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Physics of the Earth and Planetary Interiors 161 (2007) 134–141
PHYSICS OF THE EARTH AND PLANETARY INTERIORS
www.elsevier.com/locate/pepi

Short communication

The geometry of the Iapetus Suture Zone in central Ireland deduced from a magnetotelluric study

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Received 14 June 2006; received in revised form 1 December 2006; accepted 17 January 2007

Abstract

The crustal geometry of the Iapetus Suture Zone (ISZ) in central Ireland is inferred from an electrical resistivity model derived from broadband and long period magnetotelluric measurements along a 200-km-long NNW-SSE profile. The model highlights an undulating high conductivity layer of thickness 10–15 km and resistivity 2–5 Ω m, at middle to lower crustal depths interpreted as sulphide-bearing graphitic sediments deposited between the converging continents of Laurentia and Avalonia during the closure of the Iapetus Ocean. The sediments underwent sinistral, transpressional deformation during convergence, and movements along the faults transported the sediments to depths of 5–10 km forming the U-shaped conductor beneath the centre of the profile correlative with the inferred location of the Iapetus Suture Zone. Two high resistivity blocks identified above the U-shaped conductor are interpreted as Caledonian granite bodies, and likely relate to late Caledonian igneous activity.

Keywords: Magnetotellurics; Iapetus Suture; Ireland; Tectonics

1. Introduction

The Iapetus Suture Zone (ISZ) is a tectonic boundary resulting from the collision between Laurentia and Avalonia during the early-Devonian (400 million years ago) closure of the Iapetus Ocean. It is expressed in the Southern Uplands of Scotland, across the islands of Ireland and Newfoundland, and into the Appalachians of North America. A geomagnetic anomaly was discovered within the Southern Uplands of Scotland in the early 1960s (Jain, 1964), and named the "Eskdalemuir anomaly" after the geomagnetic observatory with that name. Subsequent magnetotelluric studies conducted over 20 years, reviewed in Parr and Hutton (1993), defined the electrical geometry of the ISZ in the Southern Uplands.

In the Irish segment of the ISZ uncertainty exits in defining its exact trace and geometry due to lack of exposure and lack of high-resolution, deep-probing geophysics. A number of geophysical studies (Max et al., 1983; Lowe and Jacob, 1989; Klemperer et al., 1991; Brown and Whelan, 1995; Readman et al., 1997; Brown et al., 2003) have been carried out across the ISZ in Ireland in order to investigate its structure, and all of these studies identified crustal anomalies with varying degrees of precision and uncertainty. High frequency magnetotelluric studies by Brown and Whelan (1995) identified a dipping conductor at the ISZ, but the short period data acquired in that survey provided only upper crustal structure information.

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doi:10.1016/j.pepi.2007.01.008

With the availability of state-of-the-art magnetotelluric (MT) equipment, covering a wide frequency band, coupled with improved processing and interpretation methods, it is now possible to obtain high-precision, high-resolution resistivity models of the whole crust from which inferences can be made regarding the tectonic history of a region. With this geophysical imaging tool, we conducted a study of the ISZ in Ireland. The aim of the present paper is to present the first-order features within the crust associated with the ISZ from two-dimensional (2-D) inversion of broadband MT (BBMT) and long period MT (LMT) data from a 200-km-long NNW-SSE profile.

2. Geological and geophysical setting

Fig. 1 shows a map of the general geology of Ireland with known and inferred major faults. The Caledonian Orogeny (ca. 440–360 Ma), resulting from the collision between Laurentia and Avalonia, had an intense effect, still preserved in Ireland's rock record. Ryan and Dewey (1991) outline the geological history and deep structures of the Caledonian Orogeny in Ireland, and document that, during this orogeny the majority of the crust of central Ireland was formed and modified. Two major Caledonian NE–SW trending faults of the ISZ are identified in Scotland where exposure is supe-

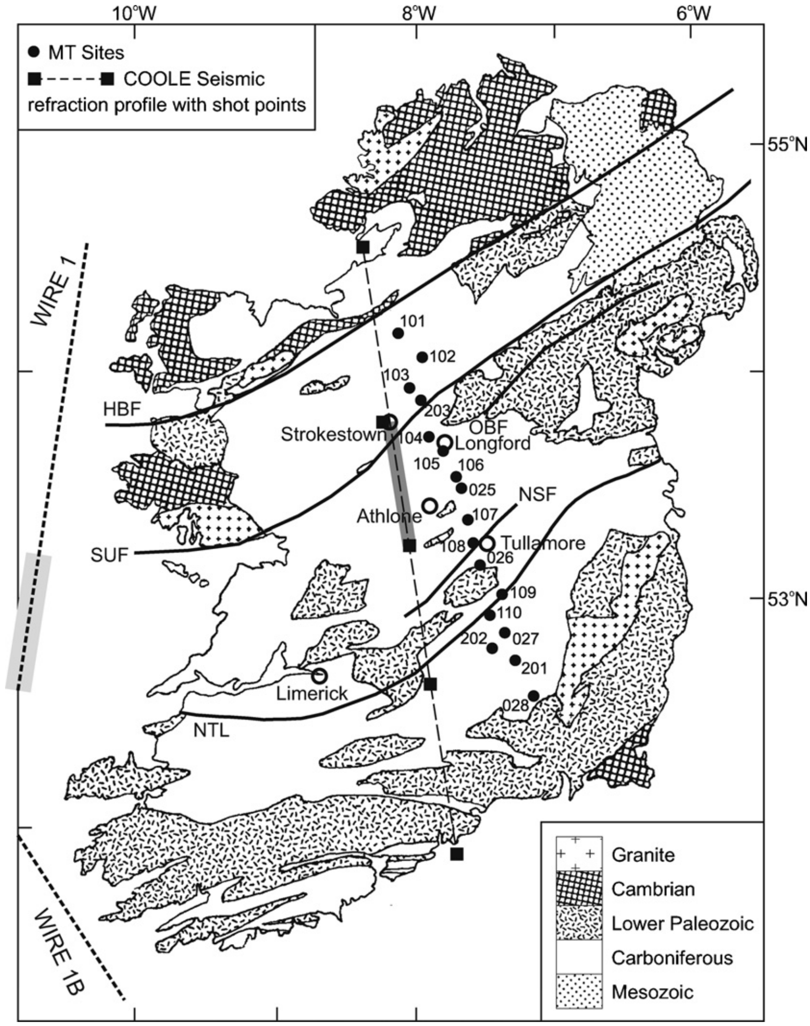

Fig. 1. Simplified geological map of Ireland with MT site locations and major faults: HBF, Highland Boundary Fault; SUF, Southern Uplands Fault; OBF, Orlock Bridge Fault; NSF, Navan Silvermines Fault; NTL, Navan Tipperary Lineament. The shaded region is the crustal deformation zone inferred from seismic refraction studies (Lowe and Jacob, 1989). The location of the offshore WIRE reflection profile of Klemperer et al. (1991) with the location of the region of N-dipping reflectors (shaded) is also shown.

rior, the Highland Boundary Fault (HBF, Fig. 1) and Southern Uplands Fault (SUF, Fig. 1), and are interpreted to continue into Ireland (Max et al., 1983; Murphy et al., 1991). Offshore seismic studies west of Ireland (WIRE lines, Klemperer et al., 1991; Fig. 1) resolved strong north-dipping reflectors in a 50-km-wide zone, between 5 and 30 km depth, in the vicinity of the putative ISZ. The COOLE (Caledonian Onshore-Offshore Lithospheric Experiment) seismic refraction study (Lowe and Jacob, 1989), which was shot parallel to our profile (Fig. 1), indicated a distinct layer in the mid-crust that consists of two laterally continuous velocity discontinuities. The depth variations occur across a zone of 60 km and wide-angle reflectors shallow significantly to 4–5 km. Lowe and Jacob (1989) proposed that this broad zone of crustal change across the Irish Midlands is a deformation complex associated with the ISZ. The Moho defined by the COOLE experiment is shown in Fig. 3.

3. Magnetotelluric experiment and data analysis

In order to image the geometry of the ISZ, magnetotelluric (MT) data were collected at 17 sites along the NNW-SSE profile shown in Fig. 1. Two different sets of equipment were used for data acquisition; broad band (BBMT) systems with a period range 0.003–3000 s, were installed at 17 sites, labelled 101–028, and long period (LMT) systems, with a range of 20–10,000+ s, were installed at 4 sites, labelled 025–028. The short period broadband data (less than 1 s) at stations 026–028 were affected by ambient cultural noise and corrupted responses were removed from analysis and interpretation.

The time series data were processed using robust, remote-reference techniques (Jones et al., 1989). Where LMT data were available the responses were merged with those from the BBMT data. Tensor decomposition was undertaken, using the multi-site, multi-frequency analysis code of McNeice and Jones (2001), on individual sites in one decade bands, and established a regional crustal electrical strike direction of N52°E for most periods at most stations, which is coincident with the local geological Caledonian trending strike of NE–SW. The error-normalized RMS misfit of the distortion models to the data was less than one at most of the stations at all frequencies, except for station 105 where RMS misfit is between 2 and 3 in the period band of 10–100 s.

The MT response functions in this direction of N52°E are parallel to strike, i.e., represent the transverse electric (TE) mode of induction in a 2-D Earth, and in the direction N38°W are perpendicular to strike, i.e., the transverse magnetic (TM) mode. The TE and TM mode decomposed impedances are shown as apparent resistivity and phase pseudosections in Fig. 2(a and b). The most striking feature in both phase pseudosections are the high phases at periods of 10–100 s, which are evidence of a region of enhanced conductivity in the middle to lower crust. The pseudosections suggest that the conductor exhibits a NW dip, and has its greatest conductance (conductivity–thickness product) beneath the centre of the profile. Another notable feature is the evidence for a highly resistive body dipping towards NW and SE directions on either side of station 105 at periods from 0.2 to 1 s. The TM phase data at stations 101–105 show changes in phase at 1000 s; the causative structure is not seen at other stations due to lack of penetration. Lateral variations are generally smooth in the TE mode, and consequently dipping features are not as obvious in this polarization.

4. 2-D Inversion and results

The MT and TZ data (TE, TM, and vertical magnetic field transfer functions in the direction perpendicular to strike) were inverted for minimum structure using the RLM2DI code of Rodi and Mackie (2001), as implemented in the WinGLink package of Geosystem srl. The TE data from station 104 were deleted prior to inversion as this mode exhibited severe distortion effects that could not be removed with distortion analysis. A uniform half space of resistivity of 100 Ω m was used as the starting model, and static shifts were treated as unknowns within the inversion, following the standard approach of e.g., DeGroot-Hedlin (1991). The regularization parameter, tau, which trades off smoothness with misfit, was set to seven after performing many inversions with varying values for tau to determine the L-tradeoff curve for these data and Earth geometry (see Booker et al., 2004). The error floors set for resistivity and phase in the TE and TM mode were 10 and 5% (equivalent to 1.5°) and 7 and 5%, respectively. The absolute error for the magnetic transfer function was selected as 0.015 in the inversion. After many hundreds of iterations, a normalised RMS value of 2.46 was attained, with most of the misfit in the TE apparent resistivity data. The final geoelectric model is shown in Fig. 3, and the model responses are shown in Fig. 2(a and b).

The main features of the 2-D inversion are: (1) a prominent conductive body at middle to lower crustal depths dipping NW and SE at its ends followed by two separate conductors on either side with clear offset in depths, and (2) a shallow high resistivity body on either side of station 107 that deepens towards the NW. These features are robust in that they appeared, in one form or

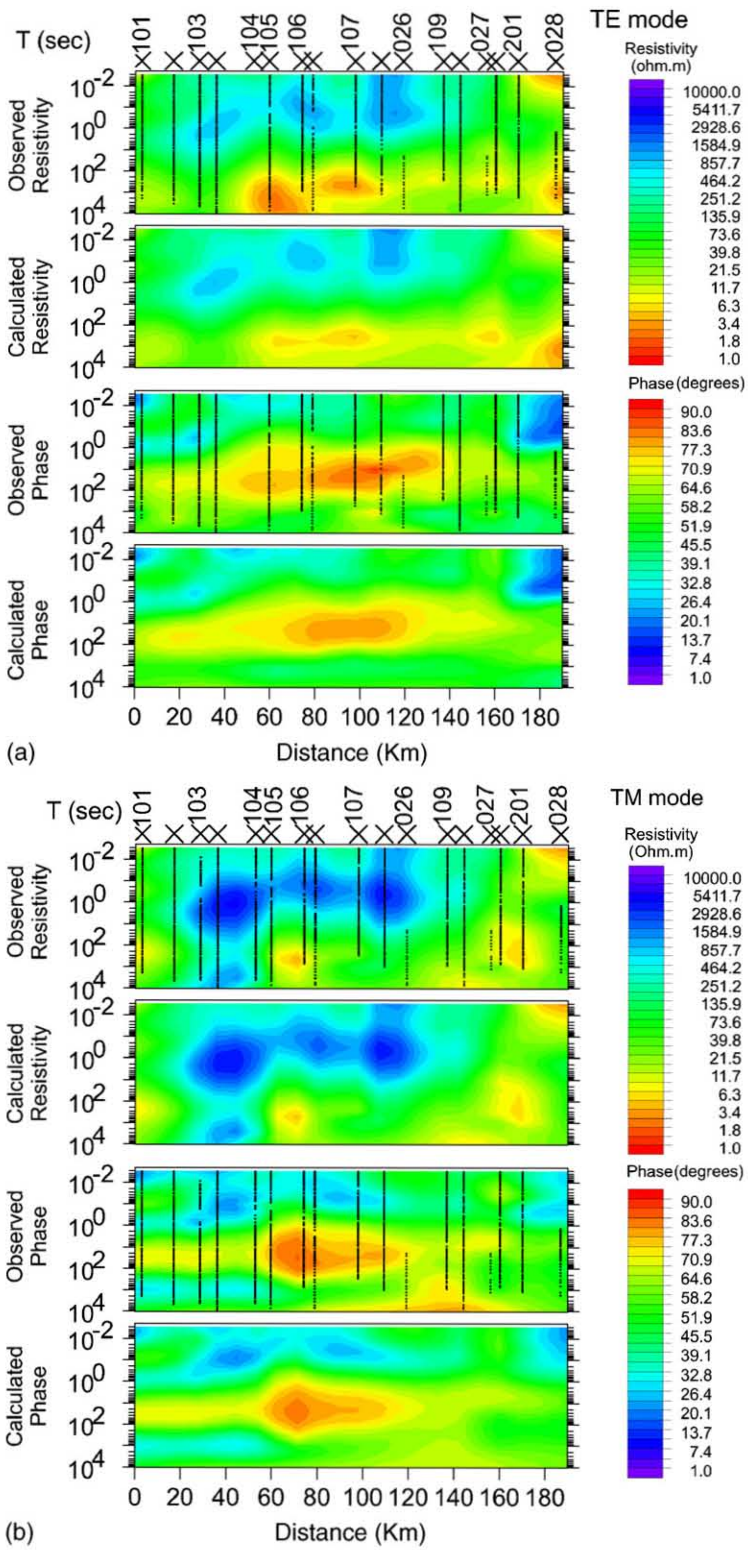

Fig. 2. (a) Pseudosections of TE mode apparent resistivity and phase of the observed and the modelled data with data points shown on observed data contours. (b) Pseudosections of TM mode apparent resistivity and phase of the observed and the modelled data with data points shown on observed data contours.

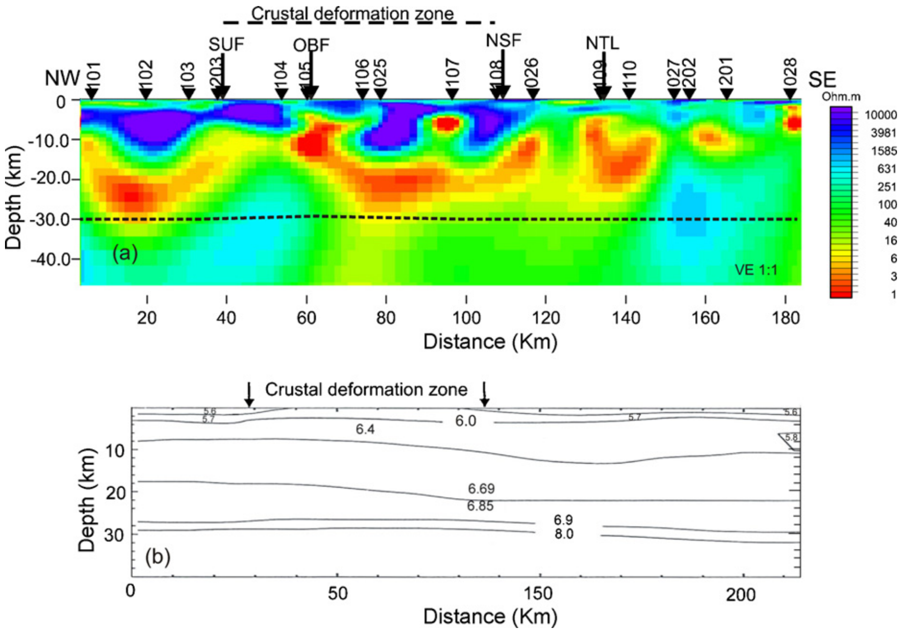

Fig. 3. (a) Geo-electric section across the Iapetus Suture Zone in central Ireland obtained from 2-D inversion of MT (TE and TM) and TZ data; SUF, Southern Uplands Fault; OBF, Orlock Bridge Fault; NSF, Navan Silvermines Fault; NTL, Navan Tipperary Lineament. The crustal deformation zone and depth to the Moho from seismic refraction studies (Lowe and Jacob, 1989) are shown with a dashed line on top and in the middle of the section, respectively. (b) Seismic refraction section of COOLE I modified from Lowe and Jacob (1989).

another, in all inversions using different combinations of data, error floors, taus, etc., and always reappeared when deleted from prior inversion runs.

5. Discussion

The main upper crustal features are two high resistivity blocks buried beneath Carboniferous sediments at stations 25 and 108 (Fig. 3a). Gravity studies by Readman et al. (1997) identified a negative Bouguer anomaly in the region, and the authors hypothesized that this was due to a central Midland granite body buried beneath sedimentary cover. Van den Berg et al. (2005) studied xenoliths from this region, and observed that a large number of granulite-facies xenoliths are metapelites. Those authors also observed a large number of xenolith samples containing granitic leucosomes, probably as a result of partial melting during late-Caledonian igneous orogeny. Thus, we favour an interpretation that the highly resistive bodies defined by MT correlate with Caledonian granite emplaced into the upper crust during late Caledonian igneous activity.

The northernmost section suggests that another resistive layer, which shoals to the surface below stations 203–104, underlies the sediments. This layer is spatially associated with the Ordovician metabasites and mafic greywackes exposed at Strokestown (see Fig. 1 for location). The high near-surface velocities observed in the seismic refraction section in Fig. 3b is interpreted as dense metabasites by Lowe and Jacob (1989). A high resistive layer, indicated in the earlier MT studies by Brown and Whelan (1995) and interpreted as volcanic rocks, corroborates with our interpretation.

The main conductor in our final model (Fig. 3a) has a resistivity of 2–5 Ω m with a thickness of 10–15 km, i.e., a total vertically integrated conductance of 2000–7500 S. The depth to the top of this conductor varies from 5 to 20 km, placing it in the middle to lower crust. This U-shaped crustal conductor closely resembles the seismic section of Lowe and Jacob (1989) (Fig. 3b) in the area of the inferred location of ISZ. The two conductors to the north and south of the U-shaped conductor show considerable offset in depth. Near the Orlock Bridge Fault (OBF, Figs. 1 and 3) in the north, and the Navan Silvermines Fault (NSF, Figs. 1 and 3) in the south, the top of the central conductor rises up to 5 and 10 km in depth, respectively. The Orlock Bridge Fault represents one of the major structural features in this region with an inferred lateral displacement across it in excess of 400 km (Anderson and Oliver, 1986). The conductors, north and south of the U-shaped conductor, are associated with the Southern Uplands Fault (SUF, Figs. 1 and 3) and the Navan Tipperary Lineament (NTL, Figs. 1 and 3).

High conductivity at middle crustal depths may be due to many factors, such as saline water, partial melt, serpentinite, sulphides, iron oxides, and graphite (e.g., Frost et al., 1989; Jones, 1992; Duba et al., 1994). High conductivity (conductance of up to 7500 S) in a tectonically non-active region is most readily explained by serpentinization or metamorphosed graphitic/sulphidic sediments. A compilation of laboratory pressure and temperature studies (Hyndman and Peacock, 2003) shows that the presence of serpentinization will reduce seismic velocity and density in subduction zones. The COOLE seismic study (Lowe and Jacob, 1989) suggests a normal lower crustal velocity of 6.9 km/s in the study region, and gravity studies (Readman et al., 1997) do not indicate any appreciable Bouguer anomalies. Both of these suggest that serpentinization as the cause for the observed high conductivity can be excluded.

The second explanation is the occurrence of low-grade metamorphosed graphitic sediments in Palaeozoic Suture Zones. Globally, the early Ordovician time was unique in tectonic history (Dewey, 1988) and was characterized by high sea level, carbonate platforms and oceans, and abundant black shales. Black shales represent a major component of flysch within accretionary sedimentary wedges at subduction zones and are often rich in metallic minerals (such as Fe sulphides (pyrite, pyrrhotite) in a sulphur-rich reducing environment) due to their formation in anoxic basins (Vine and Tourtelot, 1970). Ferry (1981), while reviewing the origin of iron sulphides in sediments and sedimentary rocks (references therein), indicated an abundance of pyrite and traces of pyrrhotite in black shales and concluded that all or almost all iron sulphide in black shales is in the form of pyrite in low-grade metamorphic rocks. With increase in grade of metamorphism, pyrite-pyrrhotite conversion occurs and the most probable reaction for this conversion is by desulfidation (Ferry, 1981). The exposed Ordovician rocks in Ireland are only low-grade metamorphic rocks (Graham, 2001) suggesting that the sulphides within the black shales likely occur as pyrite.

In the present study black shales with sulphides (pyrite, pyrrhotite) are interpreted to be the source for high conductivity in the central layer in Fig. 3a. These sedimentary sequences were subjected to sinistral transpressional deformation during the NW–SE convergence of Avalonia and Laurentia (Ryan and Dewey, 1991), which thereby led to the formation of the U-shaped conductor, and later movements along fault zones transported the sediments to depth.

Is this interpretation of the conductor reasonable, and what does the presence of this conductor tell us about the physical and chemical conditions in the middle and deeper crust of the ISZ? Magnetotelluric studies on Baffin Island, north-eastern Canada, by Evans et al. (2005) inferred a conductor with low resistivities of 1.0–5.0 Ω m and interpreted it as meta-sediments with sulphide-graphite formations. Laboratory and petrology studies on surface-derived rock samples from that area confirmed the role of graphite conduction (Evans et al., 2005). Thin sections of black shales with 5–8% of organic carbon in the Münsterland borehole (Duba et al., 1988) revealed clusters of amorphous carbon with finely dispersed carbonaceous material and devoid of graphite. In the shallow crust this free carbon acts as the interconnectivity agent in enhancing conductivity of black shales. Jödicke (1992), while reviewing the high conductivity layers in the upper crust, showed that finely disseminated and interconnected organic carbon will reach a sufficiently high coalification stage, which will lower the resistivity of the whole rock to few ohm meters. The above evidence leads us to an interpretation of carbon at grain boundaries being the reason for the high conductivity at shallow depths. But what about at depth?

Xenolith studies from central Ireland (Van den Berg et al., 2005) estimated a temperature of around 400° C at 25 km, consistent with present-day heat flow values of 70 mW/m^2 measured in central Ireland (Brock, 1989). Duba et al. (1988) demonstrated that at temperatures greater than 400° C, and in an oxidizing environment, graphite oxidizes and becomes non-conductive exhibiting high resistivity, which might negate our interpretation. However, Raab et al. (1998) on the other hand showed that the resistivity of black shales decreases with increasing temperature. Their experimental study on black shales from a borehole in Münsterland was performed with a constant pressure of 250 MPa, and they explained the contrary results observed by Duba et al. (1988) by different oxygen content in the sample environment. Raab et al. (1998) also showed an analysis of the samples after a high-pressure and high-temperature treatment (in highly reducing conditions with low oxygen fugacity), finding that the increase in conductivity is caused mainly by activation of sulphur and transformation of pyrite to pyrrhotite that together result in a high degree of connectivity between conductive components. Finally, laboratory studies on meta-anthracite samples (Nover et al., 2005) at a temperature 450° C, and pressure of 0.7 GPa detected a change in charge transport from semi-conducting carbon to metallic conducting graphite.

Thus, we suggest that the high conductivity observed at middle and lower crustal depths is most likely due to metamorphosed graphitic sediments with sulphide content formed in a reducing conditions, while carbon at grain boundaries may be the cause for the high conductivity at shallow depths.

6. Conclusions

A high conductive layer at middle to lower crustal depths within the Iapetus Suture Zone is interpreted to be due to metamorphosed graphitic sediments (rich in sulphur) that spatially correlate with a region of deformation interpreted from seismic refraction studies. The U-shaped conductor beneath the centre of the profile is interpreted to result from deformation of an accretionary metasedimentary wedge formed during the closure of Iapetus Ocean. Highly resistive blocks emplaced in the upper crust suggest Caledonian granite bodies that were intruded during final stage of late Caledonian orogeny and sourced from the accretionary wedge. Thus, our results give strong support for the accretionary wedge model for the Southern Uplands Terrane across Britain and Ireland (Ryan and Dewey, 1991).

Acknowledgements

We thank the ISLE-MT field crew and DIAS colleagues for their help in collection of the data. We acknowledge the support of local farmers and Coillte officials in granting permission to use the private and forest lands. The authors acknowledge discussions with Colin Brown, B.M. O'Reilly, and Barry Long, and useful reviews from reviewers of the paper. The project is funded by IRCSET Basic Research Grant SC/2003/237. DIAS School of Cosmic Physics publication GP189.

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