Average composition of the crust in the Australian, Fennoscandian, and Ukrainian shields from refraction seismic studies and petrophysical modelling

Alexey Goncharov[1], Barry Drummond[1], Alexander Tripolsky[2], & Lesley Wyborn[3]

Seismic velocity models of the Australian, Fennoscandian, and Ukrainian shields* fall into two broad categories: one has thin (35–44 km) crust; the other, thick (>45 km). In the Australian shield, Archaean crust is identified as thin; Proterozoic crust, as thick. The Ukrainian shield is the only one whose average models of both thick and thin crust show remarkably similar velocities in the upper 44 km of the crust. Velocities in the upper 20 km of the Ukrainian shield are noticeably higher than in other regions. The hottest assumed geotherm among the regions analysed is that of the Australian Proterozoic crust. Differences in seismic velocity distribution in the crust of the three Precambrian domains do not necessarily translate into marked differences in composition if the differences in geothermal regimes are considered.

The crust of the Fennoscandian and Ukrainian shields has been studied from a network of seismic profiles which is more dense than networks in many other parts of the world. This facilitated the development of detailed seismic models of the crust of these regions (Tripolsky 1996: Geophysical Journal (National Academy of Sciences, Ukraine), 16, 23–47; Goncharov et al. 1998: AGU Geodynamics Series, 26, 119–138). Significant parts of the north Australian Precambrian craton and Archaean Yilgarn Block in Western Australia have been studied by refraction and wide-angle reflection seismic profiles, although the density of observations is less than in the other shields. Seismic velocity models of the Australian Precambrian were summarised by Collins (1988: BMR/AGSO Report 277) and interpreted by Drummond & Collins (1986: Earth and Planetary Science Letters, 79, 361–372). We limited this study to the region above the Moho†.

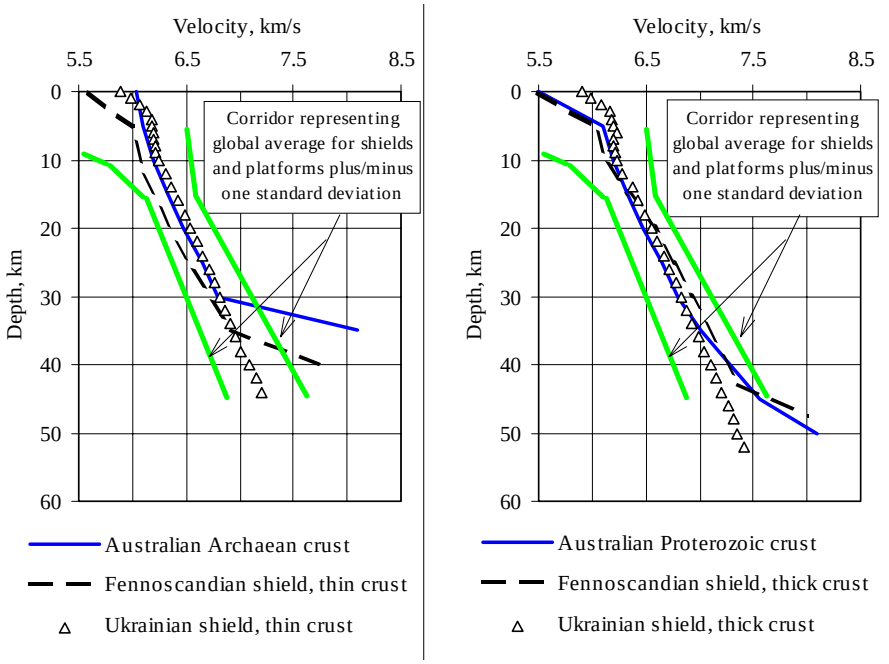

Fig. 22. Average velocity models of the Australian, Fennoscandian, and Ukrainian shields compared with the global average model for shields and platforms (Christensen & Mooney 1995: op. cit.).

Velocity models

Velocity models of all three regions fall into two broad categories: one has thin crust (35–44 km); the other, thick (>45 km; Fig. 22). Crustal velocities in the Fennoscandian thin crust are slightly lower, and in the thick crust slightly higher, than in the global average model for shields and platforms (Christensen & Mooney 1995: Journal of Geophysical Research, 100, B7, 9761–9788). The total thickness of the crust in the Fennoscandian shield is close to the global average value (41.5 km) in the thin crust model, but noticeably higher in the thick crust model, in which the shallowest Moho was defined at 45 km depth. The Australian Archaean crust is on average thinner (about 35 km) than in the global average model, and generally thinner than the Australian Proterozoic crust.

In the Australian shield, the increase in total crustal thickness correlates with an increase in seismic velocity starting at 30 km depth in the lower crust. In the Fennoscandian shield, velocities from 10 km down to the Moho are higher in the thick crust model than in the thin model. Of the three shields, the Ukrainian shield is the only one in which average velocity models of both thick and thin crust are remarkably similar through the whole crust, and the velocity–depth function of the thick crust below 44 km depth is a continuation of the trend typical for the thin crust. Velocities in the Ukrainian shield are noticeably higher in the upper 20 km but lower in the lower part of the crust compared with the other regions analysed (Fig. 22).

Low-velocity layers are quite common in the crust of the Fennoscandian shield. They were also recognised in some interpretations from the Australian shield (Finlayson 1982: Journal of Geophysical Research, 87, 10569–10578; Goncharov et al. 1997: AGSO Research Newsletter, 26, 13–16.). In the Ukrainian shield, they are mainly restricted to the upper crust (Tripolsky 1996: op. cit.). Low-velocity layers were ignored in the smoothed velocity models used for the petrological interpretation below (Fig. 22).

* Results from the Australian and Fennoscandian Shields were discussed at the workshop on Palaeoproterozoic tectonics and metallogenesis held in Darwin in September 1997 (Rutland & Drummond, Editors, 1997: AGSO Record 1997/44).

† Griffin & O'Reilly (1987: Geology, 15, 241–244) make a distinction between the Moho, whose formal definition is a seismic discontinuity, and the petrologically defined boundary between the crust and mantle. In this paper, we follow the formal definition of the Moho.

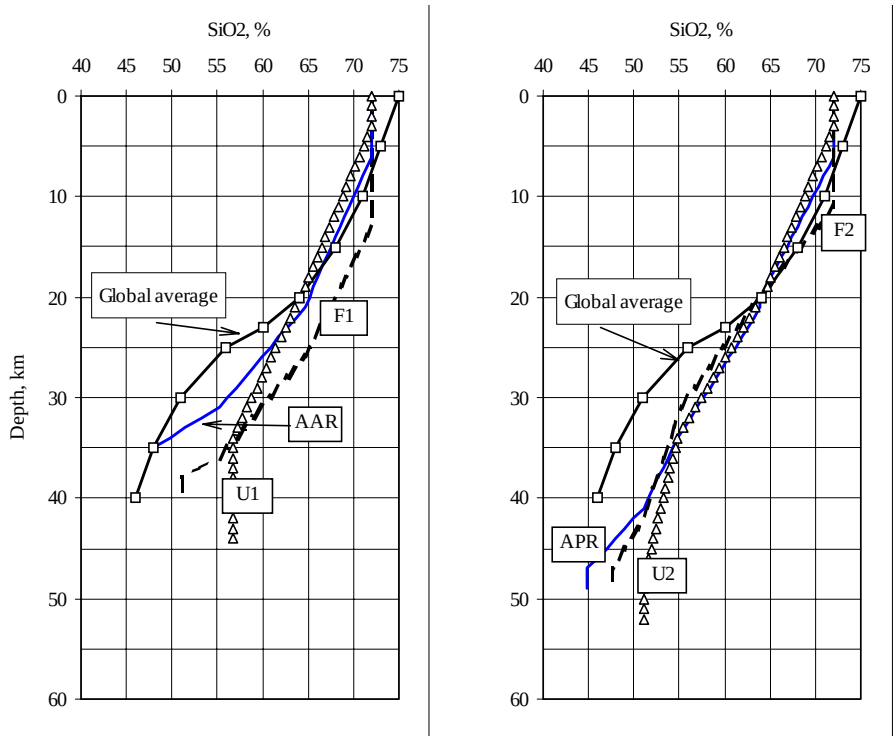

Fig. 23. SiO_2 distribution in the crust of the Australian, Fennoscandian, and Ukrainian shields compared with the global average model (Christensen & Mooney 1995: op. cit.). The abbreviations of the model names are the same as those in Table 2.

Methodology for the petrological interpretation of velocity models

The six velocity models (Fig. 22) are representative of the three shields under consideration. They were interpreted in terms of the bulk geochemistry of rocks at depth. The petrophysical modelling technique of Sobolev & Babeyko (1994: Surveys in Geophysics, 15, 515–544) was used to predict seismic velocities at depth for a range of assumed crustal compositions; it was used earlier to interpret the composition of the crust in the Mount Isa Inlier (Goncharov et al. 1997: op. cit.). The method considers igneous rocks only, and the possibility of metasediments in the deep crust is ignored.

An important feature of our approach was that we treated the crust as a mixture of a limited number of rock types ('granites', 'diorites', 'gabbros', and 'spinel lherzolites') represented by their end-members. The bulk geochemical composition within each rock type was kept constant, and the mineralogical compositions allowed to vary, to account for equilibration at the likely prevailing pressures and temperatures during rock formation. Thus, the technique accounts for the changing mineral assemblages from plagioclase-bearing and garnet-free to garnet-bearing and plagioclase-free. Our petrological interpretation gave us an estimate of the proportion of the various rock types at a number of depth ranges that have the appropriate seismic velocities (ranging in steps of 0.4 km/s from 5.7 km/s near the surface to 8.1 km/s at the Moho) observed in the models.

Temperature regimes of the crust

This approach required an estimate of the likely pressure and temperature conditions in the modern crust. The pressure–depth function that we used was computed for an assumed mean crustal density of 2.830 t/m^3, a global average for continental crust (Christensen & Mooney 1995: op cit.). The thermal regime of the crust affects seismic velocity at depth more significantly than pressure. The Australian Proterozoic crust has an estimated thermal regime hotter than the others (Fig. 24) because its surface heat flow of 60 mW/m^2 (Cull 1991: Geological Society of Australia, Special Publication, 17, 147–155) is well above the average value of 40 mW/m^2 in the other regions.

Accuracy of the petrological interpretation of seismic velocities

Uncertainties in the estimates of crustal composition arise from uncertainties in the measured seismic velocities and uncertainties in the estimated palaeo- and modern temperatures in the crust. At high pressures and temperatures, the amount of plagioclase in the equilibrium mineralogy of a cooling magma increases with increasing equilibrium temperature at a fixed pressure. Hence, the higher the

Table 2. Composition of the Australian Archaean (AAR), Australian Proterozoic (APR), Fennoscandian thin (F1), Fennoscandian thick (F2), Ukrainian thin (U1), and Ukrainian thick (U2) crust interpreted from average seismic models

Depth (km)	*Model type*	*Rock type (%)**				*Notes*
		'Granite'	*'Diorite'*	*'Gabbro'*	*'Spinel lherzolite'*	
0–10	All models	100±0†	0	0	0	
10–20	AAR, F2	85±15	15±15	0	0	
	APR	100±0†	0	0	0	
	F1	95±5	5±5	0	0	
	U1, U2	80±20	20±20	0	0	
20–30	AAR	45±15	55±5	10±10	0	
	APR	40±40	60±40	0	0	
	F1	70±25	30±25	0	0	
	F2	45±30	55±5	15±15	0	
	U1, U2	45±25	55±5	15±15	0	
30–40	AAR	0	25±15	70±20	20±20	Down to 35 km only
	APR	15±15	55±5	35±20	0	
	F1	20±20	40±5	40±25	5±5	
	F2	0	55±30	45±30	0	
	U1	15±15	70±20	25±25	0	
	U2	15±15	50±5	35±15	0	
40–50	AAR	N/A	N/A	N/A	N/A	
	APR	0	10±10	65±5	35±25	
	F1	N/A	N/A	N/A	N/A	
	F2	0	5±5	75±20	20±20	Down to 49 km only
	U1	0	50±50	50±50	0	Down to 44 km only
	U2	0	35±35	65±35	0	Down to 52 km

* Rounded to the nearest multiple of 5% value.
† Based on an assumption (see the text).

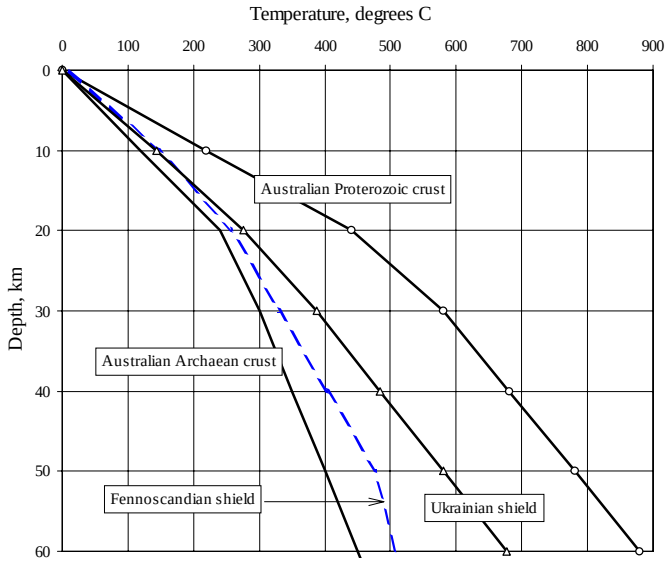

Fig. 24. Temperature in the crust of the Australian Archaean and Proterozoic domains of Cull (1991: op. cit.), and the Fennoscandian (Glaznev et al. 1997: Geophysical Journal (National Academy of Sciences, Ukraine), 19 (4), 57–60) and Ukrainian shields (Kutas 1993: Lithosphere of central and eastern Europe (in Russian), Naukova Dumka, 114-135).

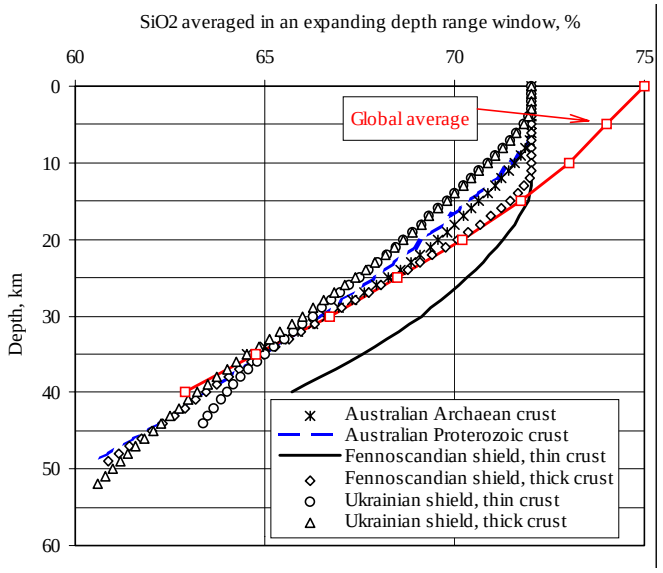

Fig. 25. SiO_2 distribution in the crust of the Australian, Fennoscandian, and Ukrainian shields averaged in an expanding depth-range window compared with the global average model (Christensen & Mooney 1995: op. cit.). The top of the expanding window was kept at the surface, and the bottom of the window gradually shifted downwards; averaged values are plotted against the depth of the bottom of this window, and hence represent average SiO_2 content from 0 km to any given depth.

equilibrium temperature during rock formation, the lower the velocity of the rock. This is the reason why the velocities vary within each group of rocks analysed — for example, 'gabbros' may have velocities ranging from 7.25 to 7.70 km/s at 30 km depth under the modern temperature regime of the Australian Archaean crust; this velocity range reflects the uncertainty in the palaeotemperature estimate of about 200°C at that depth, and is representative of the uncertainties typical for the other rock types. We did not systematically test the uncertainty which the variation in palaeotemperatures imposes on our petrological interpretation, because our probabilistic approach to the estimation of bulk crustal composition accounts for this uncertainty.

Modern crustal temperatures which affect the interpreted bulk composition are estimated from surface heat flow, based on assumptions about the distribution of heat-producing elements at depth. An increase in surface heat flow of 10 mW/m² translates into an increase of ~100°C in the temperature estimate at mid-crustal level. This in turn results in a 0.05 km/s decrease in seismic velocity value predicted by petrophysical modelling for a constant mineralogy. This is about one-fifth of one standard deviation of the average velocity models shown in Figure 22.

To estimate the combined effect of both velocity and modern temperature uncertainties on the accuracy of the petrological interpretation, we modelled the most unfavourable situation — that in which underestimated experimental seismic velocities are compared with the overestimated velocities predicted by the petrophysical modelling, and vice versa. The petrophysical modelling overestimates velocities when temperatures in the crust are underestimated. So the biggest error in the petrological interpretation will happen when seismic velocities and temperatures are both lower or both higher than the original distributions of Figures 22 and 24. We used a variation of 0.2 km/s in velocities and a temperature variation of up to 200°C in the lower crust. These differences reflect the range of velocities in Figure 22 and the uncertainties in estimated modern temperatures (Fig. 24). The resulting uncertainties in the petrological interpretation are shown in Table 2.

Petrological models of the crust

Table 2 presents the likely composition of the layers in the resulting petrological models. Seismic velocities in some layers in the upper crust are too low to be explained by the intrinsic properties of pure anhydrous rocks of granitic composition. Such low velocities may be due to open cracks and pores (assumed for further computations), or to metasediments (not modelled by this technique), whose hydrous phases and greater pore volume would result in velocities lower than in granitic rocks.

The bulk geochemistry of the rocks in all six models varies from 100% 'granite' composition in the upper 10–20 km of the crust to a mixture of mafic and ultramafic rocks in the lower 10 km. The SiO_2 content for each layer was also estimated. The top part of the crust in all our models contains about 72% SiO_2 — i.e., it is more felsic than suggested in some other studies based on the petrology and geochemistry of rock samples: 66-67% (Condie 1993: Chemical Geology, 104, 1–37), 66% (Taylor & McLennan 1985: The continental crust: its composition and evolution, Blackwell, London), and 65% (Shaw et al. 1986: Geological Society of London, Special Publication 24, 275–282). An obvious explanation for these discrepancies would be the limitations of our approach. Nevertheless, the upper crust in the global average model of Christensen & Mooney (1995: op. cit.) is even more felsic than in our models (Fig. 23), although their approach did account for the possible presence of metasedimentary rocks in the crust, and it did take seismic data into consideration as well. Therefore we conclude that further research is needed to investigate how other rock types can be incorporated into our methodology without disrupting its integrity.

Velocities in the Australian

Proterozoic, Fennoscandian thick, and Ukrainian thick crust require a >15-km-thick layer of rocks containing less than 55% SiO_2 (Fig. 23) in the lowermost crust. This content corresponds to a dioritic to gabbroic bulk composition of the lower crust. In contrast, the Fennoscandian thin crust and Australian Archaean crust require no more than 5 km of such rock in the lowermost crust. The lower part of the Ukrainian thin crust requires no such rock at all.

More significant variations in SiO_2 content are observed within the group of thin crustal models — e.g., in the upper part of the Fennoscandian thin crust model, SiO_2 is systematically higher than in the other models. Models of thick crust are more uniform in SiO_2 distribution, although the lower part of the Ukrainian thick crust is up to 5% more felsic than in other models in this category (Fig. 23). Owing to the low temperatures in the Ukrainian shield, the relatively high velocities in the upper part of the crust there (Fig. 22) do not translate into a composition noticeably more mafic than the Australian Proterozoic crust (Fig. 23). The average whole-of-crust SiO_2 content in all models of thin crust is 63.3–65.7%, which is higher than in the global average model (61.8 %) of Christensen & Mooney (1995: op. cit.). Our thick crustal models have SiO_2 content close to the global average value (Fig. 25).

Analysis of SiO_2 content averaged in an expanding depth-range window (Fig. 25) clearly shows that the curves for all models except that for the Fennoscandian thin crust merge to within 0.5 per cent at a depth of 35 km (at a depth level of the shallowest Moho in the Australian Archaean average model). This means that, although differences in composition occur throughout the crust, the averaged SiO_2 content in the upper 35 km of the Precambrian crust analysed is the same for all models, except the Fennoscandian thin crust. At province scale, we have also observed that the averaged SiO_2 content in the upper 45 km of the crust (about 10 km above the Moho) in the Mount Isa Inlier is remarkably constant (Goncharov et al. 1997: op. cit.).

The key conclusion of this work is that Precambrian crust, particularly in the top part, has a remarkably constant overall composition, and that the apparent differences in seismic models between the shields can mostly be explained by different thermal regimes affecting equilibrium mineralogies at depth. Geological explanations of why this should be so require further studies.

Acknowledgment

We thank Shen-su Sun and Clive Collins for many useful comments on the manuscript. This paper is published with the permission of the Director, Australian Geodynamics Cooperative Research Centre.

[1] Petroleum & Marine Division, Australian Geological Survey Organisation, GPO Box 378, Canberra, ACT 2601; tel. +61 2 6249 9595 (AG), +61 2 6249 9381 (BD); fax +61 2 6249 9972; e-mail agonchar@agso.gov.au, drummond@agso.gov.au.

[2] Division of Regional Geophysics, Institute of Geophysics National Academy of Sciences, Palladina 32, Kiev, 252680, Ukraine; fax +380 44 450 2520; e-mail root@igpnanu.kiev.ua.

[3] Minerals Division, Australian Geological Survey Organisation, GPO Box 378, Canberra, ACT 2601; tel. +61 2 6249 9489; fax +61 2 6249 9971; e-mail lwyborn@agso.gov.au.