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Abstract: Physical properties of gabbroic samples from Ocean Drilling Program Hole 1105A were measured in the laboratory, with a particular emphasis on the analysis of electrical properties. This data-set includes the major lithologies sampled in ODP Hole 1105A: gabbros, olivine gabbros, oxide-rich gabbros, and, for all rock types, different ranges of alteration were sampled: from fresh to highly altered. All these lithologies correspond to the seismic Layer 3 layer of the oceanic crust, and large-scale geophysical data interpretation requires a complete understanding of the physical properties of rocks in this section. Electrical conductivities measured on brine-saturated gabbros reveal strong excess conductivity for samples rich in oxide minerals and, to a lesser extent, for altered samples. However, the classical models do not explain the excess conductivity reported in the oxide-rich samples when saturated with brine. The electrical conduction via electronic processes in metallic minerals has been taken into account in our analysis of the electrical properties. The oxide minerals’ contribution has been independently estimated through measuring dry electrical resistivity. These measurements allowed quantification of the electronic conduction, which can reach 80% of the full conductivity for the most oxide-rich gabbros.

Through the last three decades, the Deep Sea Drilling Project (DSDP) and Ocean Drilling Program (ODP) have provided a unique opportunity to study the composition and structure of the oceanic crust. Our knowledge of the in situ structure of lower oceanic crust has largely been based on geophysical and ophiolite studies. Deep drilling investigations of lower oceanic crust have been achieved in several locations, taking advantage of tectonic exposure, e.g. Hess Deep (ODP Leg 147; Mével et al. 1996), the Mid-Atlantic Ridge (ODP Leg 153 at Mark Area; Karson et al. 1997) and the SW Indian Ridge (ODP Legs 118, 176 and 179; Von Herzen et al. 1991; Dick et al. 1999; Pettigrew et al. 1999). Boreholes drilled on the SW Indian Ridge have allowed study of lower-crustal rocks analogous to ophiolitic sequences, and assessment of the seismic nature of oceanic Layer 3. The analysis of geophysical data requires a complete understanding of the physical properties of the investigated section. For this purpose, laboratory measurements of the physical properties of oceanic samples provide direct insights into the physical structure of the oceanic crust. These measurements can be compared with in situ down-hole measurements. In this paper, we present a petrophysical study of gabbroic samples from ODP Hole 1105A, located 1.5 km from the reference ODP Site 735. The physical properties are investigated at room pressure and temperature in order to characterize the penetrated massif, as well as to determine the influence of alteration due to fluid circulation on rock properties. Porosity, density, electrical properties (formation factor, surface conductivity), bulk magnetic susceptibility and compressional velocity

have been measured on a set of 34 samples collected during ODP Leg 179. Electrical properties of gabbros have been investigated in detail by Pezard et al. (1991) and Ildefonse & Pezard (2001) in ODP Hole 735B, to identify downhole changes in electrical properties, porosity structure and alteration. An important result is a change in porosity as a function of depth. These works also highlighted the importance of oxide minerals in the measured electrical resistivity. In the oxide-mineral-rich samples, it was pointed out from saturated measurements that oxide ionic conductivity was involved. Unfortunately, the 735B mini-cores were lost, and further investigation of complementary measurements such as oxide content, magnetic susceptibility and dry resistivity were not possible. Our data-set, however, does allow a full investigation of the petrophysical properties in such oxide-rich gabbros.

Due to extreme sensitivity, and in spite of complexity, electrical methods are among the most precise indirect tools for the analysis of rock structures. At low frequencies (< 1 kHz), electrical properties of saturated rocks are influenced by the nature of the rock matrix; the chemical composition and salinity of the saturating fluid; the cation-exchange processes along pore surfaces, and/or the movement of fluids in the porous medium (e.g. Waxman & Smits 1968; Olhoeft 1981; Walsh & Brace 1984; Katsube & Hume 1987; Pezard 1990; Pezard et al. 1991; Revil et al. 1998). Rock-forming minerals are mostly silicates, having a high resistivity ($10^6$ to $10^{14}$ ohm m), but, when the rock matrix contains conductive minerals (Ti–Fe oxide in gabbros), the conduction current through the matrix may be appreciable as oxides reach a resistivity of $10^{-6}$ ohm m (Olhoeft 1981; Guéguen & Palciauskas 1992). The influence of the oxide minerals on the various physical properties are investigated in this paper.

Geological setting: the Atlantis II Bank

ODP Hole 1105A is located on top of the shallow Atlantis Bank (720 m below sea-level), about 18 km east of the active Atlantis transform fault and 93 km south of the present-day ridge axis (Fig. 1). The Atlantis Bank is the shallowest and largest (c. 35 km²) of a series of north–south aligned flat-topped platforms (Dick et al. 1999). This shallow structure is interpreted as the result of progressive unroofing along a north-dipping low-angle detachment fault (Karson & Dick 1984; Cannat et al. 1991; Dick et al. 1991), in a tectonic situation similar to that of the inside-corner highs of the Mid-Atlantic Ridge (Tucholke & Lin 1994; Cann et al. 1997; Tucholke et al. 1998; Ranero & Reston 1999).

The SW Indian Ridge (SWIR) is one of the slowest spreading sections of the mid-ocean ridge system, with a full spreading rate of 16 mm/a (Fisher & Sclater 1983; Dick et al. 1991). Slow-spreading ridges are characterized...
by a low magma budget, and extension appears to be accommodated by a pervasive deformation. About 50% of the dredged rocks along the Atlantis II Fracture zone are peridotites and gabbros (Fisher & Sclater 1983; Dick et al. 1991; MacLeod et al. 1998). The Atlantis Bank itself mostly consists of outcropping gabbro. Models proposed to explain the exposure of gabbros at the sea-floor involve large-scale normal faulting of the newly created oceanic crust. The gabbroic crust was accreted about 11.5 Ma ago at the SWIR axis (Dick et al. 1991).

ODP Hole 1105A is located at 1.3 km from the reference Hole 735B, which penetrates 1508 metres below the sea-floor (mbsf), following two ODP drilling cruises: ODP Leg 118 (Von Herzen et al. 1991) and ODP Leg 176 (Dick et al. 1999, 2000). The exceptionally high core recovery makes of these two boreholes quasi-continuous sample of the in situ gabbroic crust.

**Basement stratigraphy**

In Hole 1105A, a sequence of gabbroic rocks was drilled to a total depth of 158 mbsf. Core recovery in such an environment is very high and reaches 82.8% for the whole section – similar to core recovery obtained in ODP Hole 735B (Dick et al. 1999). The recovered rocks in Hole 1105A are divided into four main rock types, ranging from gabbro (36%), olivine gabbro (43%), oxide gabbro (17%), and olivine oxide gabbro (4%). The full section is presented in detail in Pettigrew et al. (1999). It is composed of 54 lithological units on the basis of variation in rock type, mineral abundances and grain size. On a broader scale, four major lithological units have been determined from petrological description (Fig. 1; Pettigrew et al. 1999). Hole 1105A lithology consists of:

1. a gabbroic unit (15–48 mbsf) characterized by more primitive rock types and by a scarcity of oxide gabbro;
2. a gabbroic unit (48–136 mbsf) characterized by a high abundance of oxide gabbro and oxide-bearing gabbro;
3. a gabbroic unit (136–150 mbsf) characterized by a lack of oxide gabbros; and finally,
4. an oxide-rich gabbro and oxide-bearing gabbro unit (150–157 mbsf). In oxide-rich rocks, oxide content reaches up to 20–25% modal Fe–Ti minerals.

**Sampling**

This study includes a series of 34 samples from ODP Hole 1105A. All minicores were drilled vertically into the core after splitting. The samples include all the major lithologies identified (gabbros, oxide-rich gabbros, olivine gabbros: Pettigrew et al. 1999) and different states of secondary alteration, from unaltered to highly altered. The samples are located along the whole section, and have been characterized according to their oxide mineral abundance and degree of alteration, from thin-section analysis. Three distinctive groups have been identified in order to allow petrographical characterization of each gabbro type, related to the objective of this paper: fresh, altered and oxide rich (Fig. 2). Distribution and abundance of oxide minerals in the thin section as shown in Figure 2 were determined by using heightened contrast to enhance the distribution of oxides (black) compared to the silicate matrix (white). Oxide mineral abundances determined by image analysis vary from 0.2 to 31.2%. Microprobe analyses obtained from ODP Hole 735B oxide minerals (Natland et al. 1991; Niu et al. 2002) show that the oxides are dominated by ilmenite and ilmenite–hematite–magnetite solid solution. For the following discussion, they will be referred to the oxide rich category. In this study, the notion of alteration is related to the surface electrical properties of alteration phases in gabbros, such as smectites, illites or zeolites (Robinson et al. 1991; Dick et al. 1999; Pettigrew et al. 1999).

Furthermore, petrophysical measurements from Pezard et al. (1991) and Ildefonse & Pezard (2001) obtained from ODP Hole 735B samples are integrated in the following discussion and compared to the 1105A analyses. Most of these measurements have been made following the same analytical procedure. This dataset does not represent the entire set of lithologies, since the primary criterion for choosing the samples was the freshness of the core. It results in a rather homogeneous sampling, without strongly altered or Fe–Ti oxide-rich samples.

**Petrophysical properties from down-hole measurements**

Physical properties were measured in situ using down-hole tools at Hole 1105A (Pettigrew et al. 1999). Wireline logging provides a continuous geophysical characterization of the penetrated formations, and is a good indicator of the lithology distribution. The Triple Combo (resistivity, porosity, density, natural radioactivity and temperature measurements) and the FMS-Sonic tool strings were deployed (Pettigrew et al. 1999). The FMS-Sonic tool string provides a measurement of sonic velocity, and includes a
Fig. 2. Standard transmitted micrograph of three representative samples. The sample diameter is about 2.5 cm. Distribution and abundance of oxide minerals in the thin section has been quantified by using heightened contrast to enhance the distribution of oxides (black) compared to the silicate matrix (white). The oxide mineral content for the ODP Hole 1105A samples are reported in Table 1. Sample 32 (140.64 mbsf); sample 10 (61.95) and sample 23 (110.3 mbsf).

micro-electrical imaging device (FMS) together with calipers and gamma-ray measurement to enable depth corrections between tool strings. Full descriptions of the measurement principles of the logging tools used on the ODP program can be found in Goldberg (1997). Figure 3 presents some of these geophysical measurements used in this discussion.

The borehole shape is shown by two orthogonal calipers (Fig. 3a), and appears to be smooth (diameter close to 10 in.), indicating that the borehole conditions required for reliable down-hole measurements are excellent here. Natural gamma-ray measurements (Fig. 3b) exhibit low values along the whole section – coherent in oceanic crust. Slight variations in gamma-ray measurements are indicative of changes in the degree of alteration. In the lowermost part of the borehole (from 103 mbsf to the bottom), gamma-ray values are slightly higher, and can be attributed to the highest degree of alteration in the gabbros (Fig. 3b). At 103 m, a strong increase in natural gamma-rays is recorded. This increase is correlated with other geophysical parameters such as low density, variation in the borehole shape (caliper), or low recovery in this interval, and may be indicative of the presence of a faulted zone or a fractured interval. Such fractured zones have been previously described in the neighbouring Hole 735 with the borehole televiewer (Goldberg et al. 1991; Dick et al. 2000). Overall, variations in
ELECTRICAL PROPERTIES OF GABBROS

Fig. 3. Down-hole measurements and mini-core measurements along ODP Hole 1105A gabbroic basement. All probes from Schlumberger and laboratory measurements were determined on the same mini-core (1.7 cm long and 2.5 cm in diameter). Mini-core measurements are reported in Table 1. White circles: fresh samples; grey circles: altered gabbros; and black circles: oxide-rich gabbros. (a) Caliper measurements (inches) from the Formation Micro Scanner. (b) Down-hole total gamma-ray content (API units) from the Hostile Natural Gamma Ray Probe. (c) Down-hole bulk density measured by the Hostile Environment Probe. (d) Down-hole electrical resistivity measured by the Dual Induction Tool. Mini-cores were saturated with NaCl (30 g L$^{-1}$, similar to the sea-water) and electrical resistivity measured at 100 Hz. (e) Down-hole capture cross-section measured with the accelerator porosity sonde. This diagram gives the oxide abundance determined on thin sections by image analysis.

The density profile mostly correspond to variations in oxide mineral abundances.

Electrical resistivity (Fig. 3d) measured with the dual induction tool (DIT) is the only quantitative assessment of the formation resistivity. Strong variations in resistivity are recorded along the section and are directly linked to the lithology. Typically, values lower than 100 ohm m are indicative of oxide-rich layers. Electrical resistivity measurements appear to be affected by highly resistive gabbros encountered in the lowermost part of the borehole. In this interval (below 140 mbsf), the induction tool reached saturation where formation resistivity values are above 9700 ohm m. Another important parameter used to distinguish the different gabbroic units is the capture cross-section (Fig. 3e). The thermal neutron absorption is a measure of the formation's ability to absorb neutrons. This measure is useful, as it is a linear function of the formation geochemistry. In ODP Hole 1105A, the extreme range in the composition of the gabbros makes this measure a good proxy to identify oxide-rich layers. Harvey et al. (1996) showed that some rare earth elements (REE: Gd, Sm, Eu, Dy) and B, C1 and H have the highest cross-section values. All these elements are abundant in oxide-rich gabbros, due to their higher degree of differentiation (high REE content as observed in the neighbouring ODP Hole 735B, Coogan et al. 2001) and also the higher degree of alteration.
High values of the capture cross-section are well correlated with oxide mineral abundance measured in thin sections. All down-hole measurements highlight the fact that oxide-rich layers are not negligible along the whole section. Good agreement is observed between the down-hole measurements and laboratory measurements presented in the following section.

**Physical properties of minicores**

Measurements of physical properties have been performed on 25-mm-diameter mini-cores sampled along the drilled section. For each sample, porosity, grain density, compressional velocity, magnetic susceptibility and electrical resistivity at different salinities were measured at laboratory temperature and atmospheric pressure. The results are presented in Table 1. A particular emphasis has been placed on electrical measurements, in order to investigate changes in pore-space morphology and alteration, as well as the influence of oxide minerals on electrical properties.

**Porosity and grain density**

The porosity and density were determined by the standard immersion method corresponding to a triple weighing (with dry, saturated and immersed samples). This method allows direct computation of porosity and grain density, independently of sample size and shape, with:

$$\Phi = 100 \times \frac{(W_{\text{sat}} - W_{\text{dry}})}{(W_{\text{sat}} - W_{i})} \quad (1)$$

where $W_{\text{dry}}$ is the dry weight, $W_{\text{sat}}$ is the saturated weight, $W_{i}$ is the immersed weight, and $\Phi$ the porosity.

The grain density ($\rho_g$) is calculated as the following:

$$\rho_g = \frac{W_{\text{dry}}}{(W_{\text{sat}} - W_{i})} \times \rho_w \quad (2)$$

where $\rho_w$ is the saturating fluid density.

Porosity, bulk density, and grain density are summarized in Table 1. For rocks with porosities lower than 1%, as in most of the samples in this study, the absolute computed error is lower than 2% for densities (i.e. about 0.06 g cm$^{-3}$), and about 15% for porosities (i.e. $\leq 0.1\%$). Values of porosity are generally low in most samples (Table 1). The highest porosities (Fig. 4c) correspond to the altered and oxide-rich samples (respectively 1.31% and 1.94% on average). Bulk density (Fig. 4a) is more variable, with an average of 2.95 g cm$^{-3}$ in fresh and altered samples, although it increases to 3.43 g cm$^{-3}$ in oxide-rich samples.

**Acoustic compressional velocity**

Compressional velocity (P-wave velocities: $V_p$) measurements were performed for each samples at 2.25 MHz, using a Panametrics Epoch III-2300 device. The Teflon jacket used for the electrical measurements was kept in place, in order to reduce the influence of desaturation during the measurements. $V_p$ was measured on saturated samples with a 30 g l$^{-1}$ NaCl brine. The precision of these measurements was determined as better than 1%, i.e. of the order of 50 ms$^{-1}$, determined by repeat measurements and standard measurements. The measured velocities ($V_p$) values range from 6.0 to 7.1 km s$^{-1}$ (Fig. 4b) and are comparable to the values for gabbroic rocks measured on Hole 735B (Leg 118: 6.713 $\pm$ 0.383 km s$^{-1}$ (Von Herzen et al. 1991); Leg 176: 6.777 $\pm$ 0.292 km s$^{-1}$, Dick et al. 1999), and are then representative of seismic Layer 3. The highest values were measured in fresh samples (with a mean $V_p$ of 6.871 km s$^{-1}$), and a slight decrease is observed in the altered samples (with a mean $V_p$ of 6.427 km s$^{-1}$). Oxide-rich samples have markedly lower $V_p$ values with a large game of value (from 4.530 to 4.5 km s$^{-1}$). These lowest velocity values can be attributed to the abundance of Fe–Ti oxide minerals, and the higher variability is likely to be caused by the variable degree of alteration and porosity (Fig. 4c) and variation in modal oxide abundance in these samples.

**Magnetic susceptibility**

A Kappabridge was used under the scalar mode for measuring the bulk magnetic susceptibility (Table 1). This measurement proved to be particularly useful on board to detect the presence of thin metallic oxide seams, as the magnetic susceptibility was measured on continuous cores recovered (Pettigrew et al. 1999; Natland & Dick 2001). The magnetic susceptibility is an intrinsic material property related to the induced magnetization intensity that may be measured on a sample. The magnetic susceptibility is a function of the nature, concentration and grain size of magnetic minerals within the sample. As a consequence, magnetic susceptibility data may be used as a proxy to clearly
### Table 1. Physical properties of the ODP Hole 110A gabbroic samples

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<tr>
<th>Depth (mbsf)</th>
<th>Oxide-content (%)</th>
<th>Mg Mb dO X F Cs_Cmi</th>
<th>Cmi m Ve</th>
<th>τ</th>
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</table>

**Note:** 
- All petrophysical measurements were performed on mini-cores at Cerege, except for dry conductivity determined at the University of Montpellier II, ISTEEM.
- Key: Mg, grain density (g cm⁻³); Mb, bulk density (g cm⁻³); dO, porosity (%); X, magnetic susceptibility (10⁻³ SI); F, electrical formation factor; Cmi, surface conductivity (mS m⁻¹) calculated from the Revil & Glover (1998) formulation. Ve, acoustic compression velocity (km s⁻¹).
- Conductivity (mS m⁻¹) was measured on saturated samples (100 g ml⁻¹); Cmi, surface conductivity (mS m⁻¹) calculated from the Revil & Glover (1998) formulation. Ve, acoustic compression velocity (km s⁻¹).
identify the occurrence of oxide minerals. As expected, a good positive correlation between the estimated oxide content is observed from thin-section analysis (2D) and magnetic susceptibility (3D) (Fig. 4d). The scatter that does occur could be explained by the highly variable content of oxide in the gabros, or by the difference of investigation methods (2D versus 3D).

**Electrical resistivity**

**Background.** The sensitivity of the electrical properties of porous media to fluid content and alteration provides a powerful means to detect conductive horizons such as fractures, either open or mineralized, in a resistive matrix (e.g. Walsh & Brace 1984; Katsube & Hume 1987; Pezard & Luthi 1988). At the metre-scale, *in situ* measurements of electrical resistivity are often analysed to derive porosity (Archie 1942; Brace *et al.* 1965; Becker 1985). The different modes by which the current is transported may be identified in the laboratory, providing insights into the degree of alteration of the rock, with the analysis of surface electrical conduction (Waxman & Smits 1968; Pezard 1990; Revil & Glover 1998). The method used was initially derived for porous media such as sandstones and clays (Waxman & Smits 1968; Revil & Glover 1998). It has also been used successfully in various low-porosity igneous rocks, such as basalts (Pezard 1990; Bernard 1999; Einaudi *et al.* 2000), gabros (Pezard *et al.* 1991; Ildefonse & Pezard 2001), and granites (Pape *et al.* 1985). For the oxide-free samples, the electrical conductivity in the samples depends upon
a combination of pore volume and pore surface conduction.

In a porous media comprising a matrix considered as infinitely resistive and a connected pore space saturated with a conductive electrolyte, two electrical conductivities are involved: an electrolytic conduction mechanism within the pore volumes, and a surface conduction mechanism at the interface between the electrolyte and minerals. While the electrolytic conduction is directly related to the nature and salinity of the pore fluid, the surface conduction is due to the presence along pore surfaces of charges which appear to guarantee the electroneutrality of the medium. In most geological settings, the mineral surfaces are charged negatively. The cations present in the fluid along pore surfaces migrate through a diffuse layer to contribute to the overall conduction (Waxman & Smits 1968; Clavier et al. 1977).

In the simplest case, i.e. when the surface conduction component is negligible with respect to the electrolytic component (in the case of a pure quartz sand, for instance), the total conductivity of the pore space \( C_o \) can be considered as directly proportional to that of the saturating fluid \( C_w \):

\[
C_o = \frac{C_w}{F} \tag{3}
\]

The dimensionless \( F \) coefficient is called the 'electrical formation factor'. The factor \( F \) describes the contribution of pore-space topology in the matrix to the electrical resistivity of a fluid-saturated medium. The electrical formation factor \( F \) has been reported to be dependent upon rock texture; distribution of pores and pore throat sizes, connectivity between pores; and flow-path tortuosity, all of which illustrate the internal 3D topology of the pore space of the analysed rocks.

When surface processes cannot be neglected with respect to electrolytic conduction, which is generally the case in the presence of alteration phases, the previous equation does not hold. The full expression for the electrolytic conductivity of the porous media is the sum of two contributions: a bulk electrolytic conductivity and surface conductivity processes (Waxman & Smits 1968; Clavier et al. 1977). Waxman & Smits (1968) have proposed an empirical model to take into account the excess conductivity \( C_s \) due to surface processes, with:

\[
C_o = \frac{C_w}{F} + C_s \tag{4}
\]

where \( C_s \) is the surface conductivity resulting from the presence of the electrical double layer (Clavier et al. 1977), and \( F \) is the electrical formation factor.

A new and more complete approach based on the pore space microgeometry has been proposed by Revil & Glover (1998), with:

\[
C_o = \left( \frac{C_w}{F} \right) \left[ 1 - t'_+(\xi) + F\xi + f(F,\xi) \right] \tag{5}
\]

where \( t'_+(\xi) \) is the Hittorf number of cations in the electrolyte (Revil & Glover 1998), and \( \xi \) is a dimensionless parameter defined by Kan & Sen (1987). The \( f(F, \xi) \) is a complex function of \( F \) and \( \xi \) detailed by Revil & Glover (1998). The predictive capacity of this model covers the adequate salinity range. From the single approach of (5), the RG model is more precise, yielding the following high- and low-salinity end-members:

\[
C_o = \left( \frac{C_w}{F} \right) \left[ 1 + 2\xi F(F - 1) \right] \tag{HS}
\]

\[
C_o = \frac{\xi C_w}{1 - \frac{\xi - 1}{\xi F}} \tag{LS}
\]

At high fluid salinity, the dominant path for current transport depends on the pore volume topology, which is represented by the electrical formation factor \( F \). At low salinity, adsorbed cations are transported along the fluid–grain interface, and the electrical conduction is dominated by surface electrical conductivity \( C_s \). Further details on this model can be found in Revil & Glover (1998), Revil et al. (1998) and Ildefonse & Pezard (2001). For the following discussion, we used the Waxman & Smits (1968) formulation.

**Experimental design**

In order to distinguish between the electrolytic and the surface conduction mechanisms, the samples were analysed by measuring the electrical resistivity with variable saturating fluid salinity. The measurements were performed at seven different saturating fluid salinities (from 0.2 to 100 g l\(^{-1}\); i.e. conductivity varying from 0.04 to 11 S m\(^{-1}\)) with a two-electrode Wayne–Kerr bridge. The samples were saturated with NaCl solution at near-vacuum conditions for the first measurement. In the following, the bath fluid was regularly checked and brines were changed when changes in the electrical response of the system had ceased. The device used a spring to keep electrodes in contact with each mini-core. The sides of the cores were
wrapped in insulating Teflon tape to restrict the
current from passing down the sides of the
mini-core. A 10 mV signal was applied to
perform each of the measurements at seven
frequencies. Only measurements realized at
100 Hz are presented in this study. This fre-
cquency value was chosen to be similar to that
used for down-hole measurements.

From these measurements (Fig. 5), we applied
the detailed relationship of Revil & Glover
(1998) to compute the electrical formation
factor ($F$) and surface conductivity ($C_s$) of each
sample.

**Porosity structure from electrical measurements**
In the absence of clay or alteration phases, the
electrical formation factor $F$ depends primarily
on the porosity value and structure. In the
absence of clay or alteration phases, $F$ depends
primarily on the porosity value and structure.
The surface conductivity $C_s$ is then negligible
when compared to the fluid conductivity ($C_w$).
The $F$ is measured or modelled to increases as
the porosity decreases or becomes more tortuous.
An empirical relationship between the electrical
formation factor ($F$) and porosity ($\Phi$) was pro-
based by Sundberg (1932), later followed by
Archie (1942) for sedimentary rocks, yielding
Archie’s law (Fig. 6a). This relationship is still
widely used in oil industry. Thus the formation
factor ($F$) was related to porosity by:

$$F = \Phi^{-m} \quad (7)$$

where $m$ refers to the cementation factor of the
sedimentary rock, and is related to the degree
of cementation between individual grains. This
relationship may also be expressed in terms of
degree of connectivity of the inner pore space,
or the inverse with electrical tortuosity $\tau$
(Walsh & Brace 1984; Katsube & Hume 1987;
Pezard 1990; Pezard *et al.* 1991; Guéguen &
Palciauskas 1992), yielding:

$$F = \frac{\tau}{\Phi} \quad (8)$$

While the cementation factor describes the non-
uniformity of the section of the conductive chan-
nels, the tortuosity relates to the complexity of
the path followed by the electrical current (e.g.
Guéguen & Palciauskas 1992) or, in a more
general sense, the efficiency of electrical flow
processes (Clennell 1997). Many different
analytical and numerical methods were devel-
oped to derive transport properties of porous
media from microstructural parameters. Clennell
(1997) provides a useful review of the different
approaches and results that have been obtained.

The electrical formation factor $F$ characterizes
the ratio between the bulk electrical conductivity
and the electrical conductivity of the saturating

![Fig. 5. Plots of the core conductivities as a function of the saturating fluid conductivities. Best-fit curves are calculated using the Revil & Glover (1998) model. Based on thin sections, samples have been divided into three types: (a) fresh samples, (b) altered samples and (c) oxide-rich samples.](image-url)
THE PRESENCE OF NUMEROUS Fe–Ti OXIDE-RICH LEVELS IN ODP HOLE 1105A (PETTIGREW ET AL. 1999)
leads to a more complex conduction mechanism for the transport of electrical charges in the rock. Matrix conduction mechanisms via electronic processes in metallic oxide grains may then become significant (Drury & Hyndman 1979; Pezard 1990; Pezard \textit{et al.} 1991). As pointed out above, the conduction via electronic processes in metallic minerals is not taken into account in these formulations of the electrical properties. No model includes the effect of a conductive phase such as the oxides present in the studied gabbros, and a new constitutive law for electrical conduction is hence required to account for the conductive phase in the mineral matrix. Pezard \textit{et al.} (1991), from ODP Hole 735B gabbros, proposed:

\[ C_w = \frac{C_v}{F} + [C_s + C_{\text{mineral}}] \]  

The \( C_{\text{mineral}} \) term is a constant related to the oxide content for a given sample, which does not depend on the salinity of the saturating fluid. Thus, the different contributions to the electrical conduction are identified, and estimated. The oxide contribution to the measured electrical resistivity is achieved through dry resistivity measurements.

\textbf{Dry measurements}

The measurements of dry sample conductivity were made in a two-electrode cell with an experimental device which allows multi-frequency measurements. The signal measured on a dry sample is a complex impedance (\( Z \)) characterized by two components: an in-phase \( R \) (or resistive) signal, and an out-of-phase \( X \) (or reactive) signal. The complex impedance can be expressed as follows:

\[ Z = R + iX \]  

where \( i \) is the complex operator (\( i^2 = -1 \)). The complex electrical resistivity is calculated from the \( Z \) measurements by:

\[ \rho = Z'(A/L) = \rho' + ip'' \]  

where \( A \) is the cross-sectional area of the mini-core and \( L \) is its length. The \( \rho' \) and \( \rho'' \) are respectively the real and imaginary parts of the complex resistivity. The electrical resistivity is the value corresponding to the measured real part of \( z \) at the frequency where \( \rho'' \) equals zero.

The dry conductivity values present a large distribution range (Fig. 7). However, as expected, oxide-rich gabbros present by far the highest conductivities. The dry conductivities show a large distribution, with five-order magnitudes from \( 2.3 \times 10^{-6} \) to \( 1.9 \times 10^{-1} \) S m\(^{-1}\). For comparison, saturated measurements at \( 100 \) g l\(^{-1}\) vary over only one order of magnitude (from \( 5.9 \times 10^{-3} \) to \( 1.1 \times 10^{-1} \) S m\(^{-1}\), Table 1), since electrical conductivity is here dominated by electrolytic processes. In a general sense, the difference between these two measurements represents the conductivity of surface and minerals. In the range 0–2% of oxide mineral abundance (fresh gabbros), their contribution to measured conductivity is about 26%; between 2 and 15% (altered gabbros), the contribution is about 37%; and for oxide contents above 15% (oxide-rich gabbros), the oxide mineral contribution reaches 82%. In some cases, particularly for oxide-rich samples, the ratio between the dry conductivity and the saturated conductivity is higher than one (Table 1). Several explanations may be involved, such as the accuracy of the electrical measurements; or the accuracy of oxide content determination (2D versus 3D); or the quality of desaturation of each sample.

In the case of multi-phase conducting porous systems, a mixing model such as:

\[ C_o = \sum_{i=1}^{N} C_i(X_i) \]  

can be used (Guéguen & Palciauskas 1992; Glover \textit{et al.} 2000). This applies to the case of a mineral, solid-phase conducting current is parallel to the more usual fluid-related phases described by Waxman & Smits (1968) or Revil & Glover (1998). Guéguen & Palciauskas (1992) and Glover \textit{et al.} (2000) have proposed a modified relationship for a two conducting phases medium:

\[ C_o = C_1(1 - X_2)^n + C_2(X_2)^n \]  

with \( C_o \) corresponding to the measured conductivity, \( C_1 \) and \( C_2 \) respectively to the phase 1 and phase 2 conductivities, and \( X_2 \) being the volume fraction of the conducting phase 2 (with \( X_1 + X_2 = 1 \)). This modified model has two exponents (\( n \) and \( p \)) that describe the connectivity of each of the two phases. As a consequence, we may propose a more analytical expression for the mineral-phase contribution by combining this approach and equation (9); the total electrical conductivity (\( C_o \)) can be expressed as:

\[ C_o = \left( \frac{C_w}{F} + C_s \right) + C_{\text{ox}}(X_{\text{ox}})^n \]
Fig. 7. Plots of (a) dry electrical conductivity; (b) electrical connectivity exponent \( q \), and (c) magnetic susceptibility versus oxide mineral content (\( X_\text{ox} \)). (d) Electrical connectivity exponent versus magnetic susceptibility (10\(^{-3}\) SI).

with \( C_\text{ox} \) being the intrinsic electrical conductivity of the oxide minerals, and \( X_\text{ox} \) their volume fraction determined from thin section; \( q \) corresponds to the connectivity exponent of the oxide phase. In the case of dry conductivity measurements, the measured electrical conductivity (\( C_\text{dry} \)) is only related to the conductivity of oxide minerals, and can be expressed as:

\[
C_\text{dry} = C_\text{ox}(X_\text{ox})^q
\]

with \( C_\text{ox} \) equal to 10\(^6\) S m\(^{-1}\) (order of magnitude for magnetite after Olhoeft 1981; Guéguen & Palciauskas 1992). From equation 14, we can calculate the solid-phase \( q \) exponent referred to as the ‘solid connectivity exponent’. The \( q \) exponent is a function of the fractional volumes of each phase, because low phase connectivities are associated with small volume fractions and high phase connectivities are associated with large volume fractions.

Conclusions

The physical properties of a set of 34 gabbroic samples from ODP Hole 1105A (SWIR), have been measured in the laboratory, with a particular emphasis on the analysis of electrical properties. The electrical ‘formation factor’ \( F \) of each sample, as well as a pseudo-surface conductivity (\( C_s \)) have been extracted from the gabbros; there is evidence of three conducting phases (matrix, surface conductivity and fluid conductivity). Dry measurements clearly show that most of the excess conductivity evident in brine-saturated
gabbros can be attributed to ionic conduction for the oxide-rich samples. Our investigations of electrical properties of ODP Hole 1105A samples enhanced the oxide mineral contribution on electrical conductivity. The conductivity measured on dry samples is correlated to the oxide mineral content, and their contribution can reach up to 80% of the measured conductivity on saturated samples.

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References


ELECTRICAL PROPERTIES OF GABBROS

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