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Correlation between crustal high conductivity zones and seismic activity and the role of carbon during shear deformation

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[1] The electrical conductivity of the lower crust is anomalously high in many locations around the world. Well-interconnected grain boundary carbon not only has the potential for increasing the electrical conductivity of the rock but also would be expected to reduce its shear strength. We report a new analysis of field observations and new laboratory measurements consistent with deep carbon-bearing rocks causing observed high conductivities and crustal weaknesses associated with increased seismicity. The field data indicate a correlation between the depths to a zone of high electrical conductivity observed in Transdanubia in Hungary, earthquake focal depths, and zones of high seismic attenuation. The laboratory triaxial deformation experiments show that progressive shearing of a fracture in carbon-bearing rock can result in a weaker more electrically conductive fracture. These results provide strong evidence for the role of carbon at depth in both electrical conduction and seismotectonics, explaining the correlation between mid-crustal high reflectivities and high conductivities observed at many locations worldwide.

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1. Introduction

[2] It has been recognized for some years that certain sections of the Earth's crust have anomalously high electrical conductivities [*Gough*, 1986; *Yardley*, 1986; *Hyndman and Shearer*, 1989; *Jones*, 1992; *Glover*, 1996]. Many physical mechanisms have been proposed to explain this, all of which rely on a single highly interconnected conductive phase. The difficulty is knowing which conducting phase or phases are responsible at any given location.

[3] Aqueous fluids are often cited as a possible conducting phase [*Hyndman and Shearer*, 1989; *Glover*, 1996; *Drury and Hyndman*, 1979; *Ohloeft*, 1981; *Lee et al.*, 1983; *Shankland and Ander*, 1989; *Shankland*, 1989; *Marquis and Hyndman*, 1992], and while they can explain many regions of anomalously high electrical conductivities in the upper crust, they run into geochemical difficulties if the lower crust is composed of anhydrous granulite as many believe [e.g., *Yardley and Valley*, 1997]. Bearing this in mind, it has recently been proposed that an anhydrous lower crust is not incompatible with the presence of high-conductivity zones if the conduction provided by mineral semi-conduction [*Freund*, 2003].

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[4] Another possibility that has been proposed is graphite [*Glover*, 1996; *Alabi et al.*, 1975; *Duba and Shankland*, 1982; *Frost et al.*, 1989; *Mareschal et al.*, 1992; *Glover and Vine*, 1992, 1994; *Nover et al.*, 2005; *Mathez et al.*, 1995; *Duba et al.*, 1988], and although it was initially uncertain whether sufficient graphite could be deposited in a sufficiently connected fashion to give rise the required conductivities [*Glover*, 1996], recent work [*Nover et al.*, 2005] has shown this to be so. It has been shown that highly conducting films of graphite can be deposited in rocks during fracturing in the presence of a CO/CO_2 fluid [*Roberts et al.*, 1999], and more recently nearly perfect crystallized graphite has been formed by pressure and temperature treatment that represents crustal conditions which led to increases in conductivity by approximately three orders of magnitude [*Nover et al.*, 2005]. The hypothesis that graphite is found on shear planes and is associated with shear movement [*Mathez et al.*, 1995] is also supported by *Bustin et al.* [1995] who showed that graphite formation is aided significantly by shear strain and by strain energy.

[5] Partial melting can also be the cause of high conductivities [*Roberts and Tyburczy*, 1999; *Hermance*, 1979; *Schilling et al.*, 1997; *Glover et al.*, 2000]. However, partial melting is only likely to be present in areas of recent tectonism where the local geotherm is high, and there is great doubt whether the geotherm in the Transdanubian Basin of about 40–50°C/km [*Lenkey et al.*, 2002] is sufficient for partial melting to be the cause in the depth range 5 km to 15 km (i.e., 250–750°C). Solid state conduction through the rock forming minerals themselves

is also insufficient to explain the observed conductivities at these temperatures even in rocks with hydrous mineralogies [*Stesky and Brace*, 1973]. Other possible conducting phases are accessory minerals such as magnetite and sulphides [*Parkhomenkho*, 1982; *Duba et al.*, 1994], but these are almost always present in distributions which have much too low connectivity to give an overall high rock conductivity.

[6] The explanation of raised conductivities within the crust is likely to arise from a number of these proposed mechanisms, and some are likely to be more dominant at some locations than at others. It is also possible that some of the proposed mechanisms will give rise to changes in other geophysically measured properties, such as seismic attenuation and seismicity [*Ádám*, 1994].

[7] The first part of this paper examines a large, highly conducting zone in north-west Hungary, and relates it to the high seismic attenuations and the seismicity of the area. The second part of the paper shows that shearing of carbon-containing rocks can result in higher electrical conductivities which increases the electrical connectivity of the carbon and we interpret to arise from smearing of the carbon. This mechanism also reduces the strength of the rock, which we believe explains the observed high seismic attenuations and the seismicity of north-west Hungary.

2. Transdanubian Conductivity Anomaly

[8] A large, highly conducting, crustal zone has been detected in north-west Transdanubia, Hungary (Transdanubian Conductivity Anomaly, TCA) by telluric and magneto-telluric (MT) observations [e.g., *Ádám and Varga*, 1990]. This zone lies between the Periadriatic-Balaton and Insubric-Raba tectonic lines (Figure 1). The formations between these tectonic lines represent material that was expelled eastward into the Pannonian Basin as a result of alpine orogeny. The high-conductivity zone consists of several wide stripes at 3–12 km depth. Analysis of high-resolution MT data from the area has shown regions of high conductivity at depth that are consistent with sub-vertical fracture zones striking 060 ± 008° (i.e., parallel to the strike of the known longitudinal fractures/strike-slip fractures of the Pannonian Basin). The conductance of the zones is high, reaching 2×10^4 S, with a high degree of lateral electrical anisotropy (approximately 1000 to 1) [*Ádám*, 1994, 2001]. In this zone the highest conductivities coincide with the direction of the *in situ* fractures, and the lowest conductivities are in the direction perpendicular to the fracture surfaces. Tracing the anomaly to the west using MT measurements reveals it to be related strongly to graphitic schists and black shales cropping out in the Gail Valley Alps [*Ádám et al.*, 1990]. It is here that the Insubric-Raba and the Periadriatic-Balaton tectonic lines converge to a narrow channel from which the Transdanubian central range and the region occupied by the TCA were squeezed out. At present, however, there are no deep boreholes in Transdanubia capable of confirming that graphite or carbon-bearing rocks exist at depth. Hence there is no direct evidence whether the highly conducting anomaly is due to either carbon or saline fluids, or both. However, the well constrained areas of high conductivity and the association with outcrops of graphitic schists suggest that graphite may be present. The additional presence of saline fluids would improve the electrical connectivity of any *in situ* graphite present.

3. Field Correlation of Electrical Conductivity and Seismicity

[9] We have examined the local earthquake catalogue and previously published earthquake analyses [*Zsíros et al.*, 1988; *Zsíros*, 1988; *Bondár*, 1994] to determine the depth distribution of earthquake epicenters. We have compared the resulting earthquake depth distribution with results from one dimensional inversions of magneto-telluric measurements at over 284 sites in Transdanubia. The high density of MT sites in this area has made it possible to compare each earthquake depth against MT data from a site less than 5 km away, and in some cases coincident with the earthquake epicenter.

[10] We find that 94% of the seismic events occurred within the depth range 3–12 km, which coincides with the depth range occupied by the high-conductivity zone (Figure 2a), and confirming an earlier pilot study using a smaller data set [*Ádám*, 1994]. There is remarkable similarity between the shapes of the distributions of the depths to the earthquake foci and the depth to the top of the conducting zone, with the earthquake distribution occurring a few kilometers deeper, indicating that most earthquakes at a particular location occur in the top few kilometers of the highly conducting zone. Location by location comparison of focal depths and depths to the top and the base of the highly conducting crust shows the correlation to be extremely good, with all but a few earthquakes falling inside the conducting zone. This is shown in Figure 2b by the 1:1 line separating the symbols representing respectively the top and the base of the conducting zone.

[11] The uncertainty in the depth to the top of the conducting zone in this data is small (<±1 km). The depth to the base of the conducting zone has a greater degree of uncertainty resulting from the derivation of conductivity from the MT conductance. If the equivalence of the conductance of the individual MT sounding curves is taken into account for the case of a conductive layer, the depth of the base of the layer can vary depending upon what value for the conductivity is used. Nevertheless, for the data used in this study (Figure 2b), the depth values for the base of the conductive layer remain above the 1:1 line (*i.e.,* deeper than the focal depth) unless unrealistically large values of conductivity are proscribed (>50 S/m). We estimate that the uncertainty in the depth to the base of the conducting layer is no more than ±3 km. The uncertainty in the determination of the hypocentral depths varies within the earthquake catalogue, but are always better than ±3 km.

4. Field Seismic Attenuation Measurements

[12] Initially, the apparent depth correlation of the conducting zone and hypocentral depths may seem strong evidence for a formal relationship between the conducting zone and the earthquakes. However, lithospheric thickness is small in the Pannonian basin in general and there is a high heat flow [*Horváth*, 1993]. The depth to the 400°C isotherm in the area is approximately 18 km, and it is equally possible that the transition to ductile behavior is constraining the

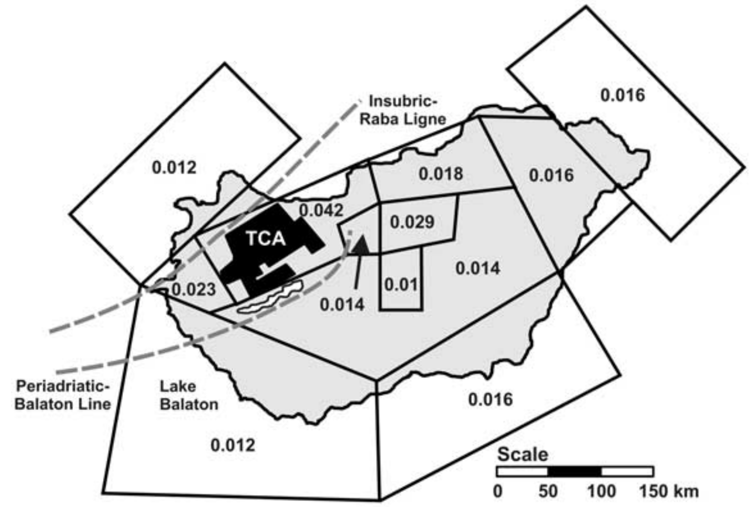

Figure 1. Map of Hungary showing the position of the Transdanubian Conductivity Anomaly (TCA) relative to Lake Balaton and the position of major structural lines. The area has been subdivided into regimes for which mean seismic attenuation coefficients (in km^{-1}) have been calculated (see Figure 3).

earthquakes to depths that happen to coincide with the high-conductivity zone. It is difficult to discriminate which case is correct. However, we have examined seismic attenuation coefficients in the Pannonian Basin and find more evidence linking earthquakes and the highly conducting zone.

[13] Graphite schists and black shales tend to have low shear strengths [*Jödicke*, 1992], which results in tectonic deformation being focused within them, and ensures that they attenuate seismic energy to a greater extent than high shear strength rocks [*Meissner*, 1986]. It would be expected that the low shear strength of carbon-bearing rocks, if present in the TCA, would set an upper limit to earthquake magnitudes in the area overlying it, as well as reducing the felt intensity of large earthquakes occurring outside the TCA.

[14] We have carried out a comparative analysis of Transdanubian earthquakes with those from neighboring areas, and have found that large earthquakes are anomalously rare within the area underlain by the TCA [*Ádám*, 1994]. Furthermore, large earthquakes occurring outside the TCA show consistently lower felt intensity values when their effect is measured within the TCA compared to measurements outside it at the same distance from the earthquake epicenter [*Zsíros*, 1985]. It hence seems that the formations underlying the TCA are particularly highly attenuating.

[15] In 1986 *Meissner* [1986] provided a qualitative relationship between the viscosity (ζ) of graphite (or fluid) and the attenuation of the seismic waves expressed as a Q^{-1} factor

$$\ln \zeta = 4.4 \ln Q + 22 \qquad (1)$$

which has been validated for the TCA [*Zsíros*, 1985]. Zsíros showed that the attenuation can be quantified by using attenuation coefficients α_k, which occur in the approximate relationship

$$I_k = I_o \exp(-\alpha_k R_k), \qquad (2)$$

where I_k is the earthquake intensity at the k^{th} isoseism a distance R_k from the epicenter, and I_o is the earthquake intensity at the epicenter. Calculation of attenuation coefficients for the earthquake catalogues for the area underlain by the TCA gives $\alpha_k = (4.2 \pm 1.4) \times 10^{-5}\ m^{-1}$, compared to $\alpha_k = (1.7 \pm 0.3) \times 10^{-5}\ m^{-1}$ for the mean attenuation coefficient of the 11 surrounding areas. Figures 1 and 3 show that the mean attenuation coefficient for each of the surrounding areas is approximately three times smaller than that in the area underlain by the TCA, indicating the existence of a source of attenuation underlying Transdanubia.

[16] In summary, in Transdanubia we have a region where there exists a high-conductivity anomaly that is co-located with a zone of seismic activity and which is highly attenuating to seismic waves.

5. Laboratory Triaxial Shearing Experiments

[17] Shear deformation in the presence of a carbon-rich pore fluid has been shown to lead to the preferential accumulation of carbon along the shear zones [*Nover et al.*, 2005; *Roberts et al.*, 1999]. In addition, we postulate that the process of shearing would also increase the connectivity of grain boundary carbon by a smearing mechanism.

[18] We have carried out a suite of triaxial deformation experiments on carbon-bearing rocks in the laboratory in order to test this postulation. In these experiments unfractured dry carbon-bearing rocks have been subjected to a hydrostatic confining pressure which was held constant while the sample was progressively strained axially at a constant rate. The pore fluid in all cases was ordinary laboratory air at low temperature (approximately 22°C), which contains only trace amounts of carbon (0.04% CO_2 by weight). The experiments were continued through failure to significant amounts of shear offset of the resulting fracture. Experiments were carried out on initially unfractured samples of black shale (BS1 and BS2) and graphite schist (GS1 and GS2) from outcrops in the Gail Valley, SE Austria. The samples contained initially between 5% and

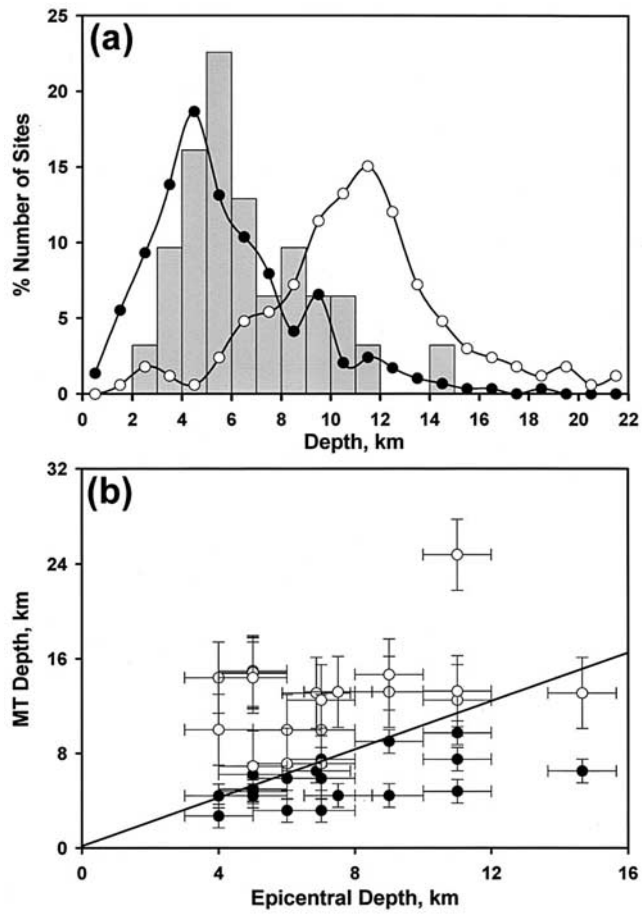

Figure 2. (a) The depth distributions of the top (solid symbols, 284 sites) and base (open symbols, 171 sites) of the high-conductivity zone derived from MT observations' depth distribution of earthquake focal depths in the same area (shaded bars, 31 events). (b) Location-by-location analysis of the depth to the top (solid symbols) and base (open symbols) of the high-conductivity zone derived from MT observations as a function of focal depth. Note that, for all events to occur within the high-conductivity zone, the 1:1 line should separate the open and solid symbols. Errors discussed in the text.

10% wt./wt. carbon. Individual values are shown in Table 1, together with supporting sample data.

[19] The samples were 25.4 mm in diameter and 65 mm long, sleeved in a transparent, impermeable and deformable polyolefin polymer, and submitted to a confining pressure of either 50 MPa or 55 MPa and a constant axial strain of either 1×10^{-6} s^{-1} or 2×10^{-6} s^{-1}, depending upon the sample (Table 1).

[20] A common source of carbon in experiments of this type is from the apparatus itself, including "O"-ring seals, gaskets and leakage into the sample of the confining pressure oil [*Roberts et al.*, 1999]. However, since the experiments were carried out at approximately 22°C, additional carbon from this source is considered to be very unlikely.

[21] Complex resistance measurements at 1 kHz were made every 50 s (strain increment 1×10^{-4} or 5×10^{-5}) with a Solartron 1260 impedance analyzer and precompressed platinum-blacked platinum gauze electrodes, together with axial stress determinations using a calibrated external load cell. The electrical measurements were made axially using a 2 electrode system as shown in Figure 4. In-phase and quadrature apparent resistivity was calculated while taking into account the axial shortening concomitant upon the deformation and assuming cylindricality is maintained throughout. We have chosen to describe the resulting measurement as "apparent resistivity" rather than "resistivity" because the formation of a finite number of macroscopic fractures in the sample introduces an inhomogeneity in the sample that make the formal use of "resistivity" inappropriate. Resistance would, perhaps, be a more appropriate parameter to use in these circumstances, however, there would be a loss of information in the displayed results (Figures 5 and 6) before localization. Hence we have used a geometric factor to convert the measured resistance into an apparent resistivity. The geometric factor takes into account (1) a constant circular cross-sectional area that does not change during deformation, and (2) a sample length that is corrected to take account of the strain to which the sample is instantaneously subjected. Figures 5 and 6 show the in-phase apparent resistivity and axial stress as a function of strain for the black shales and the graphite schists respectively. The behavior of all samples is very similar. The initial variation of apparent resistivity prefailure is consistent with compaction, leading to lower apparent resistivities due to improved carbon connectivity. As axial strain increases further the

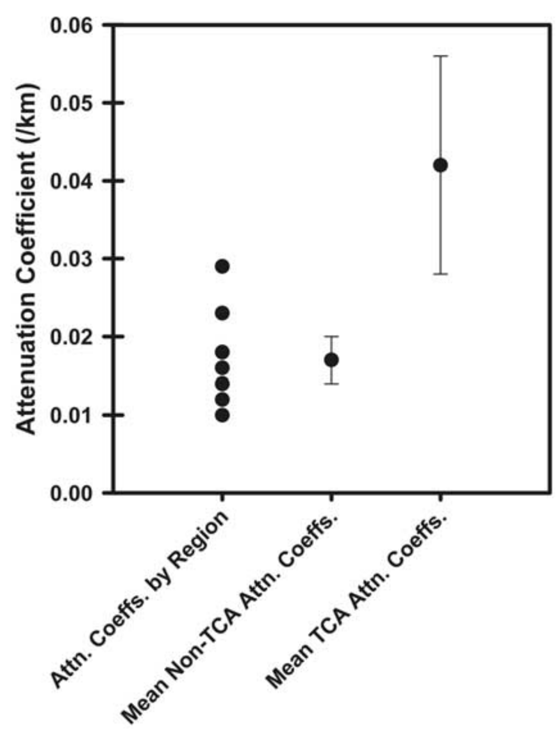

Figure 3. Mean seismic attenuation coefficients for the geographical areas in and around Hungary shown in Figure 1. Some individual points overlie each other.

Table 1. Summary of Data From the 4 Triaxial Experiments[a]

Sample Code	Prerun Carbon Content (% wt.)	Postrun Carbon Content (% wt.)	Mineralogy	Location	ϕ_o (%)	Experimental Conditions	Strain Rate (/s)	Confining Pressure (MPa)
BS1	8.12 ± 0.05	7.95 ± 0.05	56% qtz, 28% alb, 8% pyrite, 8% gr	Alps, Gail Valley, Austria	3.24	Triaxial, T = 22°C	2×10^{-6}	55
BS2	10.06 ± 0.05	10.86 ± 0.05	57% qtz, 29% alb, 4% pyrite, 10% gr	Alps, Gail Valley, Austria	2.67	Triaxial, T = 22°C	2×10^{-6}	55
GS1	3.10 ± 0.05	3.02 ± 0.05	35% qtz, 28% plag, 14% musc, 18% bio, 2% gar, 3% gr	Alps, Gail Valley, Austria	1.52	Triaxial, T = 22°C	1×10^{-6}	50
GS2	7.37 ± 0.05	7.80 ± 0.05	34% qtz, 27% plag, 12% musc, 18% bio, 2% gar, 7% gr	Alps, Gail Valley, Austria	1.03	Triaxial, T = 22°C	1×10^{-6}	50

[a]Notes: ϕ_o = porosity before experiment at laboratory pressures and T = 22°C using helium porosimetry. Carbon was measured using a Leco CS220 Carbon/Sulphur analyser. Mineralogy was measured by point counting on thin sections from offcuts.

apparent resistivity begins to increase again. We attribute the increase in apparent resistivity to reduction in carbon connectivity which results from the formation of microcracks. It should be noted that these initial variations, while the rock is still intact, are small compared to the variations in apparent resistivity at and after dynamic failure. A large increase in apparent resistivity was observed for all samples at failure, which results from a sudden gross reduction in carbon connectivity.

[22] After failure, both the in-phase and quadrature apparent resistivity and the measured stress that is required to shear the sample at the given rate progressively decrease with shear offset (Figures 5 and 6). The postfailure decrease in in-phase apparent resistivity is significantly large in all of the samples studied. We attribute this decrease to increased carbon connectivity resulting from a smearing process, which is also supported by our observation of progressive detectable decreases in the quadrature apparent resistivity. However, it is important to refute the possibility that the perifailure and postfailure complex apparent resistivity variations are simply due to a breakdown in the method used to calculate the apparent resistivity.

[23] The apparent resistivity was calculated by assuming that there was a constant conduction cross-section in the absence of any practicable method of measuring how the conduction cross-section changes during and after failure. This assumption is clearly invalid. Observation of the fractured samples after the experiment indicates that the failure in all samples took the form of a single diagonal fracture. Progressive shearing along this fracture resulted in a progressive reduction in the conduction cross-section. The breakdown of the assumption postfailure in these samples therefore leads to an overestimation of the effective cross-sectional area for conduction, and therefore to an overestimation in the calculated apparent resistivity. Since decreases in apparent resistivity are observed in all samples, we conclude that the breakdown in the assumption either (1) leads to insignificant errors, or (2) that the measured decrease in apparent resistivity is not as great as it would be if it were possible to account for the shape of the sample after failure.

[24] The quadrature apparent resistivity varies in a very similar manner to the in-phase component over the entire deformation, but is significantly smaller in value (Figures 5 and 6). The quadrature component of the apparent resistivity was about two orders of magnitude less than the in-phase component for the black shale samples, and about three orders of magnitude less than the in-phase component for the graphite schist samples. In both cases there was a detectable decrease in quadrature apparent resistivity with progressive shear, which indicates the development of a higher degree of interconnection or ordering. Once again, breakdown of the method for calculating the quadrature component of the apparent resistivity after failure would lead to an increase in the quadrature component of the apparent resistivity, implying that either any breakdown in the method leads to insignificant errors or that the real decrease in the quadrature component of the apparent resistivity is even greater than shown in Figures 5 and 6.

6. Post-Deformation Analysis

[25] Off-cuts from the samples were used to assess the initial carbon content of each of the experimental samples using a Leco CS225 Carbon and Sulphur analyzer (Table 1). Samples were also analyzed for carbon from the postdeformation sample taken near the original offcut, and these are

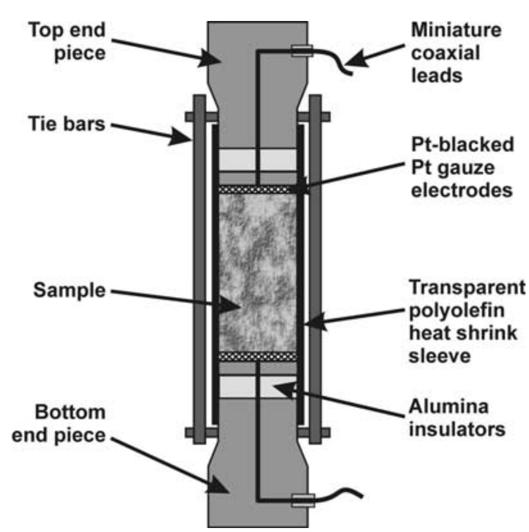

Figure 4. Diagrammatic representation of the experimental assembly showing the axial electrical measurements.

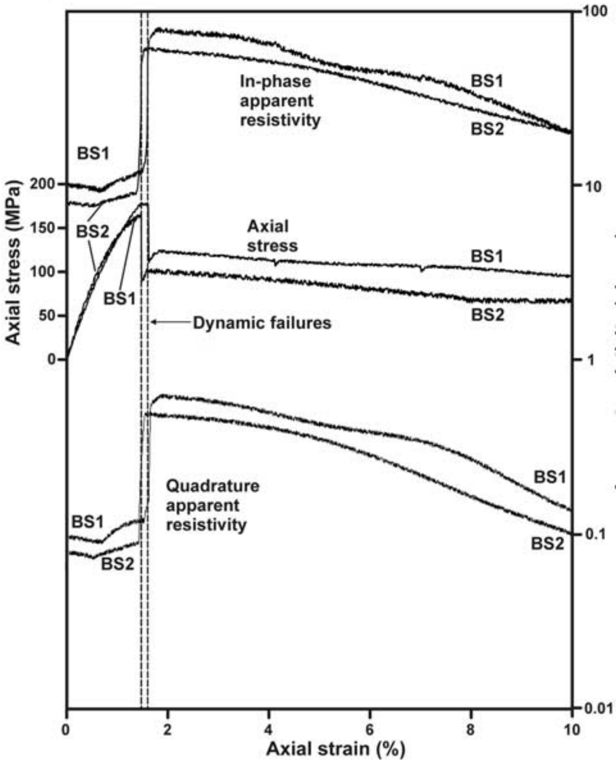

Figure 5. Experimentally determined axial stress and in-phase apparent electrical resistivity at 1 kHz as a function of axial strain during the progressive axial deformation of two samples of carbon-bearing black shale. BS1 8.12% wt/wt carbon, BS2 10.06% wt/wt carbon.

also shown in Table 1. It is clear that, within the accuracy of the measurement technique, there has been no significant change in the amount of the carbon in the samples during the experiment.

7. Interpretation of Laboratory Results

[26] The experimental results have implications for both the mechanical and the electrical properties of the fracture. The steady decrease in the stress supported by the fracture as shear strain increases postfailure (Figures 5 and 6) indicates that the fracture is unstable. Progressive shearing reduces the shear strength of the rock, and makes further shearing more likely to occur. A positive feedback mechanism which promotes further shearing is therefore present. Under such a scenario any carbon that is present is likely to be smeared along the newly created fracture and associated damage zone, improving its lubricating properties. This mechanism may also take place at depth in the crust, leading ultimately to carbon-rich slikensides.

[27] There is also a steady decrease in the apparent resistivity of the rock as strain increases postfailure (Figures 5 and 6). Some mechanism is either (1) increasing the proportion of the conducting phase in the fracture, or (2) improving the connectivity of previously existing carbon.

[28] It has been reported that shearing of fractures within the crust may lead to accumulation of further carbon along the shear zone [*Nover et al.*, 2005; *Roberts et al.*, 1999]. This mechanism may operate in the crust where a carbon-rich fluid is present. Indeed, recent experiments [*Roberts et al.*, 1999] have formed carbon along fractures during triaxial deformation experiments in a carbon-rich atmosphere. In these experiments, the researchers suggest that micro-fractures are created during deformation and carbon is formed on the new, highly reactive, mineral surfaces by reduction of the carbon-rich gasses occupying the fracture. The carbon is likely to be deposited as a continuous film if it is formed by such a process. Such deformation-induced carbon deposition would increase the conductivity of the rock and may contribute to some of the electromagnetic effects associated with earthquakes [*Nover et al.*, 2005; *Roberts et al.*, 1999]. More recent experiments have not only formed nearly perfect crystallized graphite by high pressures and temperatures but the graphite formation led to increases in conductivity by approximately three orders of magnitude [*Nover et al.*, 2005].

[29] However, deformation-induced carbon deposition is unlikely to be occurring in our experiments since these were carried out on dry, confined samples containing air with only trace carbon (~0.04% CO_2 by weight) at low temperatures (22°C). Reprecipitation in the sample from the experimental apparatus itself is possible. As previously indicated, and has been observed in experiments using an argon atmosphere at 399-441°C by *Roberts et al.* [1999].

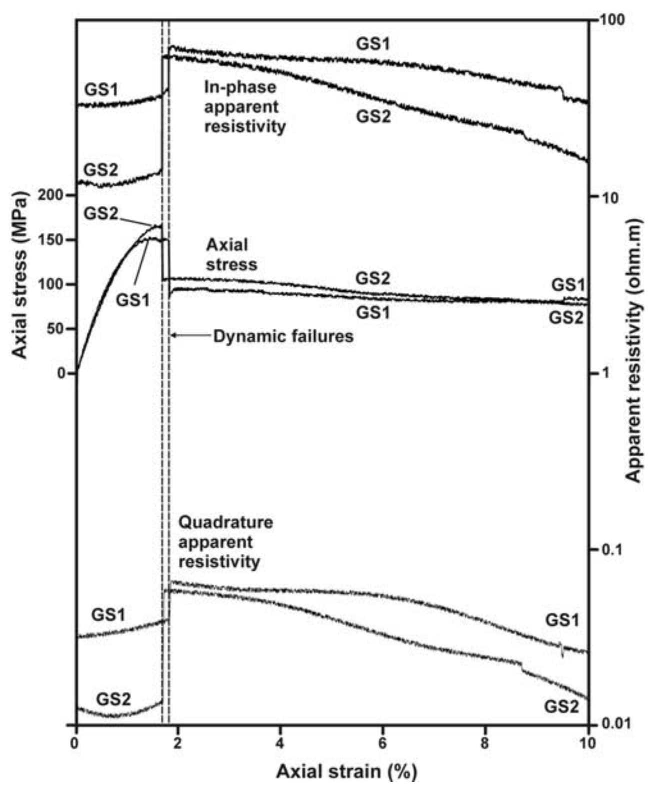

Figure 6. Experimentally determined axial stress and in-phase apparent electrical resistivity at 1 kHz as a function of axial strain during the progressive axial deformation of two samples of carbon-bearing graphite schist. GS1 3.1% wt/wt carbon, GS2 7.37% wt/wt carbon.

However, at the temperatures used in this work, it is considered to be an unlikely source.

[30] The carbon analyses (Table 1) show no significant difference between prerun and postrun carbon content. However, we would argue that it is unsafe to rely on this data since a large increase in electrical conductivity can be caused by the deposition of thin but highly connected films which represent extremely small increases in carbon content; too small to be noted by the carbon analysis.

[31] We consider that the observed postfailure increases in conductivity are more likely to be caused by deformation-induced carbon smearing leading to an increase in the connectivity of the existing carbon lining the fracture. It should be pointed out that if shearing does occur in rocks containing an enriched CO_2 phase at crustal temperatures and depths it may be possible to observe an increase of conductivity due to the processes of deformation-induced carbon smearing and deformation-induced carbon deposition occurring in tandem.

8. Discussion and Conclusions

[32] The evidence presented previously are all consistent with carbon playing a role in the crust beneath Transdanubia that is correlated with the pattern of earthquakes in the region. Indeed, it might be said that the balance of probabilities is that the evidence supports the presence of carbon. However, many of the observations are also consistent with the presence of fluids, and fluids cannot be ruled out as also having an active role in the control of the seismicity of the region. In the absence of deep boreholes, it is almost impossible to establish definitively the cause of the high-conductivity zone at depth. Nevertheless, given the strong evidence for carbon, and the likelihood that fluids are also present, we must conclude that both substances may have a role to play beneath Transdanubia, and that neither should be discounted.

[33] The laboratory experiments have indicated that there exists a mechanism whereby the presence of low shear strength carbon in a fault makes it more likely for an earthquake to occur than if carbon was not present. The deformation concomitant upon the earthquake may lead to further accumulation of graphite or amorphous carbon [*Nover et al.*, 2005; *Roberts et al.*, 1999] and may redistribute the carbon present such that it reduces the shear strength of the fracture in a positive feedback loop that makes further shear deformation more likely. The mechanisms reducing the strength of the fracture also progressively enhance the electrical conductivity of the fracture in the direction of shear compared to the other two mutually perpendicular directions. It is possible that such a situation is occurring in the TCA, where the conductance in the direction of shear is up to three orders of magnitude higher than that perpendicular to the shear plane [*Ádám and Varga*, 1990]. However, a more definitive test would be possible in an area of sub-horizontal shearing where the horizontal currents, to which the MT technique is predominantly sensitive, would be able to discriminate between the conductivities parallel and perpendicular to the shear direction in the plane of the shear zone.

[34] This scenario contrasts sharply with the situation expected of pore-saturating brines were the initial cause of high conductivities in a fracture. In the brine-saturated case, progressive shearing has been shown to lead to gouge production with the comunition of grains and reductions in fluid permeability by up to five orders of magnitude [*Ogilvy and Glover*, 2001; *Ogilvy et al.*, 2001; *Haak et al.*, 1997]. This process is associated with large reductions of fluid connectivity in the fracture zone. The combination of shear deformation with progressively reduced fluid connectivity may still promote further shearing of the fracture as the result of fluid over-pressurization in the fracture zone. This is also a positive feedback loop that promotes further shear deformation, but one that leads to progressively reduced electrical conductivity in the direction of shear.

[35] Thus we can construct a hypothesis for regions underlain by anisotropic electrically conductive zones. We postulate that, where the direction of highest conductivity is in the plane of the shear zone and in the same direction as the direction of the shear, the conductive zone is caused by carbon-bearing rocks. Conversely, where the direction of highest conductivity is perpendicular to the predominant direction of shear (either in the shear plane or perpendicular to it), the high conductivity is more likely to be caused by pore-saturating brines.

[36] The laboratory experiments indicate that carbon-aided shearing has the potential for enabling shear zones to be created at depth more easily. It is worthwhile noting that carbon-rich shear zones have been recognized during deep drilling of the continental crust in the KTB [*Haak et al.*, 1997; *Zulauf*, 1992; *Kontny et al.*, 1997], as well as cropping out and in shallow drilling of the Grand St. Bernard Nappe, Switzerland [*Losito et al.*, 2001]. It is likely that such zones would have a high seismic reflectivity. It, therefore, follows that the seismically highly reflective rocks that are commonly found worldwide in the middle continental crust, and often well correlated to high-conductivity zones [*Hyndman and Shearer*, 1989], may be caused by carbon-rich shear zones.

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