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Seismic reflectors, conductivity, water and stress in the continental crust

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The uppermost 10–15 km of the Earth's continental crust differs in several geophysical properties from the lower crust. The upper crust is electrically resistive, seismically transparent, contains nearly all intracontinental earthquake hypocentres and responds to stress elastically, with brittle fracture. The lower crust is electrically conductive, contains many seismic reflectors, is aseismic and shows ductile response to stress. I show here that the characteristics of both regions can be explained if the entire crust contains saline water, in separated cavities in the compressively stressed rocks of the upper crust, but in the lower crust forming an interconnected film on the crystal surfaces. The model may apply principally to tectonically active parts of the continental crust; beneath shields, the lower crust may be dry.

Two remarkable features of the continental crust, illustrated in Fig. 1, have been recognized in recent geophysical results from western Europe and North America. Deep seismic profiles[1–4] show many short, flat or slightly arcuate reflectors below ~10–15 km depth, in contrast to an upper crust which is much more transparent, below any superficial sediments. Although there are reflectors in many parts of the upper crust, the many profiles now available demonstrate its relative transparency at frequencies of a few hertz. The nature of the lower-crustal reflectors is speculative, but the seismic amplitudes favour multiple boundaries giving constructive interference rather than single interfaces[5–7]. Layered rocks such as mylonites, produced by prolonged shearing, or layered intrusions could provide such multiple interfaces.

The second feature is an electrically conductive layer in the same depth range as the top of the lower-crustal seismic reflectors[8–10]. Resistivities typically in the range 1–50 Ω m characterize this layer, in contrast to values of 10^3–10^5 Ω m in the upper crust. The low resistivities at mid-crustal depths could be associated with carbon or with metal sulphides, but there is good reason to expect water in fractures and pores throughout the upper crust[11], so that electrolytic aqueous solutions in interconnected cavities are the most likely widespread good conductors in the continental crust. The fluid will be called brine, for brevity.

If the upper crust contains brine, and wherever the basement is seen it is densely fractured, it is reasonable to ask why the upper crust is resistive before going on to ask why there is a conductive layer at mid-crustal depths. *A priori*, one might expect a conductive upper crust. Similarly one might ask why the upper crust is transparent, before asking why the lower crust is reflective.

A possible explanation of the resistive upper crust lies in its stress field. In the upper crust, in general, one principal stress is sub-vertical, the other two horizontal. The vertical principal stress is within ~20% of the lithostatic pressure[12] $\rho_r gz$ (where

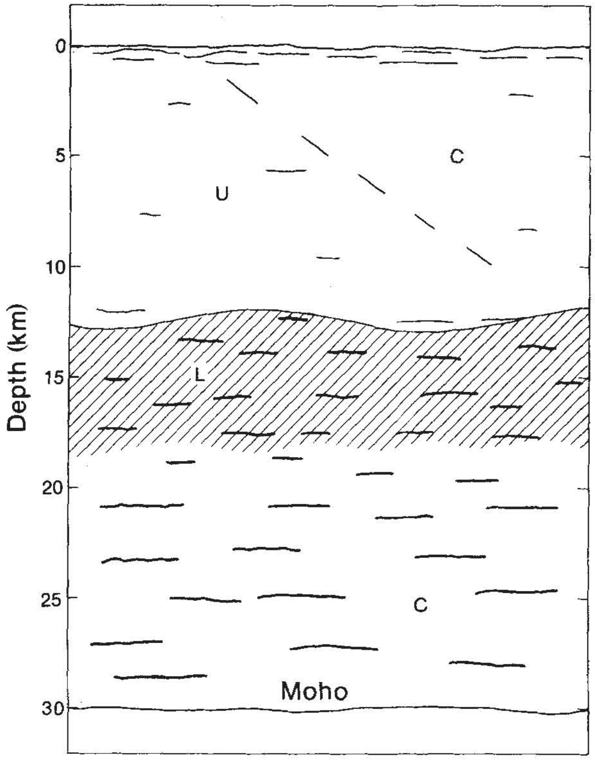

Fig. 1 The continental crust; horizontal lines represent seismic reflectors. UC, Upper crust with near-surface sediments and one through-going fault, few seismic reflectors and high resistivity. LC, Lower crust with many reflectors, low resistivity shown by shading. The top of the conductive zone is better defined than its thickness.

ρ_r is the density of the overlying rock, z is the depth and g is the acceleration due to gravity), so water at hydrostatic pressure $\rho_w gz$ cannot hold horizontal fractures open. If the lesser horizontal principal stress S_h is large enough to close fractures and isolate the brine in closed cavities, the bulk resistivity will be only slightly below that of the dry rock, and thus relatively high. Both North America east of the Rocky Mountains, and western Europe, have upper crusts under large compressive horizontal stresses of tectonic origin[13–16] and the geophysical data discussed here refer mainly to these regions. In both, the greater horizontal principal stress, S_H, exceeds the vertical lithostatic stress, and the lesser horizontal compression, S_h, is comparable to the vertical stress. Most fractures will be held closed by the horizontal compression, and the brine will be separated in unconnected cavities. If the horizontal stress remains compressive over geologically short times (thousands of years), many fractures will fill with minerals such as quartz or epidote. Only large, frequently active faults, such as through-going thrusts, might be expected to remain open. An upper crust under horizontal compression should thus be electrically resistive and also seismically transparent, except at major through-going faults. This is the situation observed[2].

In regions of strike-slip faulting, such as the San Andreas fault system of California, where the relative motion involves no underthrust cold lithosphere, earthquake foci are essentially confined to the upper crust[17]. This is true for most earthquakes in continental interiors, so that failure is clearly brittle in the top 15 km and ductile below[17]. Nearly elastic response to stress is to be expected in the upper crust until brittle fracture occurs. The high electrical resistivity implies that the fractures are closed where S_h is large enough. This will be the case except in regions of extensional stress. The least horizontal stress possible in rock is given by the elastic response to the vertical load (the lithostatic pressure), $\rho_r gz$ at depth z. This least horizontal pressure is

$n\rho_r gz/(1-n)$ in rock of Poisson's ratio n, or $\rho_r gz/3$ for $n = 0.25$. As water has density about one third of that of crustal rock, water-filled vertical cracks can remain open at all depths at which the response is elastic, in the absence of tectonic horizontal compression—that is, in a rifted region. Low and strongly anisotropic resistivities are to be expected in such regions, as is observed[18]. If the lesser horizontal stress, S_h, exceeds half the vertical stress, the upper crustal resistivity should be high and approximately isotropic. The limited available data indicate that the latter situation is the norm: where the stress field is known in continental rocks, all three principal stresses exceed the hydrostatic pressure.

A rather relaxed stress regime exists in the Kaapvaal craton of South Africa, where the upper-crustal stress field is well known from measurements in deep mines[12]. At depths of <500 m the horizontal pressures exceed the vertical. At greater depths the vertical principal stress is greatest, but the horizontal pressures are not much smaller and certainly exceed the hydrostatic pressure at all depths. As expected, the upper crust is highly resistive[19].

An orthodox view of the lower crust is that it is a very dry region, of thoroughly dehydrated granulitic composition. This view is based largely on studies of the chemistry of rocks which have passed through dehydration and rehydration reactions during burial to mid-crustal depths, followed by uplift[20,21]. Such rocks commonly show a very dry mineralogy with limited and uneven rehydration. These facts are not in conflict with an excess of a few per cent of free water in the lower crust, if water is lost during uplift and before rehydration. The extraction of metamorphic fluid is poorly understood, but probably occurs during uplift by the development of microcracks as the fluid expands more than the rock (W. S. Fyfe, personal communication). Rock cores must be compressed for reliable laboratory measurements of seismic velocities[22], because they contain many microscopic cracks. These can be explained by expansion and release of fluid during uplift.

With a dry lower crust it would be difficult to account for the ductile rheology there: one would expect earthquake hypocentres in the lower crust, not the aseismic sliding which is certainly proceeding on transform faults like the San Andreas. As intracontinental earthquakes occur mainly in tectonically active regions, the evidence for a ductile lower crust applies mainly there. The lower crust beneath shields may be of the dry granulite type. Elsewhere, the geophysical evidence invites examination of the geochemistry and mineralogy of a lower crust with a small amount of excess free water.

Fyfe[23] has calculated that a water mass equal to that of the oceans is recycled by subduction into the mantle in $\leq 10^9$ yr, and has discussed the release of large quantities of water into the basal crust in subduction zones and continental collisions[24]. Geophysical evidence for the subduction of wet sediments has recently been published[25]. It is thus reasonable to suppose that much of the lower continental crust may be a saturated environment, with excess water in equilibrium with a hydrated mineralogy unfamiliar at the surface. The suggestion that wet granitic rocks in the lower crust could account for high electrical conductivity there is not new[26]. A wet lower continental crust may prove to be a feature of plate tectonics, at least in active regions.

Even pure water has an ion density in the middle crust which is ≥ 5 orders of magnitude greater than at the surface (ref. 11, p. 26), and lower-crustal water may be a strong brine of halides as well as HCl (refs 11, 27, 28). The low bulk resistivity can be explained if the water is not contained in pockets, but coats mineral grains to form a conductive mesh. Such material might well deform in a ductile manner, with flow in response to small stress differences. In a general way, this seems promising for shear deformation producing mylonitic seismic reflectors. In terms of crustal water, the upper crust may be characterized by containment of the brine in closed cavities. In a transitional depth range ($P \simeq 3$-4 kbar, $T \simeq 200$-300 °C) the cavities may break down, so that the brine forms an intergranular film in the lower crust. The breakdown of cavities filled with brine at lithostatic pressure is unlikely to occur by simple mechanical failure in response to a stress difference. More probably, chemical reactions are involved, with accompanying mechanical failure. Hydrated minerals may contribute to the electrical conductivity of the lower crust[29,30], in addition to the intergranular film of residual brine.

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Large Variscan overthrusts beneath the Paris Basin

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The ECORS project is devoted to the deep geophysical investigation of the continental and oceanic crust in France through the study of fundamental problems such as the formation of basins, mountain belts and continental margins. The first of the profiles completed is the 'Nord de la France', which is mainly devoted to the survey of the major units of the Northern Hercynian Belt and of the deep crust below the Mesozoic Paris basin. The deep geophysical investigations undertaken on this profile have led to