



## Preface

## Moho: 100 years after Andrija Mohorovičić

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## 1. Introduction

In October 1909 an earthquake near Pokupsko, about 40 km to the southeast of Zagreb in Croatia, sparked the interest of the meteorologist and seismologist Andrija Mohorovičić. He secured copies of seismograms from many European stations and inferred the presence of a jump in seismic wavespeeds at a depth near 50 km by careful analysis of the character and times of arrival of both P and S phases. This work was published in the yearbook of the Zagreb Meteorological Institute in 1910, and was brought to wider attention by a digest in Gerlands Beiträge zur Geophysik published in 1911 that included a summary representation of his results.

The crust is relatively thick in this part of the Dinarides and so the cross-over between crustal and mantle arrivals occurs at considerable distance from the source. This large offset enabled the change in character to be recognised with the rather sparse set of information available to Mohorovičić. Subsequent work, including significant contributions from Jeffreys and Conrad, pushed forward the analysis of crustal structure using seismic waves, leading to the recognition of the Mohorovičić discontinuity as a ubiquitous feature marking the base of the crust. The name of the discontinuity is now commonly contracted to the “Moho”. The nature of the transition between crust and mantle is not always sharp and considerable variety in character and depth has been revealed across the globe.

Although recognised as a first order feature of the lithosphere, observations of the Moho remained geographically sparse for the first 50 years after its discovery. In the sixties there was consensus for a definition of the Moho as “that level in the earth where the compressional wave velocity increases rapidly or discontinuously to a value between 7.6 and 8.6 km/s. In the absence of an identifiable rapid increase in velocity, the Mohorovičić discontinuity is taken to be the level at which the compressional wave velocity first exceeds 7.6 km/s” (Steinhart, 1967). An early regional map of depth to the Moho was published by Morelli et al. (1967) for the European continent (Fig. 1). Soon after maps of depth to Moho were published for the territory of the Soviet Union (Fig. 2; Belyaevsky et al., 1973) and for the United States of America (Fig. 3; Warren and Healy, 1973). A Moho map for Australia (Fig. 4) was published by Collins (1991).

It is remarkable that the main features of these early maps are robust and remain identifiable in the newest maps published in this volume.

Resolution and regional coverage have improved considerably, so that the new maps show more details than the early contributions. A major uncertainty for estimation of Moho depth is produced by fast lower crust, with a wavespeed of >7.0 km/s which is close to the wavespeed of the uppermost mantle (>7.6 km/s). It is noteworthy that the early maps often underestimate the true crustal thickness where the top of the lower crust mistakenly is interpreted as the Moho because (1) the high velocity lower crust may be a “hidden layer” for refraction seismic interpretations, (2) it may cause the strongest observed wide-angle reflection in seismic sections, or (3) it may be the strongest converter in receiver function images. The uncertainty arising from these and other methodological and logistic challenges have been reduced with time, as seen in improved resolution and a wider depth range of determined Moho depths.

The Moho is most often the interface between the crust and the mantle, although with variable thickness of the transition zone, depending on the tectono-magmatic setting. However, in some locations the Moho may represent a metamorphic front in a gabbroic sequence which has been subject to high-pressure metamorphism into eclogite facies. In case of serpentinitization of the sub-Moho mantle, the seismic Moho may reside at the base of the serpentinites which petrologically lie inside the mantle.

## 2. Volume overview

This compilation of papers was initiated during the 100 years anniversary of the publication of the discovery made by Mohorovičić in 1910. Through a series of invited review papers the volume provides an overview of the many facets of the Moho as seen with different geophysical and geochemical tools, supplemented by regional studies covering many parts of the world. It includes five sections covering:

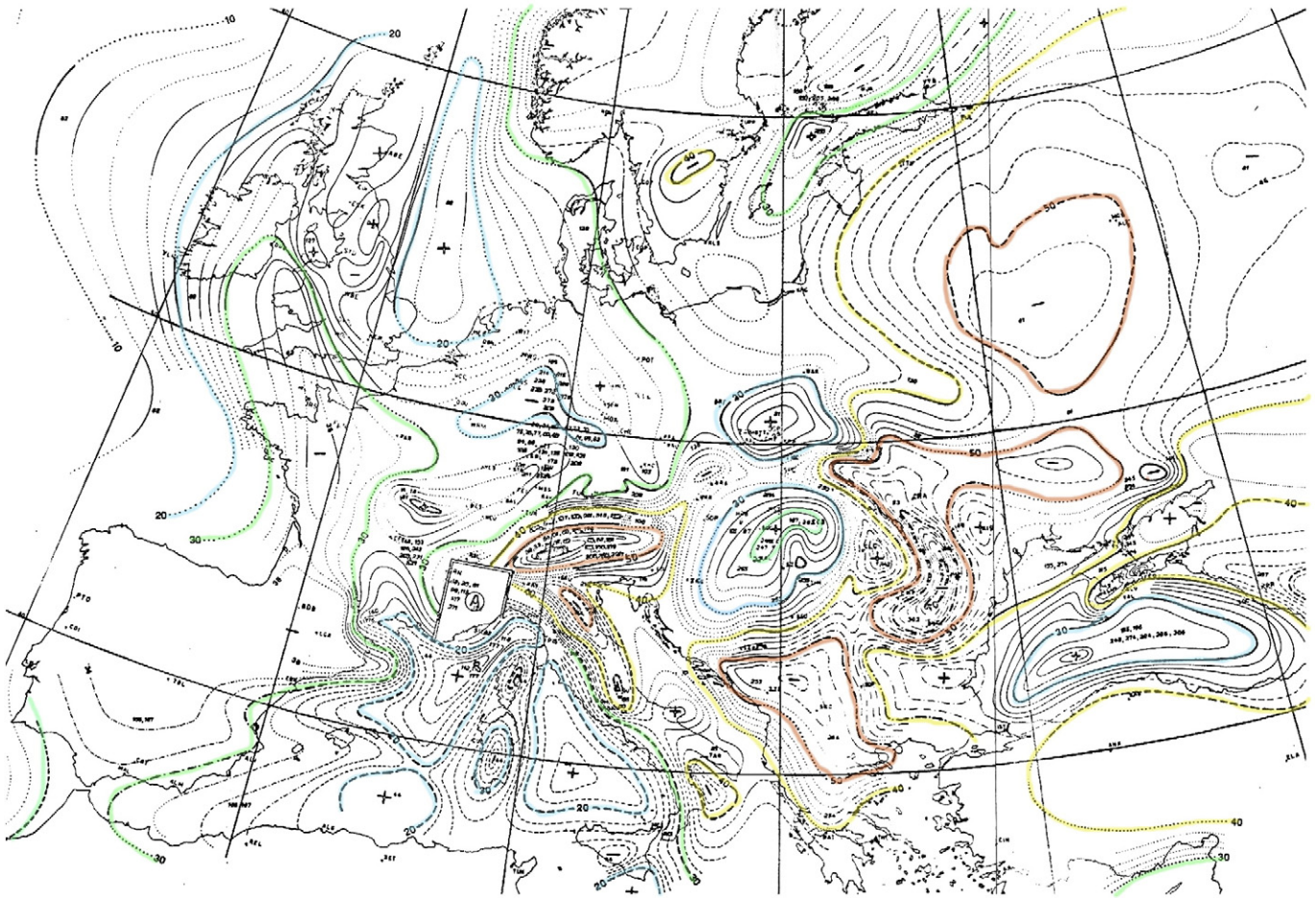
- historical introduction;
- regional models of crustal structure and Moho depth;
- physical-chemical nature of the Moho;
- processes that create and modify the Moho; and
- secular evolution of the Moho.

## 2.1. Historical introduction

The first 100 years of seismic research on the Moho is reviewed by Prodehl et al. (this volume). After a short introduction to how Mohorovičić in 1909 determined the presence of the Moho discontinuity,

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**Fig. 1.** Depth to Moho in Europe. Isolines with a 2 km step.  
After Morelli et al., 1967.

the authors provide an overview of the early techniques that were applied to determinations of crustal structure, which were mainly applying earthquakes as sources although explosion sources were also used for crustal studies. The period after World War II is characterised by increased use of explosive sources which led to higher resolution of seismic images and models, including the determination of intra/crustal velocities. The authors chronologically review the evolution of seismic methods regarding data acquisition methods, processing technology, and interpretation methods. Since the 1980s the earthquake-based receiver function method has become increasingly popular for crustal studies as a supplement to controlled source techniques, not least for providing data on the structure where controlled source profiles are sparse. The integration of the two types of methods has contributed significantly to our current knowledge of crustal structure and depth to Moho.

## 2.2. Regional models of crustal structure and Moho depth

This large section provides an overview of the current knowledge of crustal structure and Moho in a series of regional reviews with main focus on seismic results. The many new compilations show significant differences to previous global and regional compilations.

The Americas are reviewed in four papers. Keller (this volume) describes the current knowledge of crustal structure and Moho in North America, with focus on results obtained since 2005, and provides a schematic map of depth to Moho for the area. Recent research programmes in Canada and the US have provided large quantities of data on crustal and lithospheric mantle structure. Numerous suture zones, with complex internal structure provide evidence for the Precambrian assembly of the continent. Unusually thick crust with

very fast lower crust is interpreted in cratonic regions. Massive magmatic modification has been observed in rift systems and in the Basin and Range province. The highly complex crustal structure in the western part of the continent is related to the interaction between subduction, transform faulting and magmatism. Manea et al. (this volume) provides a geodynamic perspective on the crustal structure in Central America with emphasis on the effects of one of the world's most complex active subduction systems. The main processes controlling the subduction system are discussed based on a review of the tectonics, volcanism, slab geometry and segmentation along the margin. Different evolutionary scenarios for the subduction zone provide background for future modelling. Recent observations of seismic anisotropy provide evidence for mantle flow that may link deep and surface processes. Assumpção et al. (this volume) discuss models of crustal thickness in South America based on the available data from seismic refraction, receiver functions and surface wave tomography. The seismic coverage of the South American continent is highly variable with rather dense coverage along large parts of the Andean Cordillera and extremely sparse coverage in other parts. Two databases have been compiled, one based on controlled source results and the other includes results from surface wave inversion, both will be valuable for e.g. gravity interpretations. One of the maps of depth to the Moho is based on the seismic observations and contouring is guided by gravity in the poorly constrained areas. The other map is based on improved data coverage from including surface wave inversion. Not surprisingly, the authors find significant variation in crustal thickness in the Andes Cordillera, ranging from 75 km in Southern Peru and the Bolivian Altiplano, decreasing to the global continental average (~40 km) in Ecuador and southern Colombia, despite high elevation,

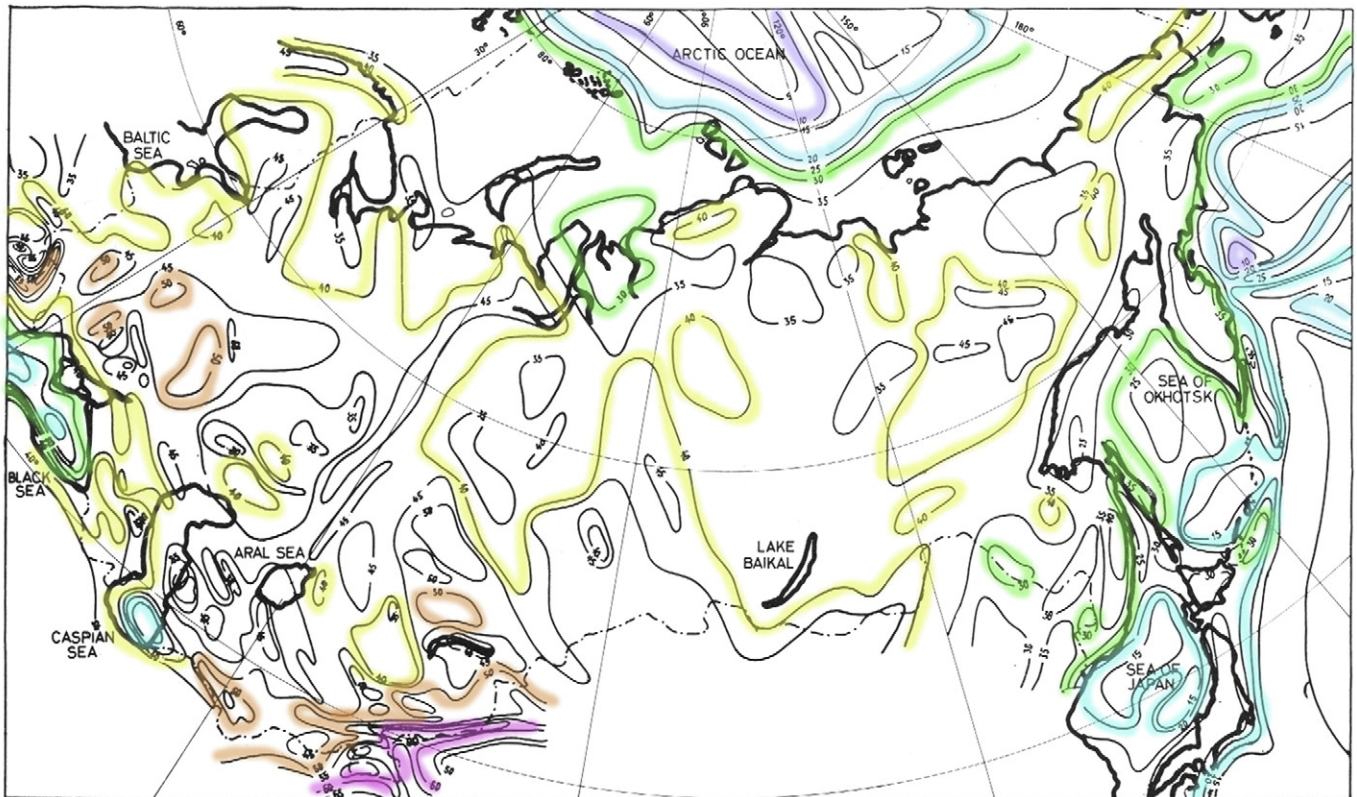


Fig. 2. Depth to Moho in USSR. Isolines with a 5 km step. After Belyaevsky et al., 1973.

and along the southern Andes of Chile–Argentina where elevation is lower than 2000 m. Relatively thick crust is observed in the Amazon craton and the Parana Basin, whereas the crust is relatively thin in other areas. A comparison is provided between crustal thickness and gravity anomalies.

The crustal structure and Moho in Europe, Greenland and the North Atlantic region is reviewed by Artemieva and Thybo (this volume) based on a fully new compilation (EUNaseis) of seismic models from the region as published in ca. 650 papers with additional constraints from receiver functions. The model is based solely on the seismic information, and it can therefore provide useful constraints for, e.g., gravity and isostasy studies in addition to seismic studies of the mantle. The crust in the on-shore and off-shore parts of the region is highly heterogeneous with significant short wavelength variations. Comparison to a new tectonic map leads to a set of conclusions, including that depth to Moho and the observed crustal parameters for Europe are different from any published global average values. Other surprising conclusions are that the thickness ratio between upper–middle and the lower crystalline crust is indicative of tectono-magmatic origin, and that a complex interplay of magmatic underplating, gabbro–eclogite phase transition and delamination is indicated in modern and paleorift zones. The bathymetry is shallow in most of the North Atlantic Ocean, where the oceanic crust also is anomalously thick, and the crustal structure of the Barents Sea shelf differs from rifted continental crust. The belt of exceptionally thick crust in the Greenland–Iceland–Faeroe Ridge may continue across the Baffin Bay.

The Asian continent is covered by four papers. Cherepanova et al. (this volume) review the crustal structure of Siberia based on a new comprehensive compilation (SibCrust) of the existing seismic profiles and point samplings from the region with quantitative assessment of the data quality. The compilation is based solely on the seismic constraints, and it has a broad range of applications. The authors find strong crustal heterogeneity, which correlates strongly with tectonic setting but only weakly with tectono-thermal age. Surprisingly, the

average crustal velocity is similar in the Siberian Craton and the West Siberian Basin. High basement velocities are proposed to indicate magmatic intrusions which may be the source zone of the Siberian Large Igneous Province. Iwasaki et al. (this volume) review the depth and nature of the Moho beneath the Kamchatka peninsula and the islands of Japan, including the Izu–Bonin volcanic arc based on all available data from artificial and natural seismic sources. Although the amount of data from Japan is much larger than in Kamchatka, the crustal structure of the two areas is generally similar, in particular regarding average crustal thickness and a gradational nature of the crust–mantle transition in active volcanic areas. Teng et al. (this volume) discuss the character of Moho in China based on 114 seismic refraction profiles acquired since 1958. The region shows large variation in depth of the Moho from 10 to 85 km. The deepest Moho is observed beneath the Tibetan Plateau and may be explained by the ongoing continent–continent collision. The North China craton has a relatively constant crustal thickness of 30–35 km, possibly due to mantle lithosphere destruction. The authors find that Moho depths determined from active seismology are consistent within 3–5 km with results obtained from gravity inversion and surface wave tomography. The variation of the Moho depth, crustal formation, and composition of different tectonic blocks contribute to controls on the spatial distribution of the seismicity and rheology in the crust beneath mainland China. Reddy and Rao (this volume) provide an overview of reflection seismic images of the continental Moho in the Indian shield. They observe large lateral variability in the reflection character of the Moho, in places being imaged as a discrete strong event or located at the termination of lower crustal reflections, to areas without any clear reflection image of the boundary. The authors propose a series of processes that may cause the observed lower crustal reflectivity and the formation of a young Moho, such as post-collisional extension, delamination, magmatic intrusion, low-viscosity ordering and underplating.

Crustal structure and Moho depth beneath Africa and the Arabian plate are discussed in three papers. Mechie et al. (this volume) review

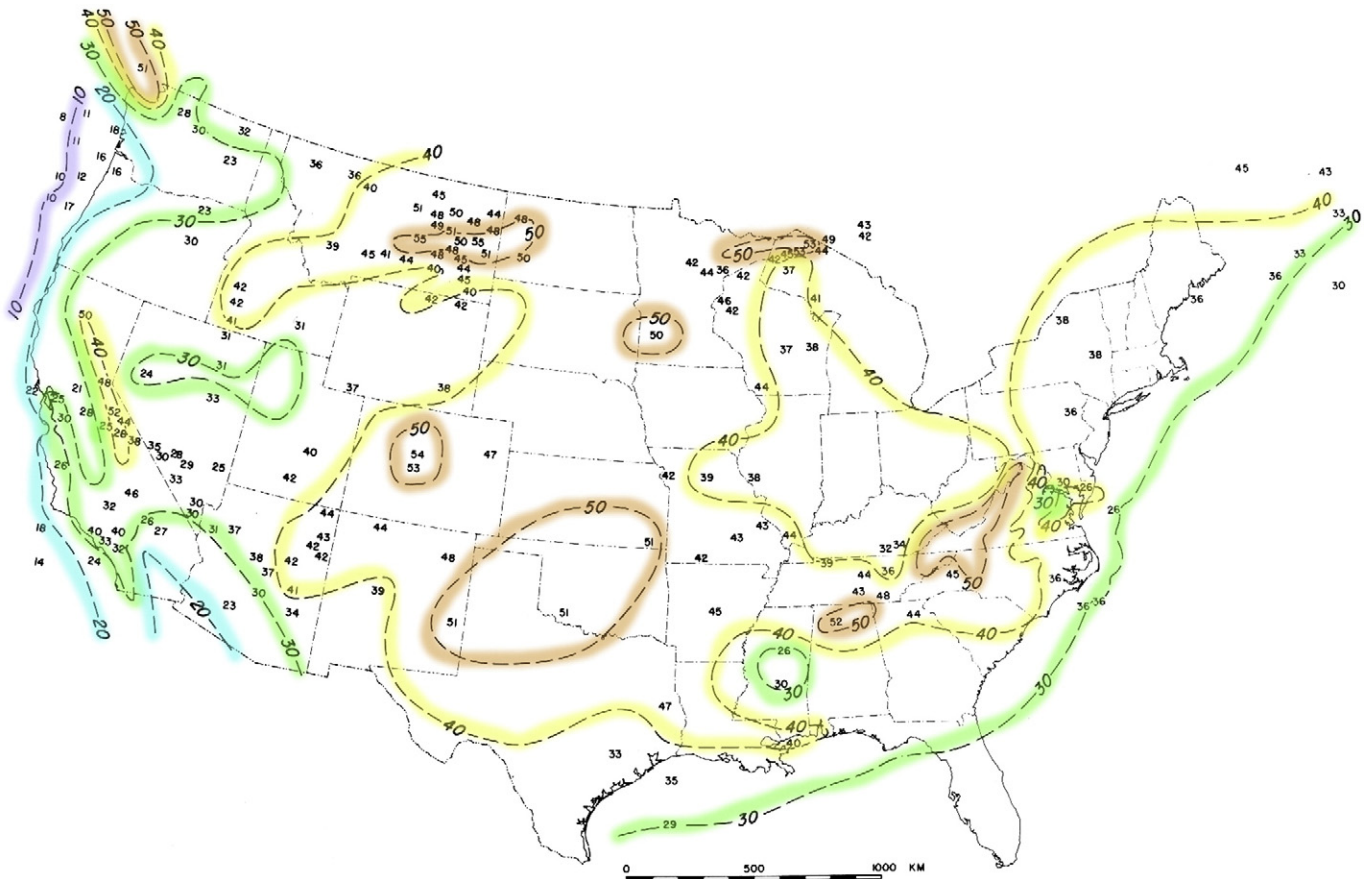


Fig. 3. Depth to Moho in USA. Isolines with a 10 km step and regional values in km. After Warren and Healy, 1973.

the crustal structure of the Arabian plate and its margins based on the available seismological data. They present a map of depth to Moho based purely on seismological data. Due to low data density, they also present two maps where the interpolation is guided by gravity data. Moho depth is typically 32–45 km depth in the interior of the Arabian plate and more than 50 km below the Zagros mountains. The Dead Sea Transform marks a decrease in Moho depth from almost 40 km beneath the highlands in the east to about 21–23 km under the southeastern Mediterranean Sea with a possible depression below the transform itself. Both Pn and Sn velocities may be higher in the northeastern than the southwestern parts of the plate interior. Differences in the transition to shallow Moho at the plate margins may reflect fundamental differences in the original structure of the margins. Tugume et al. (this volume) review the general knowledge of the Precambrian crustal structure in Africa and Arabia based on joint inversion of receiver functions and surface wave dispersion measurements. Due to the scarcity of data their new map of crustal thickness is interpolated by use of satellite gravity data. They find little evidence for secular variation in crustal structure, indicating that the processes forming the continental crust have remained stable with time, although post-formation may have concealed secular trends. Youssef et al. (this volume) provide a detailed study of heterogeneous crustal structure in southern Africa based on a large number of receiver functions, including Hk stacking. Short wavelength variations in crustal thickness, Vp/Vs-ratio, and Moho sharpness define 20 blocks that do not everywhere coincide with surface tectonic features. Crustal thickness in the cratons varies between 31 and 51 km. Delamination may have created the thinnest parts of the cratonic crust. The authors find no evidence for magmatic intrusions between the two main lobes of the Bushveld Intrusion Complex. Shallow Moho and high Vp/Vs (attributed to shock metamorphism) indicates that the

exposed section in the Vredefort impact crater is non-representative of cratonic crust. The crust in the Namaqua-Natal and Cape Fold Belts is highly heterogeneous.

The Moho in Australia and New Zealand is discussed in the review by Salmon et al. (this volume) based on results from on- and off-shore refraction experiments, supplemented by receiver functions and crustal reflection profiles. The different techniques provide consistent results where multiple sampling is available. The crust is thin below the Archaean Pilbara craton, whereas it is thick beneath most of the Proterozoic parts of Central Australia and the Palaeozoic Lachlan fold belt. Sharp contrast in Moho depth is observed in the southern part of Central Australia. Moho depth in New Zealand is mainly known from onshore data around the Australia–Pacific plate boundary, even though most continental material is located below sea level. Onshore data coverage is as dense as in Australia. Thick crust is observed beneath the Southern Alps, beneath Fiordland and the Wanganui Basin between the North and South Island, whereas thin crust is identified west of the volcanic arc, and extensive underplating is proposed below the back-arc region.

Moho depth in Antarctica between the South Pole and the continental margin is reviewed by Baranov and Morelli (this volume). A map of Moho depth with a  $1^\circ \times 1^\circ$  sampling distance is presented based on a literature study of the results of seismic experiments and receiver functions. The mean Moho depth of the continent is 34 km. The Archaean and Proterozoic crust of East Antarctica is 36–56 km thick; the crust of the Transantarctic Mountains, the Antarctic Peninsula and Wilkes Basin is 30–40 km thick; and the crust of the West Antarctic rift system is 16–28 km thick.

The crustal structure and Moho in the oceans is reviewed in the paper by Mutter and Carton (this volume) who discuss the character of the oceanic Moho based on seismic observations made since the

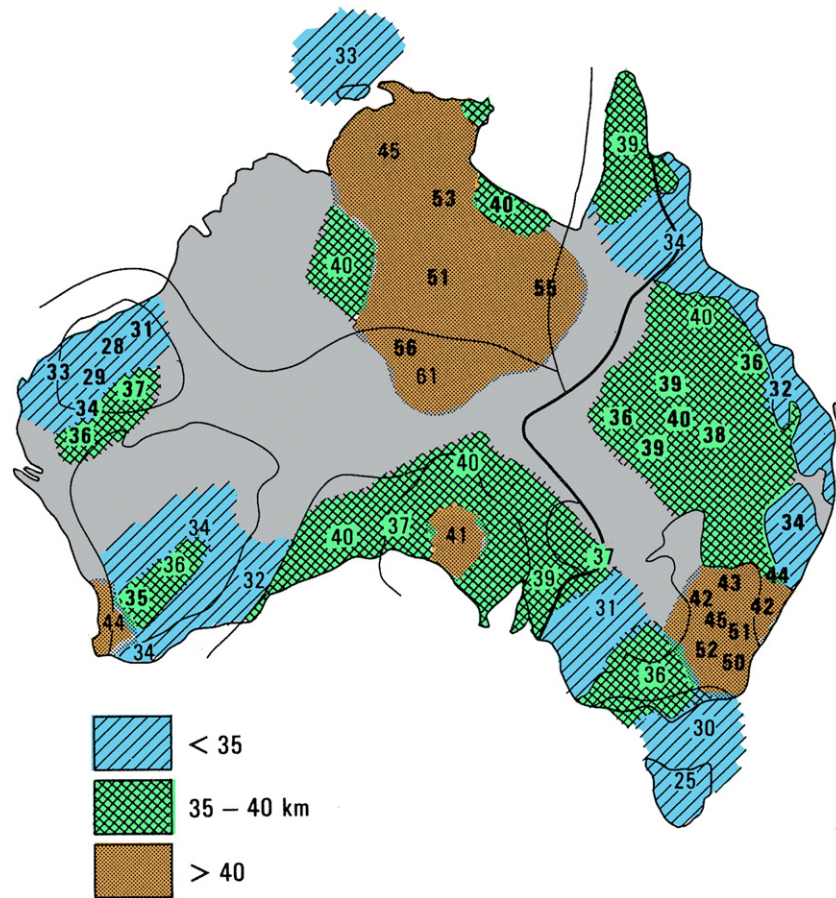


Fig. 4. Depth to Moho in Australia. Variations in shading correspond to a 5 km change in the Moho depth, regional values are in km. After Collins, 1991.

late 1970s. The earliest studies of the fast-spreading East Pacific Rise surprisingly revealed a distinct, almost continuous, vertical incidence reflection event at the same depth as the Moho inferred from seismic refraction studies. This sharp reflector was observed very close to the ridge crest, which implies that the Moho may form at essentially zero age. Subsequent studies show that Moho is highly variable, ranging from a distinct or complex feature to even being non-reflective in up to 40% of the observations. The absence of Moho reflections cannot be fully explained as an effect of scattering or attenuation.

The internal structure and the Moho in the Moon are discussed by Khan et al. (this volume) based on the seismic data that was acquired on four seismometers during the Apollo missions around 1970. The seismic results provide constraints on the origin and evolution of the Moon, including the role of melting during its formation. Early interpretations of the seismic data inferred a Moho depth of 60 km, whereas recent interpretations, including simulated annealing estimates, lead to smaller values around 30–40 km. Recent interpretations of gravity and topography data indicate significant lateral variations in Moho depth ranging from 0 to 80 km.

### 2.3. Physical–chemical nature of the Moho

This section provides an overview of the current knowledge of the changes that occur in physical parameters across the Moho through a series of papers that each focus on one or a few parameters.

Seismic constraints on the Moho are reviewed by Carbonell et al. (this volume) based on results from the various controlled and natural source seismic methods that may be applied. Frequency content and geometry determine resolution, such that different methods provide complementary data on the physical structure of the Moho and its

relationship to the petrologic crust–mantle transition. Regional passive source seismic studies usually record the Moho as a well defined, continuous structure, whereas controlled source methods with higher frequency content may determine fine structure of the boundary. The authors stress the importance of tectono-magmatic processes for the structure of the Moho, including orogenesis, orogen collapse, and underplating, although the Moho in some Precambrian terranes may have survived intact since crustal formation.

Determination of Moho depth from inversion of surface wave data is reviewed by Lebedev et al. (this volume) with validation by comparison to results obtained by other methods in selected locations. Seismic surface waves are strongly sensitive to the Moho depth as evident in dispersion curves and waveforms, but a strong trade-off exists between Moho depth and lithosphere structure, which impedes direct inversion of surface waves without *a priori* information. However, Moho-depth variations at the kilometre scale can be determined if seismic wavespeeds in the lithosphere are known. The authors propose a strategy for inversion of surface-wave data alone for the Moho depth, by first obtaining estimates of lithospheric wavespeed variation by inverting broad band data, before determining Moho depth by inversion in a narrow period range. Simultaneous inversion of surface-wave and other data, such as receiver functions, topography, or gravity, may reduce uncertainties.

Wang et al. (this volume) review the Moho as a seismic and electrical transition zone based on laboratory measurements of these properties of minerals and rocks. Pressure, temperature and metamorphism have significant influence on seismic and electrical properties of lower crustal and mantle rocks. The petrologic transition from olivine-poor to olivine-rich compositions may define the sharpness of the Moho, but due to the influence of serpentinization and eclogitization the seismic Moho may

not everywhere correspond to the petrologic Moho. Electrical conductivity of granulites and peridotites, like seismic velocity, depends on temperature and composition, but also on water content and oxygen fugacity, and with only a weak dependence on pressure. The “electrical Moho” is defined as the bottom of the relatively conductive continental lower crust ( $10^{-4}$  to  $10^{-1}$  S/m) and is often not coinciding with the seismic Moho.

The electrical Moho is discussed by Jones (this volume). Laboratory studies of crustal and mantle rocks indicate that the crust–mantle boundary may be represented by a discontinuity in electrical conductivity at the “electrical Moho” (eMoho). Numerical resolution tests show that the effects of a highly conductive lower crust implies significant problems for observing the eMoho by electrical and electromagnetic methods for generic models representing Archaean, Proterozoic, and Phanerozoic lithosphere. In the rare case where the lower crust is more resistive than the underlying upper mantle, it is possible to resolve an eMoho if data of very high quality has been acquired.

Contrasts of seismic velocity, density and strength across the Moho are reviewed by Rabbel et al. (this volume) with focus on the influence of temperature, rock composition, anisotropy and macro-scale heterogeneity, and in relation to past and present tectonic processes. Oceanic and the lower parts of old cratonic crust may appear as a single rheological unit together with the uppermost mantle, although they are seismically different unless metamorphic processes, such as serpentinization or eclogitization, destroy the seismic differences. Although the Moho is defined as a first-order discontinuity in seismic velocity, it often also represents a change in other seismic properties, such as seismic velocity gradients, anisotropy and heterogeneity scale parameters. Nevertheless, our current knowledge of these parameters and their relation to the rheology of the crust–mantle transition, is still restricted to local and regional examples.

Two papers illustrate how the Moho depth can be constrained by gravity data in regions with poor seismic coverage. Taking into account the relatively sparse coverage of large parts of South America, Van der Meijde et al. (this volume) use gravity data from satellite observations for determination of depth to Moho in South America. Despite a simple inversion model with two layers only, the calculated Moho topography correlates with most seismic observations in the stable parts of the continent. Exceptions are mainly observed in active orogenic zones. Aitken et al. (this volume) test the usefulness of gravity modelling for the determination of Moho depth in Australia. The advantages and disadvantages of several gravity modelling methods are discussed and the reliability of the methods is assessed by comparison to seismic observations. Results of a seismically constrained gravity inversion indicate that the method is useful with several limitations arising from the trade-off between density and crustal thickness, such that the results crucially depend on *a priori* knowledge of densities. The usefulness of gravity inversion is at maximum under conditions where seismic coverage is moderately dense and well distributed.

The rheological contrast at the continental Moho is reviewed by Ranalli and Adams (this volume) in terms of composition, temperature, deformation mechanism, and tectonic regime. The authors consider eight compositional layering models that are defined from the possible combinations of wet and dry regimes as well as felsic and mafic lower crust. The results show great variety of strength contrasts depending on the specific conditions. Very low Moho temperature implies that the strength contrast across Moho vanishes. Compositional stratification enhances the rheological contrasts and the strength contrast is higher in compressional than extensional tectonic regimes, although it decreases with temperature.

Chen et al. (this volume) discuss the relation between Moho, seismogenesis, and rheology of the lithosphere. The authors apply the seismic phase  $S_{\text{Pmp}}$  to obtain robust, average estimates of crustal thicknesses and relate temperature profiles with crustal thickness for defining the brittle to ductile transition in the crust and in the mantle. Laboratory measurements indicate that seismicity is limited by distinct

temperatures  $T_c$ . In warm lithosphere seismicity is therefore concentrated in the upper crust (“crème brûlée”), whereas thick, low temperature crust may result in a bimodal distribution of earthquake depths (“jelly sandwich”). Southern Tibet may be an example of the latter, as the seismicity depths include one peak in the upper crust and another below the Moho. Interestingly, in very low temperature regimes, one would expect that seismicity may occur at most depths within the lithosphere (“caramel slab”).

The relation between Moho and earthquake cycle deformation is reviewed by Wright et al. (this volume) in the context of the rheology of continental lithosphere. Recent improvement of the quality of geodetic measurements allows the authors to test whether crustal thickness exerts any control on the earthquake loading cycle. They find no global relationship between Moho depth and the seismogenic layer thickness determined geodetically, and also no clear relationship between seismogenic thickness and crustal temperature. This is contrary to oceanic lithosphere, which suggests that the effect of temperature is masked in the continents by lithology, strain-rate, grain size, or their combination. This analysis supports the “crème brûlée” model, in which the strength of the continental lithosphere is predominantly in the upper seismogenic layer. However, the distribution of geodetic observations is biased towards weak areas that favour this model.

The relation between the thermal regime and the Moho is reviewed by Mareschal and Jaupart (this volume) by comparing their model of radiogenic heat production with thermal regime and the evolution of the continental crust. By analysing global data sets, the authors find that there is no correlation between heat flow and crustal thickness. This result is explained by large spatial variations in crustal composition and heat production within individual geologic provinces. The Moho temperature may vary by up to 300 K for a given crustal thickness, depending on the surface heat flux and crustal heat production. Therefore, generic models cannot be used for calculation of crustal geotherms, but regional and local data have to be considered. The authors argue that lower crustal temperatures impose a limit on the maximum thickness that stabilized crust may attain.

The relation between the Moho and the crust–mantle boundary is discussed by O'Reilly and Griffin (this volume). The understanding that the Moho does not always coincide with the base of the (petrologic) continental crust impacted our understanding of discrepancies between observations from seismology and rock samples from the deep Earth in the 1980s. The authors propose that a transitional crust–mantle boundary may change in depth and thickness through time. The differences in depth to the observed Moho and the crust–mantle boundary imply large uncertainties in the calculation of mass balances relevant to crust-formation processes, and the composition of the convecting mantle.

#### 2.4. Processes that create and modify the Moho

This section provides an overview of processes, including deformation and metamorphism, which form and affect the Moho in various tectonic regimes.

The Moho in Subduction Zones is discussed by Bostock (this volume). Subduction zones may involve at least two Mohos associated with the subducting oceanic and the overriding plate with a complex relation to a landward dipping, low-velocity zone (LVZ), which appears to coincide with the Wadati–Benioff zone. Bostock presents a model of the LVZ being oceanic crustal Layer 2, which has become hydrated by circulation at the ridge. It becomes overpressured by metamorphic dehydration reactions between an impermeable plate boundary above and a low porosity gabbroic Layer 3 below. The resulting seismic velocity contrast may be up to 50% for S-waves, which overwhelms the effects of the underlying oceanic Moho. Eclogitization of the oceanic crust that has subducted to greater depths leads to gradual disappearance of the LVZ and releases fluids. These fluids penetrate into the cool forearc mantle wedge, where they may cause serpentinization which, together with additional free fluids, reduces velocities within the wedge, and thereby

decreases or even inverts the seismic contrast associated with the Moho of the overriding plate.

The Moho in extensional tectonic settings is discussed by Cloetingh et al. (this volume) on the basis of thermo-mechanical models. The authors propose that lithospheric memory is the key to the results of lithosphere extension and later tectonic reactivation, although migration of extension and surface processes may also be important. The finite strength of the lithosphere influences both basin geometry and the rate of vertical motion during and after rifting as demonstrated by the evolution of some of Europe's extensional systems. The thermo-mechanical structure of the lithosphere determines continental break-up and associated basin processes, which are further controlled by duration and rate of extension, thermal evolution, and possible mantle plumes. Compressional reactivation may have important consequences for post-rift inversion, as illustrated by the deformation history in the Black Sea and the Pannonian Basin region.

The relation between Moho and magmatic underplating in continental lithosphere is reviewed by Thybo and Artemieva (this volume). The original definition of underplating implied regional addition of mafic melts to the base of the crust, but the available geophysical data do not confirm widespread occurrences of such material. This may be because magma is rather added locally or interacts with the pre-existing crust, thereby becoming indistinguishable from the crustal material. New seismic data demonstrate that addition of magma around the Moho depth may take the form of lower crustal or uppermost mantle sill-like features, which produces complex seismic reflection patterns as recently observed in active and extinct rift zones as well as at continental margins. Employing the broad definition, underplating is observed in various tectonic settings, including island arcs, wide extensional continental areas, rift zones, continental margins and palaeo-suture zones in Precambrian crust.

Metamorphic processes around the Moho in continental collision zones are discussed by Austrheim (this volume) based on examples from the exposed crustal root zone of the Caledonian mountain belt in W-Norway. Fluids and deformation are found to have a critical role in metamorphic transformations and in changing petrophysical properties around the Moho, whereas dry rocks generally remain unaffected by high pressures. Four main processes are identified: formation of granulite facies areas, transformation of granulites to eclogites, retrogression of eclogite facies rocks to amphibolite and green schist facies rocks, and the spinel lherzolite to garnet lherzolite transition. The new metamorphic facies are identified on metre to kilometre scale, and ductile eclogite facies shear zones may nucleate along the brittle structures. The author proposes a model of the Moho as a rock-processing zone between a metastable dry and strong lower crust and the upper mantle, where earthquakes and tremors result in fluid flow and high-pressure metamorphism, with development of new fabrics (LPO) in the transformed rocks. Tremor and earthquakes may record ongoing metamorphic transitions.

Mjelde et al. (this volume) provide a global review of the knowledge of passive margins with focus on upper mantle peridotites or lower crustal eclogites below the seismic Moho. They find that eclogites may mark the Moho in about 6% of the total profile length studied, which confirms that the Moho generally represents the top of the mantle. Lower crustal eclogite bodies are often inferred close to lines of major changes in strain, which indicates that they may be guiding basin evolution. The presence of eclogitic bodies would significantly increase the crustal thickness compared to current assumptions, with significant implication for estimates of stretching history, subsidence and hydrocarbon maturation.

### 2.5. Secular evolution of the Moho

The early crustal evolution remains enigmatic and several models have been proposed, leading to strong variation in the rate of crustal formation. This section reviews models of crustal

formation and observations of the evolution of Archaean crust after its formation.

Continental growth and the crustal record are reviewed by Hawkesworth et al. (this volume). The variability of the record of rocks on Earth indicates a heterogeneous evolution with peaks and troughs in crustal formation. However, the distribution of rocks may instead reflect the different preservation potential of rocks generated in different tectonic settings, rather than fundamental pulses of activity. It appears that the peaks may be linked to the timing of supercontinent assembly. Geochemical analyses based on U–Pb, Hf and O isotope ratios of zircons suggest that ~60–70% of the present volume of the continental crust was generated before 3 Ga. Until then, the growth of continental crust may have been continuous, followed by a marked decrease in crustal growth rate. Considering that only <10% of pre-3 Ga crust has been preserved, significant crustal recycling must have taken place by plate tectonic processes since 3 Ga.

Arndt and Davaille (this volume) advocate an Episodic Earth Evolution. They notice that U–Pb ages of zircons from Precambrian granitoids show major peaks at about 2.7, 2.5, 2.1, 1.9 and 1.1 Ga, and they find that this is strong indication for the existence of periods with fast crustal growth that may have been related to episodic convection of the mantle. The authors present results of fluid mechanics experiments that may further our understanding of mantle convection and its relation to crustal growth. Their model assumes the presence of a dense layer at the base of the mantle until 2.7 Ga when it destabilized and generated large domes that rose into the upper mantle. This convection accelerates subduction processes which leads to increased granite magmatism at the convergent margins and thus to a pulse of crustal growth. The heat from the domes increases partial melting of the upper mantle which causes production of thick oceanic crust that resists subduction. This leads to a period of subdued plate motion until the next generation of mantle domes arrives. The authors propose that this Archean-Proterozoic period of episodic crustal growth was preceded and followed by quasi-continuous plate tectonics.

Stankiewicz and de Wit (this volume) discuss 3.5 billion years of reshaped Moho in southern Africa based on analyses of recent seismic data along swaths 2000 km in length across southern Africa and its flanking ocean, which allows comparison of Moho depths between adjacent Archean, Proterozoic and Phanerozoic crust. The authors find no simple secular change in depth to Moho, but instead significant variation in depth to Moho beneath both Archean and Proterozoic crust which is ascribed to alteration by tectono-metamorphic and igneous processes. Reconstructing the Moho of the early Earth remains a formidable challenge. The authors propose that 'fossilised' Archean crustal sections in the Vredefort impact crater for the continental crust and the Barberton greenstone belt for oceanic crust may provide information on pristine Archean Moho transitions.

The character of the Moho and lower crust in Archean cratons is discussed by Abbott et al. (this volume) based on generalisations of seismic observations. The authors find that undisturbed mid Archean crust is different from post Archean crust, as it is nearly always seismically transparent, lacks a seismic high-velocity lower crust and has a flat, sharp Moho. On this basis they argue that known, basaltic lower crust in Archean terranes is normally the result of post Archean underplating. Based on the above characteristics, the authors propose a model in which mid Archean crust has been delaminated by losing dense lithologies which has resulted in a flat, sharp Moho reflector and a thin and felsic-intermediate crust.

Hamilton (this volume) presents an opposite view on the Evolution of the Archean Mohorovičić Discontinuity from a synaccretionary protocrust. He argues that fractionation of most crustal components took place during planetary accretion to produce a mafic protocrust by ~4.5 Ga. This early mafic protocrust was the primary source of the tonalite, trondhjemite, and granodiorite (TTG) that dominate preserved Archean crust to its base. The heat from a high content of radioactive elements would melt part of the lower TTG to form magma that erupted

as dense volcanic rocks. Garnet-rich residual protocrust simultaneously delaminated through the upper mantle. In this model the Archean and earliest Proterozoic craton stabilization, including development of the Moho, was completed between ~2.9 and 2.2 Ga.

The variety of views in the discussion of the early formation and development of the Moho clearly calls for new observation, including geophysical imaging of the crust and upper mantle, where the Moho is a major observable. We hope that the present volume may provide an overview of current knowledge on the Moho, and that it may be a useful guide for planning the observational programmes of the coming years.

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