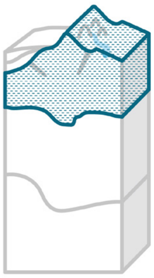
Australian Government
Geoscience Australia

Exploring for the Future

Constraints on continental crustal thickness and density structure

S. N. Stephenson[1], M. J. Hoggard[2], M. W. Haynes[3], K. Czarnota[3] and B. Hejrani[3]
[1]University of Oxford, UK, [2]Australian National University, [3]Geoscience Australia



The continental crust directly hosts or underlies almost all natural resources on which society depends. Despite its importance, its structure is poorly characterised. In particular, its density structure is surprisingly uncertain due to the difficulty of directly measuring it from the surface. Here, we collate a global database of crustal thickness and seismic velocity measurements. In combination with a compilation of published laboratory experimental constraints on the seismic velocity of different rocks across a range of pressures, we develop a scheme to convert seismic velocities into density as a function of pressure and temperature. Applying this approach to the Australian crystalline basement, we find that the crust is highly heterogeneous, ranging in bulk density from 2.7–3.0 g cm^{-3}. This result is consistent with other regions in our global analysis. We also explore the utility of our database for testing hypotheses concerning the location and endowment of natural resources, using porphyry copper deposits as a case study. Our results provide an improved framework for mapping crustal density structure using seismic data that can underpin future gravity and magnetic studies. They also allow us to explore the subsidence and thermal evolution of sedimentary basins, as well as probing relationships between different economic resources and crustal architecture.

The physical properties of continental crust are a primary control on geothermal heat flow, surface uplift and subsidence, and the circulation of fluids that can lead to formation of economic resources. One such physical property, density, is an important proxy for a combination of the lithological composition and temperature of the crust with depth. However, the density of continental crust is challenging to constrain. Often, modelling of gravity anomalies is carried out to constrain variations in crustal density. A significant problem with this approach is that gravity is sensitive to the sum of density over all depths within the Earth and so cannot place reliable constraints on precise crustal density structure without additional external constraints. To sidestep this issue, another common approach is to use seismic velocity estimates from geophysical experiments as a proxy for density (e.g. Ludwig et al., 1970; Christensen and Mooney, 1995; Brocher, 2005). Since seismic velocities are not direct measurements of density, using this approach requires prior knowledge from laboratory and field experiments concerning how to accurately map seismic velocities into density.

Density and seismic velocity both depend upon pressure and temperature, each of which increases with depth, as well as the intrinsic composition of the rock (e.g. Christensen and Mooney, 1995). Furthermore, density, P-wave, and S-wave velocities (hereafter denoted Vp and Vs, respectively) all have different sensitivities to temperature and pressure, rendering constraining the individual contribution of each of these two properties difficult to deconvolve.

Despite significant challenges in measuring it, the density structure of the continental crust can both directly inform exploration for resources and also provide general insights into the geodynamic processes that might lead to their formation. For example, mineral deposits are often associated with sulfide minerals and may therefore be expected to have high density. Furthermore, common ore forming processes, such as those that generate porphyry copper deposits, may be associated with mineral fractionation and can therefore leave fingerprints in lithological and density stratification of the crust (Lee and Tang, 2020). Finally, where sedimentary basins obscure bedrock, the properties of crystalline basement can only be indirectly inferred. Since standard gravity measurements are often dominated by the effects of shallow, low-density sedimentary cover, seeing into the underlying crystalline basement by constraining the vertical density structure of continental crust therefore has important scientific and economic motivation.

Our aim in this work package is threefold. First, we compile a global database of over 26,000 estimates of crustal thickness derived from local seismic experiments in order to characterise the thickness and seismic velocity structure of continental crust (i.e. the SeisCruST database; Stephenson et al., 2024a). Next, we exploit this database to calibrate a seismic velocity-to-density conversion scheme (i.e. SMV2rho; Stephenson and Hoggard, 2024) and use it to constrain the density of continental crust in Australia and elsewhere. To this end, we have compiled an inventory of rock samples that are representative of continental crustal compositions and have been analysed in the laboratory for seismic velocity as a function of pressure at surface temperature (Stephenson et al., 2024b). Finally, we explore ancillary uses of the SeisCruST database in assessing the distribution of economic resources.

Crustal database

We have compiled a database of 26,725 crustal thickness estimates from approximately 500 published studies that utilise both controlled- and passive-source seismic energy Figure 1; Stephenson et al., 2024b). Our database is primarily composed of (i) crustal thickness estimates determined by the H-κ stacking method of Zhu and Kanimori (2000), which exploits the P- and S-wave energy from distant earthquakes and reverberations between the surface and base of the crust; (ii) a subset of receiver function analyses that have been combined with surface-wave dispersion data to provide absolute S-wave velocity profiles as

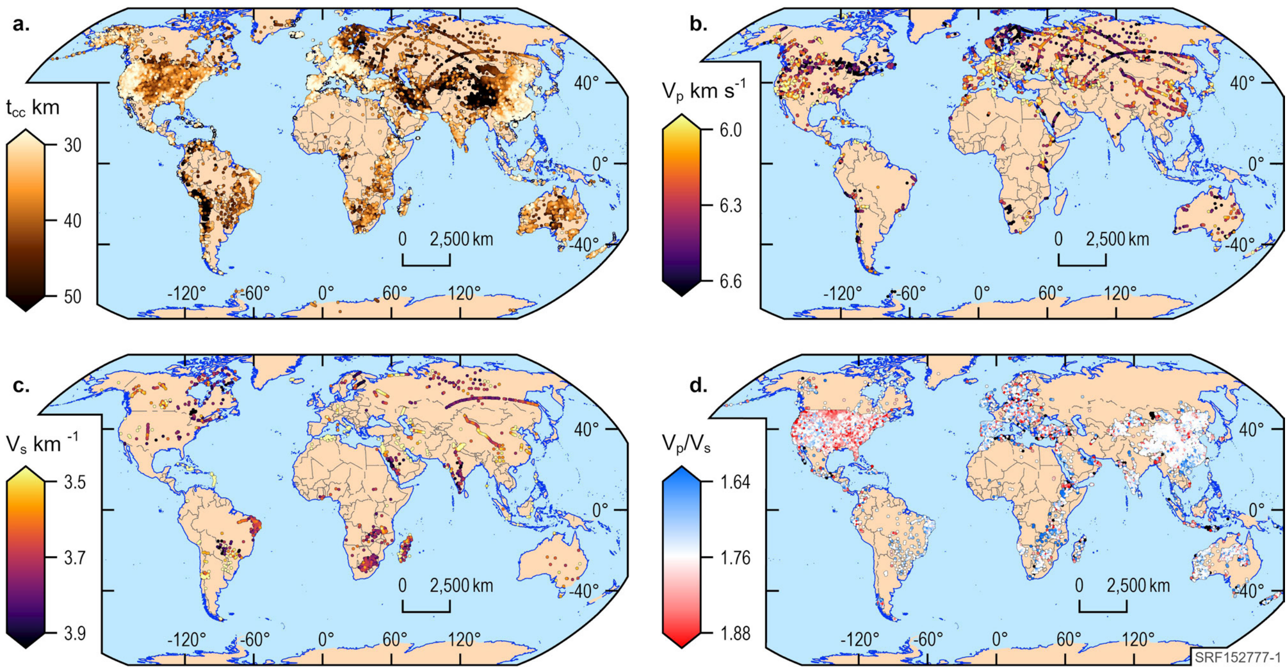


Figure 1 Global SeisCruST database of spot-estimates of crustal structure compiled in this study (Stephenson et al., 2024b). (a) Crustal thickness. (b) Bulk primary-wave velocity, Vp, where available. (c) Bulk shear-wave velocity, Vs, where available. (d) Bulk primary/shear wave velocity ratio (i.e. Vp/Vs ratio) from H-κ stacks (Stephenson et al., 2024b).

a function of depth, Vs(z); and (iii) a collation of seismic refraction/wide-angle experiments that rely on a local, anthropogenic seismic source that refracts and reflects from the Moho and internal layers within the crust. A further, small subset of these data are derived from deep seismic reflection imaging. We exclude studies that use any other techniques in order to standardise the database. In Figure 1a we present a global map of crustal thickness spot-estimates calculated using these approaches. Readers are referred to the associated data repository for a full bibliography of data sources. Note that globally continuous crustal thickness models that rely on a subset of these data have previously been published and made available (e.g. Laske et al., 2013; Mooney et al., 2023), but these models include interpolations over wide regions that have limited-to-no local control on crustal thickness. In Australia, the AusArrray program, as well as institutional and state-level seismometer deployments, have yielded increasing coverage in the last decade (e.g. Kennett et al., 2023) and will be further enhanced by the 200 x 200 km-spaced array in coming years (Gorbatov et al., 2024).

Figure 1b & c show average crustal Vp and Vs, respectively. Seismic velocity is generally higher in continental shields and lower on Phanerozoic crust and in sedimentary basins. Figure 1d shows bulk Vp/Vs ratio as estimated by H-κ stacking studies (which cannot provide independent constraints on Vp and Vs). Note that there is substantial noise in the velocity data, owing partly to variable resolution and sensitivity of the different seismic imaging approaches and partly to the existence of local, short-lengthscale variability in crustal velocity structure.

Velocity-to-density conversion

One of our key aims is to estimate density of the continental crust as a function of depth. To this end, we develop a scheme to convert from seismic velocity into density (i.e. SMV2rho; Stephenson et al., 2024b; Stephenson and Hoggard, 2024). For a given rock sample, laboratory experiments across multiple studies have shown that seismic velocity depends approximately linearly on pressure and temperature under typical crustal conditions (e.g. Christensen, 1974). Important exceptions to this behaviour occur at low pressures, where velocity reduces exponentially due to the opening of pore space and microfractures, and at high temperatures, where anelastic effects and phase transitions may become important. For conditions away from the high-temperature regime, we exploit these empirical observations to construct a generalised seismic velocity (either Vp or Vs)-to-density conversion scheme for continental crust that accounts for the effects of pressure and temperature.

In this empirical scheme, velocity, v, at a given pressure, P, and temperature, T, and sample density under standard laboratory conditions, ρ_O, is given by

$$v(P, T, \rho_O) = v_O + bP + (d_O + d_P P)\rho_O + mT - ce^{-kP},$$

where v_O is velocity at reference pressure and temperature, b and m are the slopes of velocity with respect to pressure and temperature, respectively; and d_O and d_P are the slope of velocity with respect to surface density and the rate of change of that slope with respect to pressure. The constants c and k control the exponential drop-off in velocity at low pressure as pore-spaces open. We optimise the constants in this equation using a least-squares approach and then rearrange and solve for density at surface temperature and pressure. To do so, it is necessary to estimate the local geothermal gradient (i.e. temperature as a function of depth). We assume that the globally averaged Moho and surface heatflow are representative of average crustal temperature structure, subject to internal heat generation that decays exponentially with depth within a single upper crustal layer (Stephenson et al., 2024b). Finally, we correct the reference density at surface conditions for the effects of pressure and temperature to estimate true crustal density at a given depth. In this way, it is possible to convert a seismic velocity profile into a density profile. The approach differs from commonly used empirical relationships, such as the Nafe-Drake relationship (Ludwig et al., 1970). That scheme, formalised by Brocher (2005) using a polynomial function fitted to field and laboratory measurements, ignores the effects of temperature and pressure, resulting in systematic underestimation of crustal density relative to our new method.

A final consideration is whether we can potentially infer crustal density in those places where crustal thickness has been estimated, but the seismic velocity structure has not. Applying our conversion scheme to the global database of crustal velocity profiles, we find that there is a ubiquitous increase in crustal density with depth. This relationship, when averaged globally, can be used to place a crude constraint on the expected density of the crust in a location where precise seismic velocity is unknown (Stephenson et al., 2024b). We find that bulk crustal density in g cm^{-3} can be estimated using

$$\rho_{cc}(t_{cc}) = 2.75 - (2.73 \times 10^{-3})\, t_{cc} + (2.52 \times 10^{-4})\, t_{cc}^2 - (2.56 \times 10^{-6})\, t_{cc}^3,$$

where t_{cc} is crustal thickness in km. It is important to note that, while there are substantial additional uncertainties associated with applying this relationship (e.g. ~ ±0.13 g cm^{-3}), the systematic increase in bulk crustal density as a function of crustal thickness will not be otherwise captured. Next, we apply these relationships to assess the density structure of Australian crust.

Applications

Australian crustal density estimates

In Figure 2, we present estimates of bulk density of the Australian crust. We supplement the global SeisCruST database with reflection and refraction constraints included in AusMoho (Kennett, et. al., 2023). In the central Northern Territory and western Queensland, we complement the spot estimates derived from our SeisCruST database with a preliminary, continuous ambient noise velocity model obtained from an AusArray EFTF deployment between 2016 and 2020 in the region enclosed by Tenant Creek, Mount Isa and Yulara. It consisted of 50 km spaced broadband instruments and has been exploited for both receiver function estimates of crustal thickness and for ambient noise inverse modelling of 1D and 2D seismic velocity structure (Gorbatov et al., 2020a,b; Hejrani, 2023).

To exclude the crustal layer most affected by opening of pore space and microfractures, we assume that the uppermost 7 km of the crust has a constant density of 2.75 g cm^{-3}. This assumption furthermore largely excises the effect of sedimentary basins. The pattern of bulk density variations presented in Figure 2 can therefore be considered representative of sub-cover crystalline basement.

The bulk density of Australian crust ranges from less than 2.8 to greater than 3.0 g cm^{-3}. The Northern Territory is characterised by generally high-density crust, with available

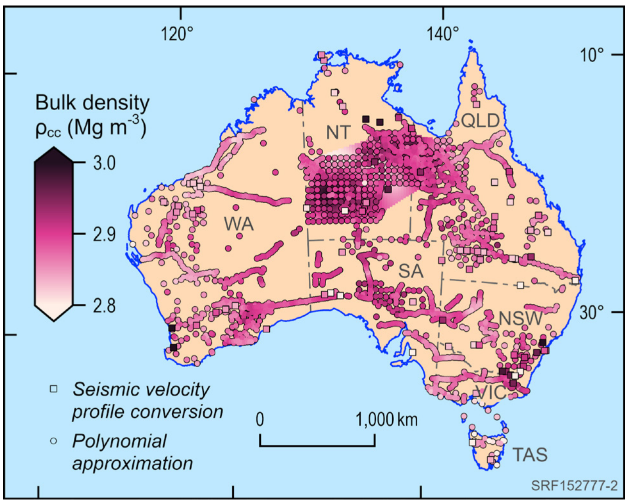


Figure 2 Bulk density estimates of Australian crust. Squares = values calculated by converting seismic velocity profiles into density. Circles = locations without local seismic velocity information where bulk density is instead estimated using polynomial approximation. Background grid = continuous density model calculated by converting ambient noise velocity model of Hejrani (2023) into density.

constraints suggesting that values beneath the Amadeus and McArthur Basins approach 2.95–3.0 g cm^{-3}. On the other hand, density of the crystalline crust beneath the Pilbara Craton, the Paterson Orogen and much of the Yilgarn Craton is substantially lower, around 2.80–2.85 g cm^{-3}, although reliable seismic velocity constraints are sparser in this region. Much of the Phanerozoic crust of eastern Australia is characterised by lower densities (which is consistent for both velocity-derived density estimates and those estimated using the crustal thickness-to-bulk density relationship). An important exception occurs, however, in the region straddling the border between New South Wales and Victoria, where constraints derived from seismic velocity profiles suggest that the crust may have a bulk density as high as 3.0 g cm^{-3}.

This mismatch highlights the value of obtaining more, high-accuracy estimates of local crustal seismic velocity structure through ongoing expansion of Australia's seismometer coverage in coming years (Gorbatov et al., 2024). Furthermore, as passive seismic coverage continues to improve, the velocity-to-density conversion scheme developed here can be used to generate a starting crustal density model for use in future inversions that leverage Australia's exceptional gravity data coverage (cf. Lane et al., 2019; Goodwin, 2024).

Accurate constraints on crustal density are also critical for interpreting heat flow during tectonic extension, since lighter crust will experience greater subsidence for the same extension factor. The corollary is that, for a sedimentary basin of a given depth, greater extension, and therefore potentially higher heat flow, will have occurred if the crust is denser than normal. Indeed, changing density by 0.2 g cm^{-3} leads to a change of approximately ±1 km of water-loaded subsidence when the crust is thinned by 10 km. Knowledge of the density of continental crust underlying basins therefore underpins accurate thermal modelling of basin evolution and associated resource genesis.

Resource potential mapping

Another application of our global compilation of constraints on local crustal architecture is to quantitatively assess potential relationships with the distribution of different natural resources. Here, we demonstrate an example using a global database of porphyry copper deposits.

Porphyry copper systems account for around three-quarters of copper resources. They are thought to form in the shallow crust of arcs from fluids associated with oxidised, intermediate magmas (Sillitoe, 2010). Despite their importance, the primary lithospheric controls on their formation are poorly understood. It has long been argued based on geochemical data that a pre-requisite for their formation is the presence of thick crust (e.g. Chiaradia, 2014; Lee and Tang, 2020). This hypothesised association arises from: (a) the higher abundance of evolved magmas in thicker arcs (Leeman, 1983); and (b) the location of the largest known porphyry copper deposits in the central Andes, where crust is among the thickest in the world. Crustal thickness has therefore become a key parameter in assessments of copper porphyry fertility. Nevertheless, most studies that have investigated the link between deposit occurrence and crustal thickness have not directly used local measurements of crustal thickness (e.g. Chiaradia, 2014; Tang et al., 2018). Instead, they have exploited either interpolated crustal grids, which may not be locally constrained by reliable crustal thickness estimates, or associated proxies, such as the height of topography. Our new, comprehensive crustal database therefore provides an opportunity to reliably test this association and thereby quantitatively assess the value of crustal thickness as a parameter in assessing copper porphyry fertility.

Figure 3a shows the global distribution of endowment in porphyry copper deposits. These deposits are concentrated in modern or recent continental arcs. In order to explore the relationship between porphyry copper endowment and crustal thickness, we first average crustal thickness estimates into 2 x 2 degree geographic bins. For each average crustal thickness measurement, we then sum the total copper endowment within a 2-degree radius. A plot of the resulting copper endowment as a function of crustal thickness is shown in Figure 3b. We can detect no discernible relationship between crustal thickness and porphyry copper endowment (the Pearson's rank correlation coefficient is -0.06).

This negative result is important because it suggests that using thick crust as a guide for porphyry copper and gold exploration may be erroneous. It has therefore not been used in EFTF assessments of the mineral potential of the Delamerian Orogen (Cheng et al., 2024). Furthermore, it has only been possible to make such an inference by compiling a global database of local crustal thickness constraints.

Conclusions

We have collated a global database of over 26,000 continental crustal thickness and seismic velocity constraints derived from passive- and controlled-source seismic experiments. We have combined these constraints to develop a new, open-source temperature- and pressure-dependent seismic velocity-to-density conversion scheme (i.e. SMV2rho). This scheme was applied to available constraints from the Australian continent, including a continuous ambient noise velocity model from the 2016–2020 AusArray deployment. Results show bulk crustal density of up to 2.95–3.0 g cm^{-3} beneath the Amadeus Basin and in southeastern Australia, while crust may be lighter beneath the Pilbara, southwestern, and eastern Australia. The variation in Australian crustal density suggests that modelling of basin subsidence and heat flow may be enhanced with improved crustal density constraints. Finally, our crustal database can be used to probe controls on the distribution of natural resources. We present a case study that appears to disprove a hypothesis that porphyry copper deposits are related to thick crust, highlighting the importance of having an extensive distribution of local crustal thickness constraints for interpreting the drivers of resource formation.

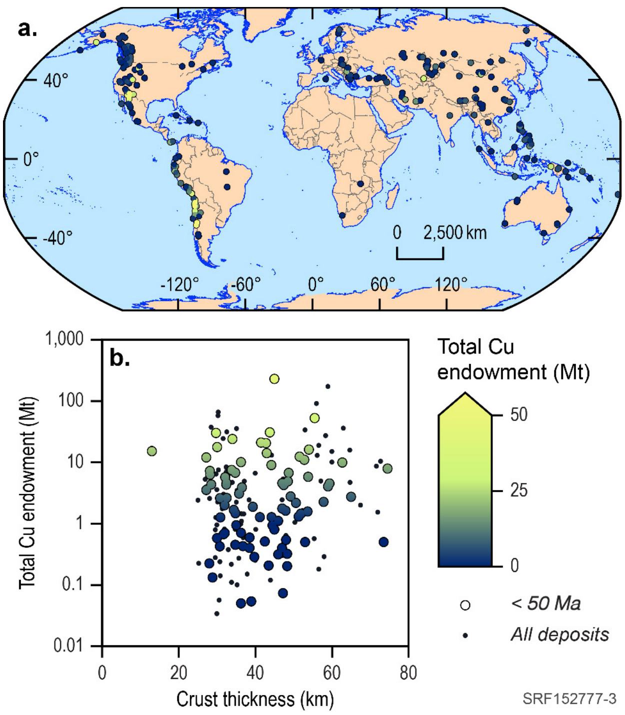


Figure 3 Porphyry copper endowment as a function of crustal thickness. (a) Location of porphyry copper deposits and porphyry-like copper deposits coloured by deposit endowment summed in 2 x 2 degree bins (Sillitoe, 2010). (b) Copper endowment summed in 2 x 2 degree bins as a function of crustal thickness averaged over 2-degree radius from given deposit location. Coloured circles/black dots = younger than 50 Ma/all deposits.

Dataset availability

The SeisCruST dataset is available from doi.org/10.5281/zenodo.10017428 and the crustal seismic velocity-to-density conversion code is available from doi.org/10.5281/zenodo.10017540. An accompanying publication can be accessed at doi.org/10.26186/148960. The Australian crustal density data shown in Figure 2 are a supplementary dataset attached to this Extended Abstract and are available at doi.org/10.26186/149336.

Acknowledgements

Geoscience Australia acknowledges the traditional owners and custodians of Country throughout Australia and acknowledges their continuing connection to land, waters and community. We pay our respects to the people, the cultures and the elders past and present. We thank Krystian Czado for useful discussions about porphyry copper deposits. Walter Mooney provided a copy of the Global Seismic Catalog of the US Geological Survey. Alexei Gorbatov provided AusArray EFTF receiver function results. We thank reviewers Roger Miller and Alexei Gorbatov for providing constructive feedback.

eCat 149336 doi: https://doi.org/10.26186/149336

References

Brocher T.M., 2005. Empirical relations between elastic wavespeeds and density in the Earth's crust. Bulletin of the Seismological Society of America 95:2081–2092. https://doi.org/10.1785/0120050077

Cheng Y., et al., 2024. Mineral systems and metallogeny of the Delamerian Orogen margin. In: Czarnota K., (ed.), Exploring for the Future: Extended Abstracts. Geoscience Australia, Canberra. https://doi.org/10.26186/149657

Chiaradia M., 2014. Copper enrichment in arc magmas controlled by overriding plate thickness. Nature Geoscience 7:43–46. https://doi.org/10.1038/ngeo2028

Christensen N.I., 1974. Compressional wave velocities in possible mantle rocks to pressures of 30 kilobars. Journal of Geophysical Research 79:407–412. https://doi.org/10.1029/JB079i002p00407

Christensen N.I. & Mooney W.D., 1995. Seismic velocity structure and composition of the continental crust: A global view. Journal of Geophysical Research: Solid Earth 100:9761–9788. https://doi.org/10.1029/95JB00259

Goodwin J.A., 2024. Australia-wide 3D Density and Magnetic Susceptibility Models. Geoscience Australia, Canberra. https://doi.org/10.26186/149226

Gorbatov A., et al., 2020a. AusArray: Quality passive seismic data to underpin updatable national velocity models of the lithosphere. In: Czarnota K., et al., (eds), Exploring for the Future: Extended Abstracts. Geoscience Australia, Canberra. http://dx.doi.org/10.11636/135284

Gorbatov A., et al., 2020b. Moho variations in northern Australia. In: Czarnota K., et al., (eds), Exploring for the Future: Extended Abstracts. Geoscience Australia, Canberra. http://dx.doi.org/10.11636/135179

Gorbatov A., et al., 2024. AusArray continental-scale deployment. In: Czarnota K. (ed.), Exploring for the Future: Extended Abstracts. Geoscience Australia, Canberra. https://doi.org/10.26186/149640

Hejrani B., 2023. Ambient noise tomography of Australia: Application to AusArray deployment - Update. Geoscience Australia, Canberra. https://dx.doi.org/10.26186/148676

Kennett B.L.M., 2023. Refining the Moho across the Australian continent. Geophysical Journal International, 233:1863–1877. https://doi.org/10.1093/gji/ggad035

Lane R.J.L., et al., 2020. 2019 Australian National Gravity Grids. Geoscience Australia, Canberra. http://pid.geoscience.gov.au/dataset/ga/133023

Laske G., Masters G., Ma Z. & Pasyanos M., 2013. Update on CRUST1.0 - A 1-degree global model of Earth's crust. In: EGU General Assembly Abstracts. [Online] Available at: https://igppweb.ucsd.edu/~gabi/crust1.html

Lee C.A. & Tang M., 2020. How to make porphyry copper deposits. Earth and Planetary Science Letters 529:115868. https://doi.org/10.1016/j.epsl.2019.115868

Leeman W.P., 1983. The influence of crustal structure on compositions of subduction-related magmas. Journal of Volcanology and Geothermal Research 18:561–588. https://doi.org/10.1016/0377-0273(83)90026-4

Ludwig W.J., Nafe J.E. & Drake C.L., 1970. Seismic refraction. In: Maxwell A.E. (ed.), The Sea Vol. 4. Wiley-Interscience, New York, pp. 53–84.

Mooney W.D., Barrera-Lopez C., Suárez M.G. & Castelblanco M.A., 2023. Earth Crustal Model 1 (ECM1): A 1° x 1° global seismic and density model. Earth-Science Reviews 104493. https://doi.org/10.1016/j.earscirev.2023.104493

Sillitoe R.H., 2010. Porphyry copper systems. Economic Geology, 105:3–41. https://doi.org/10.2113/gsecongeo.105.1.3

Stephenson S.N. & Hoggard M.J., 2024. SMV2rho: Crustal density from seismic velocity [software], v1.1.0. Zenodo. https://doi.org/10.5281/zenodo.10017540

Stephenson S.N., Hoggard M.J., Holdt M.C. & Galbraith-Olive H., 2024a. SeisCruST: Seismic crustal structure and thickness [dataset]. Zenodo. https://doi.org/10.5281/zenodo.10017428

Stephenson S.N., Hoggard M.J., Holdt M.C. & White N.J., 2024b. Continental Residual Topography Extracted from Global Analysis of Crustal Structure. Journal of Geophysical Research: Solid Earth, 129, e2023JB026735. https://doi.org/10.1029/2023JB026735

Tang M., Erdman M., Eldridge G. & Lee C.A., 2018. The redox "filter" beneath magmatic orogens and the formation of continental crust. Science Advances 4:eaar4444. https://doi.org/10.1126/sciadv.aar4444

Zhu L. & Kanamori H., 2000. Moho depth variation in southern California from teleseismic receiver functions. Journal of Geophysical Research: Solid Earth 105:2969–2980. https://doi.org/10.1029/1999JB900322

GA SRF162988