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Continental crust composition constrained by measurements of crustal Poisson's ratio

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DECIPHERING the geological evolution of the Earth's continental crust requires knowledge of its bulk composition and global variability. The main uncertainties are associated with the composition of the lower crust. Seismic measurements probe the elastic properties of the crust at depth, from which composition can be inferred. Of particular note is Poisson's ratio, σ; this elastic parameter can be determined uniquely from the ratio of P- to S-wave seismic velocity, and provides a better diagnostic of crustal composition than either P- or S-wave velocity alone[1]. Previous attempts to measure σ have been limited by difficulties in obtaining coincident P- and S-wave data sampling the entire crust[2]. Here we report 76 new estimates of crustal σ spanning all of the continents except Antarctica. We find that, on average, σ increases with the age of the crust. Our results strongly support the presence of a mafic lower crust beneath cratons, and suggest either a uniformitarian craton formation process involving delamination of the lower crust during continental collisions, followed by magmatic underplating, or a model in which crust formation processes have changed since the Precambrian era.

Estimates of the bulk composition of the Earth's crust are limited by the uncertainty in the composition of the lower crust. A variety of approaches, including seismic, crustal xenolith and isotopic studies, as well as direct examination of exposed crustal sections, have led to various estimates of lower-crustal compositions ranging from felsic to mafic[2–5]. Seismic measurements, perhaps the most direct method for probing the lower crust, have been impeded by the non-uniqueness of compressional-wave velocities (v_P) for the lower crust where both higher metamorphic grade and increasing mafic content can have similar effects[2] on v_P. The non-uniqueness is partially alleviated by the addition of shear-wave (v_S) data to estimate v_P/v_S (ref. 1), and hence Poisson's ratio, σ. For common rock types, σ varies from 0.20 to 0.35 and is particularly sensitive to composition; increasing the silica content lowers σ and high mafic content increases it (ref. 6). For lower-crustal rocks, low σ (<0.26), intermediate σ (0.26–0.28) and high σ (>0.28) are characteristic of felsic, intermediate and mafic compositions, respectively[2]. Although the importance of σ has been recognized for at least two decades[1], a comprehensive, 1992 review paper[2] cited only 11 reliable *in situ* measurements of Poisson's ratio. We use a simple teleseismic method, and data from the growing global network of digital broadband seismograph stations, to increase the number of estimates of Poisson's ratio by a factor of seven.

We measure the travel times of converted waves in the P waveforms of a teleseism recorded at a single seismic station to estimate the v_P/v_S of the crust beneath the site. A teleseismic P-wave incident on the base of the crust generates a converted S-wave (Ps) and a converted P-wave multiple (PpPms) within the crust[7] (Fig. 1). The converted phases are isolated from source effects by deconvolving the vertical from the radial component of the P waveform to produce a time series called a receiver function[8–10]. The ratio of the Ps–P time and the PpPms–Ps time is directly related to v_P/v_S, independent of crustal thickness but with a slight dependence[11] on v_P; for a range in v_P of 6.0–6.75 km s^{-1}, the change in v_P/v_S is at most 0.05 and the change in σ is no more than 0.02. Our approach is similar in principle to another single-station teleseismic technique[12]. This other method uses the redundancy of multiple phases within one seismogram, but our method does not require computation of synthetic seismograms so making it suitable for a rapid global survey. As a test of our methodology, we compared our measurements with those from a coincident seismic refraction study. Both compressional- and shear-wave Moho reflections were recorded in a recent seismic refraction experiment in eastern Ontario and northern New York state[13]. The ratio of the S-wave and P-wave travel times indicates a Poisson's ratio of 0.28 ± 0.01 for the crust in the southeastern Precambrian Grenville province[14]. We

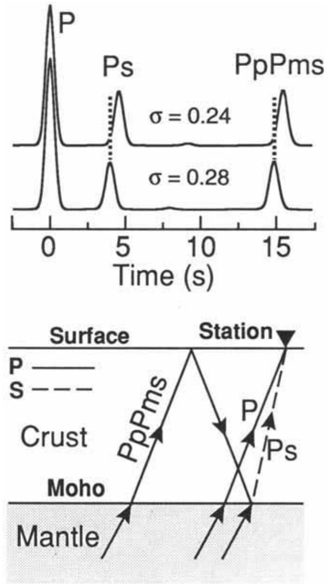

FIG. 1 Bottom, geometry of ray paths for the P wave, the converted wave Ps, and multiple converted wave PpPms generated by a teleseismic plane wave interacting with the impedance contrast at the base of the crust. Top, synthetic receiver functions for a crust with Poisson's ratio of 0.24 (upper trace) and 0.28 (lower trace). We calculate v_P/v_S (then σ) from the ratio of differential times (Ps–P)/(PpPms–Ps) and estimate the crustal thickness using the Ps–P time and the estimated value of v_P/v_S for a range of average crustal P-wave velocities. The main assumption in this method is that the Ps and PpPms phases propagate in a laterally uniform crust over the distance sampled by the phases (20–50 km). A tangential receiver function is non-zero only in the presence of lateral heterogeneity and is used to assess the quality of measurements made using the radial receiver function. We minimize the effect of lateral heterogeneity on our result and enhance the multiples by using data with periods longer than 3–5 s.

TABLE 1 Poisson's ratio and crustal thickness by crustal type

Crustal type*	Vol. %†	No. obs‡	v_P§ (km s^{-1})	σ_{ave}	σ_{sd}	σ_m	h_{ave} (km)	h_{sd} (km)	h_m (km)
Shield	16	14 (0)	6.5	0.29	0.02	0.29	36.9	2.9	35.7
Platform	51	7 (3)	6.5	0.27	0.03	0.26	41.5	6.8	40.7
Pal.	19	17 (4)	6.5	0.27	0.03	0.27	33.4	5.6	33.4
M–C	14	24 (2)	6.25	0.25	0.04	0.24	32.6	6.8	31.1
IA	—	4 (1)	6.75	0.31	0.05	0.33	28.5	3.6	27.6

σ, Poisson's ratio; h, crustal thickness.
* Defined in Fig. 2 legend.
† Normalized continental crustal volume percentage calculated from surface area percentage[16] and our estimated average crustal thicknesses.
‡ Number of measurements used to calculate average (subscript ave), standard deviation (sd), and median (m). Numbers in parentheses are measurements truncated from calculation because they were more than ±0.07 from the initial average.
§ Average crustal velocity used in the calculation of Poisson's ratio and crustal thickness. Estimates taken from global compilations of seismic refraction and reflection studies[29].

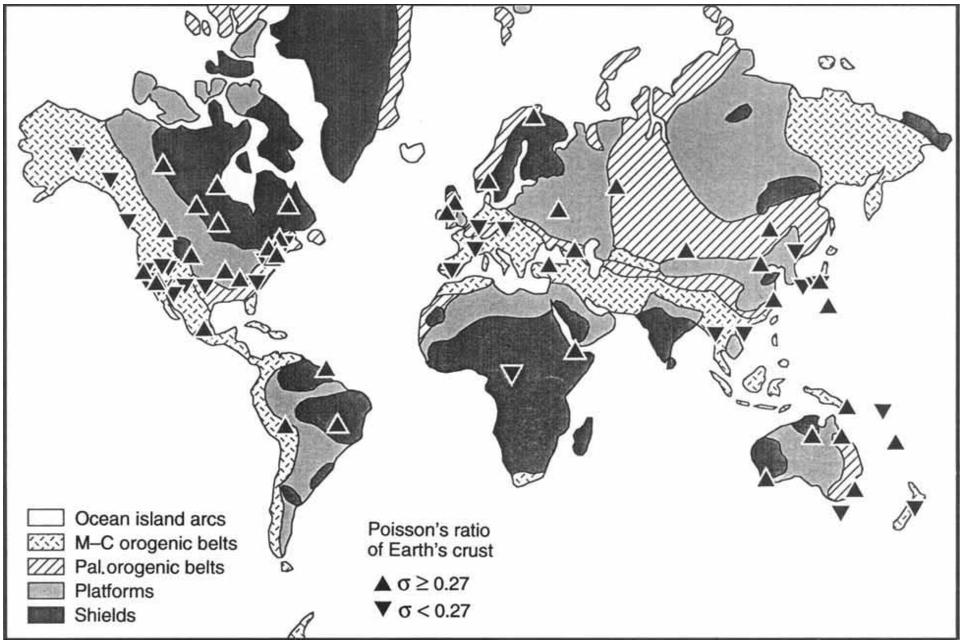

FIG. 2 Global variation of Poisson's ratio measured at digital broadband seismograph stations accessible through international, national and regional data centres. The crust is divided into five categories[16,22]. Shields are areas of exposed Precambrian-age crust, usually found in the interiors of the major continents. Platforms (Plat.) are shield-like crust with sedimentary cover 1–5 km thick. Orogenic belts are curvilinear regions of crust that have experienced one or more Phanerozoic-age tectonic events. Palaeozoic (Pal.) orogenic belts are relatively stable with eroded mountains lacking significant crustal roots. Mesozoic–Cenozoic (M–C) belts are often still tectonically active, with considerable surface relief and crustal thickness variations. Island arcs (IA) form at ocean–ocean convergence zones and are regions of oceanic crust thickened by magmatic additions. Continental volcanic arcs are included in the M–C orogenic belts.

determined a similar Poisson's ratio of 0.27–0.28 from receiver functions at RSNY, the closest broadband station to the seismic refraction study. Our measurement is also consistent with an independent teleseismic estimate for eastern Canada of $\sigma > 0.33$ for the lower crust with an average crustal value[15] of 0.27.

We examined receiver functions at 114 stations with data obtained electronically from a world-wide group of data collection organizations, and reliable estimates were made at 76 stations. At the remaining stations, either a crustal multiple could not be identified or the receiver functions were judged to be too complicated for a survey study. The distribution of global seismic stations (and hence the sampling of the crust) is heavily weighted towards North America and continental Mesozoic–Cenozoic orogenic belts, although we have some data from all the major continents except Antarctica. We separate the measurements on the basis of crustal type, namely shields, platforms, Palaeozoic orogenic belts, Mesozoic–Cenozoic orogenic belts, and ocean island arcs[16] (Fig. 2). Shields and platforms are tectonically stable and are often grouped together as cratons[16]. Based on this five-category crustal classification, an interesting pattern emerges from the σ measurements (Table 1; Fig. 3). Precambrian shield crust has consistently high values of σ, averaging 0.29 ± 0.02. platform values are more variable but average 0.27 ± 0.03. The average shield crustal thickness is 37 km and platform areas average ~42 km. The lower σ and 4–5 km additional thickness of the platform crust probably represents the effects of sedimentary cover rich in silica. Quartz has an extremely low σ (0.09) and a thick clastic sedimentary section will lower the average σ and increase the average crustal thickness. Palaeozoic orogenic belts are characterized by Poisson's ratios with a 0.27 average and median, and a crustal thickness average of 33 km. Measurements from the Mesozoic–Cenozoic regions of active or recent tectonics are variable, but in general lower, averaging about 0.25 ± 0.04 for σ, and 33 ± 6.8 km in thickness. We believe that the large standard deviation in both σ and thickness for the Mesozoic–Cenozoic crust reflects, in part, the variety of tectonic terranes encompassed by this broad classification. However, a more detailed classification is not yet justified by the number of available measurements. Additional, but less well-constrained, measurements along some island arcs of the southwestern Pacific have very high σ, averaging 0.31 ± 0.05 and crustal thickness average of 28.5 km. By weighting the averages of each crustal type by the volume percentage

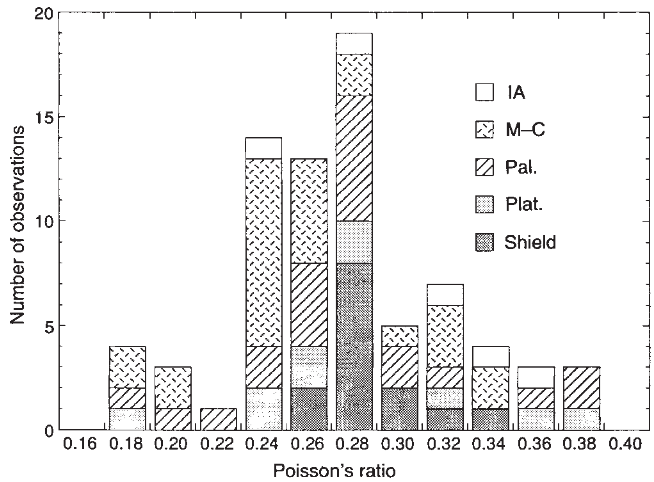

FIG. 3 Stacked histogram for all measurements of Poisson's ratio, sorted into 0.02 bins and stacked by crustal type (see Fig. 2 for definitions of crustal types).

of each type (Table 1), we estimate that the average Poisson's ratio for the bulk continental crust is 0.27, consistent with an intermediate composition. There is a significant number (18) of outlier measurements with values <0.23 or >0.33 (Fig. 3). We suspect that some of these are biased by complex structure, although there is independent evidence for unusually low Poisson's ratio in some thickened crust[17].

Our most robust observation is the high σ (0.29) for shield crust. The upper crust of shields has been estimated from numerous studies to have a felsic-to-intermediate composition[18,19]. Based on this composition and available measurements, we estimate the Poisson's ratio of the upper crust is $\leqslant 0.26$. If the bulk value of the entire crust is >0.28, the lower crust must have a value of ~0.30. This range of Poisson's ratio and high v_P for the lower crust[2] is indicative of a mafic composition, the presence of water or another volatile component under high pore pressure, or both[15,20]. High pore pressure also significantly decreases the velocity of both P and S waves[21]. The observed high v_P of cratonic lower crust and our observation of high Poisson's ratio strongly suggests a mafic composition rather than high pore pressure. With our limited data, we observe no systematic difference between Archaean and Proterozoic crust, in contrast to some previous studies[22].

We interpret the low Poisson's ratio (0.25) for Cenozoic–Mesozoic crust as indicating a predominantly felsic composition. The higher values for older crust are interpreted as reflecting a more intermediate-to-mafic composition. Specifically, Precambrian cratons have a bimodal composition distribution with a felsic-to-intermediate upper crust and a mafic lower crust. These conclusions have several possible implications for continental crustal evolution. Two main processes have been invoked in continental growth: the amalgamation of island arcs onto the edges of pre-existing continents, and pervasive intrusion and underplating of magmas derived from the upper mantle[23]. Both processes add predominantly mafic components to the crust[24,25]. The felsic composition of young orogens then implies that if magmatic addition occurs during orogenesis, either a delamination-type process must operate to remove the mafic component[24], or there is little new crust added by magmatic processes, and young orogenies mainly involve reworking of existing continental crust[26]. If the orogeny involves remobilization of an older and more mafic crust, again, some refining process such as delamination must operate to produce a predominantly felsic crust. If delamination is a common process, it raises the question of why older crust is more mafic.

There are two endmember scenarios. In a uniformitarian model, continental crust grows by amalgamation of island arc (mafic) terranes but evolves toward a more intermediate composition, first by delamination of a mafic lower crust during continental collisions. Then the remaining felsic crust is stabilized with a more mafic composition by pervasive underplating of mantle-derived magmas[27]. In this scenario young orogens, which have a felsic composition, involve crust that has not yet evolved to completion. Alternatively, the Precambrian cratons may have evolved in an entirely different manner, by a process that generated an initially more intermediate-to-mafic crust that stabilized by developing a refractory mantle root close to the time of crust formation[28]. In this scenario, processes in young orogens are fundamentally different from the processes active in the Precambrian; young orogens involve recycling and refining of existing continental crust with little crustal growth[26]. □

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Complex morphology of subducted lithosphere in the mantle beneath the Tonga trench

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AT the Tonga trench, old Pacific sea floor subducts at a rapid rate below the Indo-Australia plate, generating most of the world's deep earthquakes (focal depth >300 km)[1,2] and producing a deep slab of former oceanic lithosphere. The seismogenic part of the slab has been mapped in detail[3,4], but its fate has remained enigmatic. Here I present evidence from seismic tomography that the Pacific plate descends deep into the Earth's mantle along a trajectory that is more complex than previously thought. In the north, the slab deflects in the transition zone (between about 400 and 700 km depth) before continuing into the lower mantle (below 700 km). Further south, penetration into the lower mantle occurs without a kink. The slab morphology can be explained in terms of the recent tectonic evolution of the subduction system, and reconciles pre-existing evidence from this region for both local horizontal flow in the transition zone[2–8] and slab penetration into the lower mantle[9–12].

In the southwest Pacific (Fig. 1*a*) the large age (>120 Myr) of oceanic lithosphere and the high rate of subduction (>10 cm yr^{-1})[13] combine to produce a deep, negatively buoyant slab of former oceanic lithosphere. This slab was the subject of pioneering work on deep seismicity that further substantiated the concept of plate tectonics[2,5,6]. Analyses of travel times of seismic waves revealed fast P-wave propagation below the deepest earthquakes, suggesting the continuation of the slab into the Earth's lower mantle[9–12]. On the other hand, locations and focal mechanisms of deep earthquakes indicate internal deformation and horizontal flow in the transition zone[2,9,14] which has been interpreted as evidence against the continuation of the slab below 700 km depth, or for the detachment of the slab[7,14,15].

In a recent tomographic study R.v.d.H. and E. R. Engdahl (manuscript in preparation) used nearly 10^6 travel times of first and later-arriving compressional waves to map mantle structure to a depth of 1,600 km below the Fiji–Tonga region. Earthquake locations and phase data resulted from nonlinear hypocentre relocation and phase re-identification using arrival times from the International Seismological Centre[16,17]. Results of this investigation confirm some inferences from an earlier study[11], but the new images are of improved quality owing to better (and more) phase data and hypocentres, denser sampling due to inclusion of later-arriving phases, and the use of the iasp91 reference model[16–18]. Moreover, they are given a different interpretation. Here I focus on the relationship between large-scale slab structure and lateral displacement of the Tonga subduction system. Mantle structure further north is complex, owing to the subduction of the New Hebrides basin beneath the clockwise-migrating