COINCIDENT MAGNETOTELLURIC AND SEISMIC IMAGES OF THE LOWER CONTINENTAL CRUST BENEATH THE WEARDALE GRANITE: EVIDENCE FOR A DRY LOWER CRUST.

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With the aim of constraining the spatial relationship between deep-crustal electrical conductors and seismic reflectors, a broad-band (10^{-4} - 10^{2} Hz), high resolution, magnetotelluric survey was conducted across the Weardale granite in north-east England, coincident with pre-existing compressional-wave and shear-wave, deep, seismic data. Magnetotelluric soundings were conducted at 26 sites located over the Weardale granite at approximately 1km intervals. Following robust processing and Groom-Bailey decomposition, two-dimensional inverse modelling revealed the presence of a mid-crustal zone of high conductivity spatially separated from a previously imaged zone of intense, lower crustal seismic layering.

It has previously been postulated that zones of both high electrical conductivity and seismic layering may be ascribed a single physical explanation and, more specifically, that both result from the presence of free, interconnected fluids. Synthesis of the magnetotelluric and seismic data, together with gravity and borehole resistivity measurements, leads to the conclusion that zones of seismic layering and electrical conductivity do not necessarily coincide in tectonically stable regions and that the lower-most crust in this stable tectonic region contains no significant volume of free fluid.

The temperatures (300°-400°C) inferred for the mid-crustal depths at which the conductor is imaged lend credence to the hypothesis of free fluids trapped in the mid-crust, around the brittle-ductile transition. Graphite cannot be ruled out as contributing to the observed conductivities, but saline fluids are interpreted to be the primary cause, providing the necessary interconnected conduction pathways and accounting, also, for an apparent correlation with a mid-crustal zone of weak amplitude reflectors.

INTRODUCTION

It is now 25 years since man first beheld lunar rocks, yet the tantalizing inaccessibility of the lower crust, in spite of its relative proximity to the earth's surface, endures. The origin and preservation of globally observed lower crustal laminae (e.g. Matthews, 1986; Meissner, 1989), on the one hand, and anomalous deep conductivities (e.g. Haak and Hutton, 1986), on the other, are particular issues which remain highly contentious and enigmatic. Numerous explanations have been advanced to explain either one or both of these phenomena, including the presence of mafic sills (e.g. Furlong and Fountain, 1986), variations of metamorphic grade (e.g. Fountain and Salisbury, 1981) anisotropy (Kern and Fakhimi, 1975) or alpha to beta quartz transitions (Christensen, 1989) to explain the seismic layering, the presence of graphite (e.g. Duba et al., 1988; Frost et al., 1989) or sulphides to explain enhanced electrical conductivities, or the presence of aqueous fluids (e.g. Shankland and Ander, 1983; Hall, 1986; Gough, 1986; Hyndman and Shearer, 1989), partial melts (e.g. Gough, 1989) or shear zones (e.g. Matthews, 1986) to explain both phenomena. Of these principal candidates, free aqueous fluids, being theoretically able to provide a mechanism for explaining, jointly, both deep crustal zones of seismic layering and anomalous electrical conductivity are the most frequently, yet contentiously, ascribed cause.

Contention to the hypothesis of lower crustal, free aqueous fluids being responsible for seismic lamellae and electrical conductivities arises from the realisation that being of relatively low density and therefore gravitationally unstable, such fluids would tend to percolate upwards, evacuating the hot, ductile, lower crust within geologically short time periods. For example, applying Darcy's Law and assuming realistic porosities, Warner (1990) calculated a maximum of 10^{6} years for the expulsion of interconnected water from the lower crust.

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Several mechanisms whereby the lifetime of free, interconnected, lower crustal fluids may be extended to geologically significant time periods have been proposed. The most commonly cited of these mechanisms is permeability sealing, usually expressed as an impermeable layer, at mid-crustal depth, created by mineral precipitates. Numerous researchers have hypothesized saturated solutions of silica rising in the lower crust being induced by changes in temperature and pressure to precipitate the silica along grain edge boundaries (e.g. Etheridge et al., 1984). However, whilst an impermeable layer might present a transient barrier to ascending fluid, it would also present a boundary for the concentration of fluid by gravity, such that the boundary pressure might eventually be expected to intensify sufficiently for the fluid to egress. Sanders (1991), drawing on evidence of the preservation of dry, anhydrous rock samples circumjacent with wet, low grade metamorphic conditions, advances the hypothesis of 'self-sealing hydration'. This model assumes extensive, lenticular, lower crustal, granulite lozenges, divided by a network of anastomosing, retrogressively satiated, brine-soaked, ductile, shear zones. The products of marginal hydration reactions form impermeable envelopes around the granulite lozenges, arresting further retrogressive advances into the granulites and preserving their interior dryness. However, Frost and Bucher (1994), considering fluid-amphibole equilibria reactions at lower crustal temperatures and pressures, conclude that such hydration ceases only when all free fluid has been taken up. In contrast to the ductile lower crust, the crystalline upper crust is relatively cold and exhibits brittle/elastic behaviour. Upper crustal rocks, by virtue of their elastic strength and slower textural equilibration, can thus resist compaction. The upper crust, however, is resistive, an observation attributable to the removal of free water by retrogressive hydration reactions and expulsion through brittle fractures. Such considerations, combined with the often poor spatial resolution of electrical conductivity data, have spawned suggestions of interconnected fluids trapped in the mid-crust (e.g. Gough, 1986), with the brittle-ductile transition zone acting as a sealant against ascending fluids.

Global correlations, suggestive of a possible causal relationship, between surface heat flow (indicative of temperature at depth), and the depths to the upper boundaries of high conductivity layers, have been made by Ádám (1978). Such correlations, placing the tops of conductive zones in the temperature range 300-400°C, have been associated with the transition from brittle-elastic to ductile crustal behaviour (e.g. Hyndman and Shearer, 1989).

The degree to which the lower crust is pervaded by free water is of pertinence to the modelling of all geodynamic processes, yet, to date, crustal fluid distributions are poorly constrained. Through the combined and complementary interpretation of coincident compressional-wave and shear-wave, deep, seismic reflection data and magnetotelluric data, tighter and more reliable constraints are sought.

EXPERIMENTAL LOCATION AND RATIONALE

The Weardale granite, embracing the properties of high resistivity and low seismic attenuation is an ideal upper crustal unit through which to probe the deep crust using combined seismic and electrical techniques. Being overlain towards its centre by less than 1km of sedimentary cover (Evans et al., 1988), this batholith of crystalline rock, intruded into now stable tectonic crust during the Devonian (Fitch and Miller, 1965), may be considered as a 'window' to deep continental crust representative of stable tectonic regimes.

In 1986, bright, layered reflections from the lower crust beneath the Weardale granite were recorded by the British Geological Survey. In 1988, BIRPS acquired the first, continuous, lower crustal, shear-wave (s-wave) data, coincident with the highest quality segments of the BGS, compressional-wave (p-wave), reflection profiles. Lower crustal seismic layering is revealed in both p- and s-wave sections (Ward et al., 1992). Magnetotelluric data in the period range 10^{-2} - 10^{4} Hz was acquired during the summer months of 1991 and 1992. Three approximately linear profiles were sampled at intervals averaging 1000m. Fuller details of the data acquisition are presented in Simpson et al. (1994).

Concomitance has been inferred between deep-crustal zones of high conductivity and seismic layering (e.g. Hyndman and Shearer, 1989). However, in magnetotelluric studies, spatial uncertainty has been spawned by the lack of constraint imposed on the thickness of the conducting layer. The affliction of static shift further impairs spatial resolution such that, to date, poorly constrained models of upper and lower conductivity boundaries have rendered such inferences contentious (e.g. Jones, 1987).

Calculations using Chapman's relations (Chapman, 1986) and incorporating anomalously high heat flow measurements over the Weardale granite indicate that the brittle-ductile transition should occur at about 10 - 12 km depth, whilst the onset of bright seismic layering is not seen on the reflection data until around 22 km. Such an abnormally wide gap between the mid-crustal, brittle-ductile transition and lower crustal layering affords a good opportunity to discern the spatial relationship between deep-crustal zones of enhanced electrical conductivity and seismic reflectivity and the brittle-ductile transition. If electrical conductivity and seismic reflectivity coincide then the depth to the upper boundary of the high conductivity will be anomalously deep, whereas if the two phenomena are inconcomitant the upper boundary of electrical conductivity will be anomalously shallow in keeping with the relatively elevated depth of the brittle-ductile transition.

RESULTS AND DISCUSSION

Following robust processing (Egbert and Booker, 1986) and Groom-Bailey decomposition (Groom and Bailey, 1989) (as documented in Simpson et al., 1994), two-dimensional inverse modelling of the decomposed tensors was performed using Smith and Booker's (Smith and Booker, 1991) so-called 'Rapid Relaxation Inversion' and employing a six step procedure (also documented in Simpson et al., 1994), involving the successive incorporation of the four modal responses (TE mode apparent resistivity, TE mode phase, TM mode apparent resistivity and TM mode phase) and allowing for the determination of static shifts.

The Weardale granite was imaged as an almost homogeneous resistive layer (average resistivity approximately 3.4×10^3 Ωm) overlain by 2 km of more conductive sediments (average resistivity approximately 160 Ωm). Such resistivities are consistent with those logged in the nearby Rookhope borehole. The base of the granite was modelled at 8-12 km depth, which broadly agrees with the spatial extent of the granite predicted by gravity modelling.

A conductive feature was modelled in the mid-crust with its roof at a depth of approximately 14 km, or less. In contrast, the onset of seismic layering is delayed until approximately 22 km depth. A feature of the resistivity-depth modelling is that the base of a conductor is always less well-constrained than its top, but the conductive feature does not appear to extend through depths encompassing the lower crustal layering. There is, however some evidence of concomitance between the mid-crustal conductor and a zone of weak amplitude seismic reflectors.

The temperature-depth profile for Weardale, calculated using Chapman's relations (Chapman, 1986) and utilizing thermal conductivities and heat flow measurements logged in the Rookhope borehole, suggest that the onset of enhanced mid-crustal conductivity occurs at a temperature of approximately 350°C. Thus, the apparent global correlation between the depths to the top of deep crustal conductors and the temperatures inferred for such depths (300-400°C) appears to be upheld. Such geothermal considerations tend to lend credence to the hypothesis of saline water trapped around the brittle-ductile transition zone. If graphite were to be the primary cause then some process must be forwarded whereby interconnected films might form and be preserved at extant temperatures of around 400°C, but be broken as the earth cools and the brittle-ductile transition deepens. Graphitic films could also not be expected to account for the zone of weak amplitude seismic reflectors imaged in the mid-crust, for which it would then be necessary to advance some further explanation. It may be that graphite contributes to the high conductivities, but that fluids are the primary cause, providing the interconnectivity necessary for conduction and accounting, also, for the weak seismic reflections. During drilling of the KTB borehole both graphite and free, interconnected water have been monitored at depth in the upper crust (e.g. Rauen et al., 1993).

Meanwhile, the reflection coefficients and Vp/Vs ratios (Ward et al., 1992) are such that the very bright, sub-horizontal, laminated reflectors seen in the lower-most crust beneath the Weardale granite may be the result of magmatic underplating and intrusion and/or ductile shearing, but cannot be explained by the presence of free, interconnected fluids.

It is thus concluded that zones of seismic layering and electrical conductivity in this stable tectonic region are spatially separated and that, whereas it has often been assumed that combined consideration of reflective and conductive crustal signatures demands a wet lower crust, the lower-most crust in this region contains no significant volume of free fluid. Fluids can be entirely confined to mid-crustal depths where their presence is revealed via their conductive signature. Thus, it is not necessary to contest the evidence of petrologists (e.g. Frost and Bucher, 1994) precluding the presence of free water in the lower crust, or to propose complicated models for the preservation of lower crustal free fluids.

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