northern and southern hemisphere cratons (36-62 km, with an average of 45 km, and 30-43 km, with an average of 35 km, respectively). The difference in crustal thickness between northern and southern cratons disappears for crust younger than ~2.0 Ga. Using our estimates of the thermal thickness of middle and late Proterozoic lithosphere, buoyancy requires that the sub-crustal lithosphere should be depleted by ~ 0.6-0.7 % relative to the asthenosphere.

**Conclusions**

1. The steady-state thermal conductivity equation was used to estimate temperature distribution and thermal thickness of Precambrian lithosphere. We estimated the temperature distribution in Precambrian lithosphere and produced maps for temperatures at depths of 50, 100 and 150 km. The thermal state of Archean/early Proterozoic and middle/late Proterozoic cratons differ. On average, their respective lithospheric temperature distribution is close to the geotherms estimated by Pollack and Chapman (1977) for surface heat flow of 40 and 55 $mW/m^2$, respectively. The estimated temperatures at the base of the Archean/early Proterozoic and middle/late Proterozoic crust are 300-500$^o$C and 500-800$^o$C, respectively.

2. Lithospheric thermal thickness was calculated as a conductive layer above a mantle adiabat of 1300$^o$C. We found a global trend in a secular thinning of the continental lithosphere from about 250 $\pm$70 km in Archean lithosphere, through 200 $\pm$40 km in early Proterozoic, to 140 $\pm$40 km in mid-late Proterozoic lithosphere.

3. Archean cratons have two characteristic average lithospheric thicknesses: about ~210 km and ~350 km. The cratons with relatively thin lithospheric roots are presently located mainly in the southern hemisphere and include South Africa, Western Australia, and South America. Archean cratons of the northern hemisphere with a very thick lithosphere include the Baltic Shield, the Siberian Platform, West Africa, and possibly the central and northern Canadian Shield.

4. Buoyancy estimates show that the same degree of lithospheric mantle depletion (1.5%) is required for all Archean/early Proterozoic cratons. Isostatic balance of the lithosphere is achieved by thermal effects and variations in crustal thickness: the thicker lithosphere of the northern hemisphere has an average crustal thickness of ~45 km, whereas the thinner lithosphere of the southern hemisphere has an average crustal thickness of ~35 km.

5. Analysis of the age dependence of the lithospheric thermal thickness allows us to hypothesize three stages in the formation of the continental lithosphere: >2.5 Ga, 2.5-1.8 Ga, and <1.8 Ga. We relate these three stages to a gradual decrease in mantle temperature that was accompanied by changes in mantle convection patterns. Support for this hypothesis can be found in restricted ages of greenstone belts, komatiites, banded iron formations, and giant dyke swarms.

**References**

Artemieva I.M. and Mooney W.D., 2001. JGR, 106, 16387-16414.
Ashwal L.D., Morgan P., Kelley S.A., and Percival, J.A. 1987. Earth Plan. Sci. Lett., 85, 439-450.
Boyd F.R., 1984. Geology, 12, 528-530.
Boyd, F. R. 1989. Earth Planet. Sci. Lett., 96, 15-26.
Boyd F.R., Gurney J.J., and Richardson S.H., 1985. Nature, 315, 387-389.
Doin M.-P., Fleitout L., and Christensen U., 1997. JGR, 102, 2771-2787.
Ekström G., Tromp J., and Larson E.W.F., 1997. JGR, 102, 8137-8157.
Fountain D.M., Salisbury M.H., and Furlong K.P., 1987. Can. J. Earth Sci., 24, 1583-1594.
Grand S.P., 1994. JGR, 99, 11591-11621.
Jaupart C. and Mareschal J.-C., 1999. Lithos, 48, 93-114.
Jordan T.H., 1975. Nature, 257, 745-750.
Kopylova M.G., Russell J.K., and Cookenboo H., 1999. J. Petrology, 40, 79-104.
Kukkonen I.T. and Peltonen P., 1999. Tectonophys., 304, 301-315.

Lachenbruch A.H., 1970. JGR, 75, 3291-3300.
Lachenbruch A.H. and Morgan P., 1990. Tectonophys., 174, 39-62.
McLennan S.M. and Taylor S.R., 1996. J. Geol., 104, 377-396.
Mooney W.D., Laske G., and Masters T.G., 1998. JGR, 103, 727-747.
Nataf H.-C. and Ricard Y., 1996. Phys. Earth Planet. Inter., 95, p. 101-122.
Nicolaysen L.O., Hart R.J., and Gale N.H., 1981. JGR, 86, 10653-10661.
Pinet C. and Jaupart C., 1987. Geophys. Res. Lett., 14, 260-263.
Polet J. and Anderson D.L., 1995. Geology, 23, 205-208.
Pollack H.N., Hurter, S.J., and Johnson, J.R., 1993, Rev. Geophysics, 31, 267-280.
Ritsema J. and van Heijst H., 2000. Geology, 28, 63-66.
Ritzwoller M.H. and Levshin A.L., 1998. JGR, 103, 4839-4878.
Rudnick R.L. and Fountain D.M., 1995. Rev. Geophys., 33, 267-309.
Rudnick L.R., McDonough W.F., and O'Connel R.J., 1998. Chem. Geol., 145, 395-411.
Rudnick L.R. and Nyblade A.A., 1999. In: Y. Fei, C.M. Bertka and B.O. Mysen (Eds.), Mantle petrology: Field observations and high pressure experimentation: A tribute to Francis R. (Joe) Boyd. Chem. Soc. Spec. Publ. No. 6, 3-12.
Shaw D.M., Cramer J.J., Higgins M.D., and Truscott M.G., 1986. In: J.B. Dawson et al. (Eds.), Nature of the Lower Continental Crust, Geological Society of London (U.K.) Special Pub. 24, 275-282.
Van der Hilst R, Kennett, B.LN. and Shibutani, T., 1998. In: Braun J. et al.. (Eds.), Structure and evolution of the Australian Continent, AGU Geodynamics Series, AGU, Washington, D.C., 39-57.
Van der Lee S. and Nolet G., 1997. JGR, 102, 22815-22838.
Van Heijst H.J. and Woodhouse J., 1997, Geophys. J. Int., 145, 209-230.
Weaver B.L. and Tarney J., 1984. Nature, 310, 575-577.
Zhang Y.-S. and Tanimoto T., 1993. JGR, 98, 9793-9823.

The results are available from the authors at http://www.geofys.uu.se/~iartem.