

Is the illite group the cause of high electrical conductivity in certain lithospheric areas?

Gabriella Losito and Michela Muschietti

Dipartimento di Ingegneria Civile, Università di Firenze, Italy

Abstract

This article discusses the problem of the mineralogical-petrographic interpretation of the «anomalous» conductive layer inside the lithosphere, which has resulted from electromagnetic deep soundings. Three situations can be found: 1) a resistivity of less than $1 \Omega \cdot m$ in the Very High Conductivity Layer (VHCL); 2) a resistivity of $1 \div 100 \Omega \cdot m$ in the High Conductivity Layer (HCL); 3) a resistivity of $10^2 \div 10^3 \Omega \cdot m$ in the Continental Lower Crust (CLC). We have focused our attention on the HCL because of its widespread distribution. Most authors attribute HCL conductivity to the presence of salt water or graphitic materials, that are uniformly and continuously distributed inside rocks. Other hypotheses from the literature are the presence of oxides and/or sulphides, rock melting, and brine-bearing rocks. Each one of these elements can cause high electrical conductivity, depending on the petrophysical conditions, but much discussion involves the necessary physical continuity of the conductive elements. We forward one more hypothesis as follows. By means of experiments on rock samples from different geographical and deep areas, under simulated *in situ* physical conditions (*e.g.*, pressure, temperature, saturation), we have found resistivity values similar to the *in situ* ones. Chemical, mineralogical, and petrographic analyses have shown the presence of large amounts of phyllosilicate minerals, such as illite. These minerals act in two ways: they produce the physical continuity of associated conductive minerals, and they decrease the resistivity of rocks. This second hypothesis is consistent with both the very widespread diffusion of illite inside the Earth's crust, and with the good conductivity found in depth.

Key words *electrical anomaly – lithosphere resistivity – high conductivity layer – phyllosilicate – graphite*

1. Introduction

The mineralogical-petrographic interpretation of the conductive layers in the middle and upper crust coming from Electromagnetic Deep Soundings (EMDS) is a topic still deserving valid explanations.

Many hypotheses have been made that are founded on laboratory data from both deep and superficial samples. The hypothesis most followed relates to the presence of a continuous and compact graphitic layer. Recent laboratory and *in situ* measurements have shown, however, that this layer cannot always produce high electrical conductivity in the crust being studied. Other causes are thought to contribute to the conductivity of rocks, such as the hydraulic saturated network and special minerals (*e.g.*, clays).

We discuss here data taken from the literature and collected during our own experiments, which could contribute to interpreting the nature of some rock layers resulted as electrically «anomalous».

Mailing address: Dr. Gabriella Losito, Dipartimento di Ingegneria Civile, Università di Firenze, Via di S. Marta 3, 50139 Firenze, Italy; e-mail: losito@dicea.unifi.it

Table I. Areas with conductive and high conductive layers in the crust, as follow from deep electromagnetic soundings. Location = geographic area; Z (km) = depth; H (km) = thickness; ρ ($\Omega \cdot m$) = conductive layer resistivity; Hypotheses = geologic interpretation.

Location	Z (km)	H (km)	ρ ($\Omega \cdot m$)	Hypotheses	Authors
AFRICA					
East rift	1-30		< 10	Magma	Jones (1992)
Kaapvaal craton	30	10	1-100	Recent sediments	De Beer <i>et al.</i> (1991)
	35		40	Graphite	
Zimbabwe craton	35		50	ρ/T effects	Shankland and Ander (1983)
AMERICA (north)					
Kapuskasing uplift	25	10	100	Graphite	Jones (1992)
Sierra Nevada N (orogene)	1-10	Many	< 1-100	Fluids	Gough (1992)
				Magma	Gupta and Jones (1995)
				Graphite	Jones and Dumas (1993)
Sierra Nevada S (orogene)	15		10-100	Oxides, sulphides	Kinn <i>et al.</i> (1994)
				Pre-melting	
ANTARCTICA					
	8		40		Kong <i>et al.</i> (1994)
	22		15		
EUROPE (north)					
Baltic shield	1-12	Many	< 10		Korja <i>et al.</i> (1989)
Ladoga margin	8	10	< 10		Jones (1992)
Iceland volcanoes	5-10		50	Magma	Shankland and Ander (1983)
Iceland	3-15		100		Beblo and Bjornsson (1980)
Iapetus suture	4		1-100		Jones (1992)
	5	10	1-100	Graphite	Banks and Livelybrooks (1994)
				Black shales	Brown <i>et al.</i> (1992)
EUROPE (central)					
External Alps (orogene)	0-8	1	1	Graphite	Ádám <i>et al.</i> (1990)
	10-20	5	< 1	Fluids	
	10			Graphite	Bahr (1992)
Pannonian basin	0	8	< 10	Recent sediments	Ádám (1992a)
	20	5	< 1	Graphite	Ádám <i>et al.</i> (1990)
				Fluids	
Rhinen area	12	6	< 10	Graphite	Jones (1992)
				Fluids	
	6-14	2	1-40	Black shales	Erceugt Group (1992)
	26	2	1	Black shales	
Rhinen graben	0	1-5	< 10	Recent sediments	
	9	1	< 1	Black shales	
Bohemian massif	0-2		< 10	Graphite	Haak <i>et al.</i> (1991)
	7	< 1		Graphite	Nover (1995)

Table I (continued).

Location	Z (km)	H (km)	ρ ($\Omega \cdot m$)	Hypotheses	Authors
Bohemian massif				Oxides, sulphides Fluids	
	10				Osman <i>et al.</i> (1994)
German basin S	0 5	7 < 10	< 50 1	Recent sediments Fluids	Erceugt Group (1991)
German basin N	0	2.5	20	Black shales	
Saxoturingian basin	10	< 1	1	Recent sediments Graphite Fluids	
EUROPE (south)					
Alpine chain NE	10	2-10	< 10	Fluids	Braitenberg <i>et al.</i> (1994)
Tuscan geothermal area	0-20	Some	< 100	Melting	Fiordelisi <i>et al.</i> (1995)
Bradanic trench	0-7	< 4	< 10	Magma	Muschiatti (1993, 1995)
Sardinia	30		50	Recent sediments Mantle	Peruzza <i>et al.</i> (1990)
RUSSIA					
Baikal rift	14	10	30		Jones (1992)
Baikal platform	25	15	200		Feldman <i>et al.</i> (1994)
Caucaso	0-25 35		10	Black shales	
Kamchatka	10			Fluis Magma	Moroz (1994) Jones (1992)
Siberian shield	5		$\ll 1$		

Before discussing the cause of such anomalies, it is important to emphasise that at least three situations exist: 1) a resistivity of less than $1 \Omega \cdot m$ (Very High Conductivity Layer, VHCL); 2) a resistivity of $1 \div 100 \Omega \cdot m$ (High Conductivity Layer, HCL); 3) a resistivity of $10^2 \div 10^3 \Omega \cdot m$ (Continental Lower Crust, CLC) (Jones, 1992).

We have focused our attention on the HCL because of three considerations: its widespread distribution inside the lithosphere, the strong interest of many researchers, and personal curiosity.

The topic has been dealt with in a review both of the areas in which the HCL has been found at different depths and also of the possible causes for the *anomalous* deep conductivity. A discrimination has been made between physical conditions (*e.g.*, pressure and temperature) and petrography.

For historical purposes and applications, in the following we use the *resistivity* parameter, rather than the *conductivity* parameter.

2. Lower-crust electromagnetic model from MT-EM surveys: a review

From deep electrical and magnetotelluric soundings, that are able to investigate the middle and lower crust, it can be seen that large areas of the planet show very high electrical conductivity (in some places, the measured resistivity is less than $1 \Omega \cdot m$). The mineralogical-petrographic interpretation of this observation is still an open problem. Table I is a summary of the state of the art.

By a careful analysis of these data, we can conclude that a special lithological structure results, mostly 2D, that is about 10 km deep is

the main evidence. The structure has «anomalous» electrical resistivity values ($1 \div 100 \Omega \cdot m$). Different interpretative hypotheses have been made regarding the electrical conductivity.

The low resistivity values can easily be attributed to fluids and to the high temperatures of magmatic bodies, with the consequent partial melting in geothermal and volcanic areas. In other situations, the geological-petrographic interpretation of the HCL is much more complicated, because only geophysical prospecting data are available, and in general their interpretation is affected by equivalence.

3. Thermal hypothesis: melting and pre-melting

3.1. Data from the literature

It is well-known that under particular conditions of pressure and temperature rocks can partially change their structure and/or mineralogical composition. The aforesaid conditions can sometimes be found in the middle-to-upper crust, with a consequent melting of the rock.

This situation is typical of volcanic and geothermal areas (Moroz, 1994; Kinn *et al.*, 1994; Fiordelisi *et al.*, 1995; Jones and Gough, 1995; Manzella *et al.*, 1995), and sometimes of tectonically-active areas (Braitenberg *et al.*, 1994). Here, given the high temperature gradient, the same rock can be at very different temperatures and, consequently, have different resistivities (even less than $10 \Omega \cdot m$). In this case, the associated conductive layers have a clear origin but a limited extension.

The major effect on conductivity changes must be attributed to temperature, and not to pressure. In fact, according to Lastovicková *et al.* (1993) and from personal experience, the conductivity ranges related to temperature are about 10 orders of magnitude, while pressure can produce conductivity ranges of a maximum of 1 order.

4. Mineralogical-petrographic hypotheses

There are many mineralogical-petrographic hypotheses regarding the formation of the High

Conductivity Layer (HCL). These hypotheses are based on information from various geophysical, geological and geochemical data.

Obviously, different petrophysical factors often coexist in the Earth's crust. The simultaneous actions do not enable us to identify the main cause of the measured electrical «anomaly». For instance, if C-O-H fluids come into contact with chemical elements such as chlorine, water formation and storage both occur inside the pores, together with the sedimentation of graphite (Haak *et al.*, 1991). As a consequence, there are ionic and metallic conductivities acting at the same time.

This article reviews the different mineralogical-petrographic hypotheses described in the literature and verified by the authors by means of laboratory studies (table II and table III). Sometimes, these hypotheses have been confirmed by experimental studies, made both in the laboratory on samples coming from boreholes and also in log. An interesting result is the presence of conductive layers at a depth of several kilometres found by logs (Stoll, 1994; Rauen and Lastovicková, 1995).

4.1. Oxides and sulphides

4.1.1. Data from the literature

In order for them to cause the high conductivity observed in the HCL, rocks must contain almost 80% oxides and sulphides if they are disseminated inside highly-resistive minerals (Parkhomenko, 1967) and if they do not create a continuous network (Haak *et al.*, 1991; Jödicke, 1992b; Duba *et al.*, 1994).

A high content of oxides and sulphides inside the Earth's crust is the conclusion reached in the works of De Beer *et al.* (1991), Gupta and Jones (1995), and Hoffman *et al.* (1994); but the areas described correspond to metallic mineralised zones and can obviously have only a limited extension.

A considerable presence of oxides and sulphides has been found in samples coming from the Continental Deep Drilling Project boreholes in Bavaria (KTB here as follows) (Duba *et al.*, 1994). In this particular case, it has been

Table II. Rock sample resistivities measured in laboratory (from literature). Location = geographic area; Mineralogic composition = main mineralogical composition of the sample; T_{\max} ($^{\circ}\text{C}$) and $\log \rho_T$ = maximum temperature reached during the experiment and relative resistivity logarithm; P_{\max} (MPa) and $\log \rho_P$ = maximum pressure reach during the experiments and relative resistivity logarithm; f (Hz) = frequency interval measurement; \parallel sample parallel to the foliation; \perp sample perpendicular to the foliation.

Location	Mineralogic composition	T_{\max} ($^{\circ}\text{C}$)	$\log \rho_T$	P_{\max} (MPa)	$\log \rho_P$	f (Hz)	Authors
KTB – Germany							
H003C12 (4253 m)	Foliated hornblende gneiss	1000	$5 \div 2 =$ $7 \div 3 \perp$	0.1			Rauen and Lastovicková (1995)
KTB – Germany							
H031 (7012 m)	Altered hornblende gneiss with quartz, graphite, pyrite, oxides	20		200	2	$0.1 \div 10^5$	Rauen <i>et al.</i> (1994)
IVREA zone (I)							
A	Granite	500	$4 \div 3$	200		1592	Glover and Vine (1995)
B	granodiorite		$3 \div 2$				
E1	amphibolite	900	$3 \div 1$				
F1	2-pyroxene granulite		$5 \div 3$				
H1	orthopyroxenite		$5 \div 2$				
KAPUSKASING							
(Canada) PBA79-32 (surface)	Graphitic paragneiss	20	3			10^{1+6}	Mareschal <i>et al.</i> (1992)
KTB – Germany							
H003 (4149 m)	Amphibolite with oxides, sulphides, graphite	25	2	250 0.1	2	10^{3+6}	Duba <i>et al.</i> (1994)
V420 (1858 m)	gneiss with oxides, sulphides, graphite		$1 =$ $2 \perp$				
769 (surface)	amphibolite		3				

emphasised that the metallic rock component was associated with graphite, mica, chlorite, and zeolite, each one having a low resistivity.

4.1.2. Data from experiments at the Florence laboratory

At the Florence laboratory, some effects of sulphide on the electrical behaviour of rock were measured. For the experiments, we used H_2O -saturated samples consisting of silica and

sulphide grains (silica: diameter = 1.7 mm; sulphide: diameter = 0.5 mm) in different weight percentages (Losito and Muschiatti, 1987).

The electrical resistivity measured was dependent on the sample composition. In fact, the 5% sulphide sample showed a resistivity close to that of the saturated silica (about $500 \Omega \cdot \text{m}$), whereas the > 50% sulphide samples had a resistivity of $\rho < 100 \Omega \cdot \text{m}$, which is typical of a saturated sulphide grain sample.

From these experiments we obtained the conductivity fluid effect in a 2-mineral rock

Table III. ρ logarithms of rock samples studied under simulated physical conditions at the Geophysical Laboratory in Florence ($T \leq 180$ °C, saturated samples) and in Prague ($T = 1000$ °C, dry samples). Area = geographic area; rock type = petrographic classification of the rock sample; MPC = measurement physical conditions, used to simulate natural conditions. Sample = sample code; PSP = parameters of physical simulation; f = frequency; pi = internal pressure; pe = confining pressure; \perp = sample's axis perpendicular to foliation; $\log \rho$ = resistivity logarithm at stated experimental temperatures.

Area Rock type MPC	Sample	PSP	$\log \rho$ 20 °C	$\log \rho$ 50 °C	$\log \rho$ 80 °C	$\log \rho$ 110 °C	$\log \rho$ 150 °C	$\log \rho$ 180 °C	$\log \rho$ 1000 °C	
FARMA	FP	f		0						
Graphitic schist $f = 2 \cdot 10^{-3} + 2 \cdot 10^3$ Hz $pe = 3$ MPa	F212			1						
	F268			2		2				
	F278		3	3	3	1	3	4	0	
SWISS	SOM7	f	0	0	0	0	0			
Graphitic schist $f = 10^{-3} + 2 \cdot 10^2$ Hz $pe \leq 39$ MPa $pi \leq 24$ MPa	CH5 =	pi	0	0	0	0	0			
		pe	0	0	0	0	0			
		f	3	2+3	2	2	2			
	CH5 \perp	pi	2	2	2	2	2	2		
		pe	2	2	2	2	2	2		
		f	3+4	3	3	3	3+4	4		
		pi	3	3	3	3	4	4	4	
pe	4	3	3	3	4	4	4			
BOLSENA	RC	pe	4	4	5	4	4	4		
Limestone RC Tephrite LAVA $f = 10^{-3} + 2 \cdot 10^2$ Hz $pe \leq 39$ MPa	RC	pe	2	2	2	2	2	2		
	2° cycle									
	LAVA	pe	2	2	1	1	1	1		
CLAYS	P1	f	1							
Clay P1, P2, P3, P78, P97 Sand S, SP02 $f = DC + 5 \cdot 10^3$ Hz $pe \leq 12$ MPa	P2	f	1			1				
	P3	f	2	2	2					
	P78	f								
	P97	f		1						
	S	f	2+4							
	SP02	f		2	2	1				
PUGLIA 1	N2		6	6	6	5	5	4	2	
Sandstone N3, N4 Dolomite N6 Mix N2 $f = 2 \cdot 10^{-3} + 2 \cdot 10^1$ Hz $pe \leq 39$ MPa $pi \leq 36$ MPa	N3	f	4	2	2	2	2	2	2	
		pi	3	2	2	2	2	2	2	
		pe	3	2	2	2	2	2	2	
	N4			4	4	4	4	4	5	1
		f	3	2	2	2	1	3		
		pi	3	2	2	2	1	3		
		pe	3	2	2	2	1	3		
N6			5	5	5	4	4	5	2	
	f	6	5	5	5	6	6			
	pi	6		5	5		6			
	pe	6		5	5		6			
		7	7	6	6	6	6	2		

Table III (continued).

Area Rock type MPC	Sample	PSP	log ρ 20 °C	log ρ 50 °C	log ρ 80 °C	log ρ 110 °C	log ρ 150 °C	log ρ 180 °C	log ρ 1000 °C
KTB	N1	⊥	7	7	6	6	6	6	1
Biotitic gneiss		<i>pi</i>	4		3	4		4	
N1, N3		<i>pe</i>	4		3	4		4	
Amphibolite	N3	⊥	6	5	5	5	5	5	1
N4, N8		<i>pi</i>	7		3	4		3	
		<i>pe</i>	7		3	4		4	
$f = 2 \cdot 10^{-1}$ Hz	N4	⊥	7	6	6	6	6	6	2
$pe \leq 39$ MPa		<i>pi</i>	5			4		4	
$pi \leq 36$ MPa		<i>pe</i>	5			4		4	
	N8	⊥	6	6	6	6	6	6	1
		<i>pi</i>	5						
		<i>pe</i>	5						

sample. The measurements indicated that the conductivity of non-pure and non-continuous sulphide rock cannot reach the high values observed *in situ*.

4.2. Graphite

4.2.1. Data from the literature

The presence of conductive graphitic layers at different depths inside the crust was proposed by Ádám (1992b), Ádám *et al.* (1990a,b), Bahr (1991), Banks and Livelybrooks (1994), Brown *et al.* (1992), De Beer *et al.* (1991), Haak *et al.* (1991), Vanyan (1995), and Zhamaletdinov (1994). It should be noted that these field data show very low resistivity values (less than $10 \Omega \cdot m$); otherwise, borehole samples coming from the KTB and studied in the laboratory have not always confirmed the graphite interpretation.

The KTB rocks were very old (middle Palaeozoic age). Their main mineralogical components are graphite, metallic oxides, sulphides, garnets, biotite, sillimanite, muscovite, and amphibolites. The samples were investigated under simulated physical conditions: pressure confined up to a few Gpa; temperature up to 1200 °C; different degree of saturation with more or less salted fluids.

The laboratory results of Duba *et al.* (1994), Glover and Vine (1995), Rauen *et al.* (1994), Rauen and Lastovicková (1995), Rauen and Soffel (1995) indicated intermediate resistivity values ($10^3 \Omega \cdot m$) under simulated *in situ* conditions.

Also, the experiments presented in Marschal *et al.* (1992) on samples coming from surface old rocks (Phanerozoic Kapuskasing uplift, Ontario) came to the same conclusions.

The above laboratory results were due to different conducting minerals (such as oxides and phyllosilicates) scattered inside the saturated resistive bulk. In the sample analysed, the graphite did not have a continuous network and consequently could not produce the high conductivity found in the field. Moreover, the graphitic film was quite unstable: this is because the continuity of graphitic film depends on the past and present geological history of the rock (high temperatures, fluid circulation, low pressures).

The graphite hypothesis is in good agreement with the VHCL, that it is restricted to few areas. In the HCL, graphite is one of the conductive minerals in the layer.

In fact, Jödicke (Volbers *et al.*, 1990) attributed the very high conductivity ($< 5 \Omega \cdot m$) in some restricted areas of Germany (the Münsterlan basin) and Italy (the Calabrian arc) to black shales formation, a metamorphic rock

containing shales and interconnected graphite. The laboratory data of Duba *et al.* (1994) also confirmed that the conductive minerals must be petrographically connected, and that they open up a new path in the global interpretation of the Earth's high conductivity layer.

4.2.2. Data from experiments in the Florence laboratory

The graphite effect of electrical conduction on rock was observed in black shale samples (table III, table IV) in laboratory experiments in Florence. Borehole samples were selected from an area in Italy (Farma, Tuscany) and from one in Switzerland (Alpine Chain).

The following samples from ENEL-FARMA1 borehole were studied: FP (32 m deep), F212 (212 m deep), F268 (268 m deep), and F278 (278 m deep). All samples were carboniferous schists, and FP also contained considerable pyrite elements.

Only small dispersive frequency phenomena were observed, at frequencies which are typical of clay and graphite polarisation, whereas

the temperature effect, that was related to the internal fluid status (marked changes around $T = 100\text{ }^{\circ}\text{C}$), was strong.

The electrical data, interpreted on the basis of mineralogical and petrophysical analyses, indicated that the high conductivity of the rock depended mainly on shaly minerals associated with graphite and sulphide minerals (Losito, 1982).

Three samples from two boreholes in Switzerland were studied: SOM7 (51.5 m deep), very fine-grained and layered at 45° with respect to the axis sample; CH5 and CH5-bis (318 m deep), fine-grained and layered, respectively, parallel with or perpendicular to the axis sample. These samples were impermeable graphitic schists, with varying percentages of metallic and graphitic elements held in a shaly matrix.

Despite the similar appearance of the samples, their resistivities already at room conditions were quite different, and were strictly related to their petrographic structure (see table III). The pressures and the temperature acted on the electrical behaviour of the sample in standard manner. The resistivity differences

Table IV. Chemical composition of some samples studied at the Geophysical Laboratory in Florence. The values are in % wt. (see table III).

Sample	SiO ₂	TiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	CO ₂	FeO	MnO
PUGLIA 1												
N1	0.2		0.6	0.1	36.6	11.2	0.1			49.5		
N2	1.4		0.7	0.1	21.5	29.3	0.1	0.2		46.8		
N3	67.3	0.8	13.6	3.9	2.5	1.1	0.3	2.5	0.1	7.6		
N4	75.0	0.5	8.7	3.8	2.6	1.2	0.2	1.3	0.1	6.2		
KTB												
N1	66.5	0.7	15.8	0.8	1.8	1.6	3.0	2.2	0.2		4.2	0.1
N3	64.1	0.9	16.5	0.5	2.3	1.5	2.1	2.5	0.1		5.7	0.2
N4	51.1	1.6	16.0	2.0	6.6	8.4	3.1	1.0	0.2		7.4	0.2
N8	53.2	1.3	17.1	0.7	5.4	6.8	3.3	1.0	0.2		8.2	0.2
SWISS												
SOM7	55.5	1.1	30.0	3.7					9.4			
CH5	68.1	0.5	22.9	4.0					3.1			

between the two CH5 samples had to be attributed to rock foliation. The very low resistivity of SOM7 was carefully analysed, and constituted a real problem as regards interpretation.

It can be concluded from all the aforesaid data that the high conductivity of these rocks could be due to the fine continuous connection between the clay and the graphitic components, joined to a minor metallic part.

4.3. Fluids

The effect of fluids on the electrical behaviour of rock has been evaluated in several laboratories, by studying samples with different mineralogical and petrographic structures. The main results are summarised here as follows.

4.3.1. Data from the literature

The presence of free water at great depth (up to 12 km) has been observed in boreholes, as reported by Stoll (1994) and Vanyan (1995). Other authors (Gough, 1992; Jones, 1992; Moroz, 1994; Jones and Gough, 1995; Marquis *et al.*, 1995) have proposed the presence of salt fluids to explain the high conductivity found by EM-MT soundings. Glover and Vine (1995) hypothesised from laboratory data that an electrolyte is the prevailing cause of the conductivity in acid wet rocks.

The origins of the fluids could be meteoric phenomena in the presence of porous and/or permeable rocks, the diagenesis of sedimentary basins, or low-grade metamorphic reactions in the subducting oceanic crust (Jones, 1992). These fluids must have large-scale circulation in order to produce the enormous extension of the CLC layer. The areas in which this hypothesis can be applied show different resistivity values with relation to salt-water composition and effective rock porosity. It is sufficient to think that natural salt concentrations can be found up to 60% in weight in some conductive layers (Jones, 1992). We expected to find this salt layer attached to other marine sediments, according to their geochemical evaporite cycle.

Consequently, the saline layer can be associated with carbonatic acid and clay sediments, creating a thick conductive sequence.

4.3.2. Data from experiments in the Florence laboratory

Typical fluid effects on the electrical resistivity of rock were measured in the laboratory (see table III) by studying rock samples coming from the ENEL-LATERA 4 borehole, in a geothermal area of Bolsena (Italy) under simulated physical conditions. The samples were saturated before proceeding with the experiments.

As described in Losito *et al.* (1991a,b), the Rhaetavicula Contorta (RC) limestone (1445 m deep), that has a nodular structure and very low effective porosity (< 0.1% in volume), showed an electrical resistivity that was 100 times higher than the electrical resistivity of leucitic LAVA (765 m deep), which has a homogeneous structure, higher effective porosity (\approx 1% in volume), and salt content. This behaviour was in agreement with the classical Archie's law.

Only thermal and fluid pressure stresses can modify the initial porosity network and, consequently, change the electrical resistivity of rock. The thermo-baric stress effect was measured by effecting a second saturation of the RC sample, which adsorbed 6% of water in volume, and a second thermo-baric cycle, that pointed out resistivity values that were 100 times less than those of the first cycle.

The said electrical responses of saturated rock samples made it possible to conclude that the presence of fluids can be the most important cause of conductive layers in geothermal areas, even if the rock temperatures are not very high (less than 100 °C).

4.4. Phyllosilicates

4.4.1. Data from the literature

Very low resistivity values were measured on areas characterised by sediments having a high percentage of phyllosilicate minerals

(Ádám *et al.*, 1990b; Ádám, 1992a; Jones, 1992; Muschietti, 1993). In these areas two main geological-mineralogical groups rich in phyllosilicates can be found: 1) recent and superficial layers up to several kilometres in thickness; and 2) old layers, up to several kilometres in thickness, derived from feldspar alteration. It can be concluded that the age of the rock is not determinant for the conductivity if the sediment remains at high internal pore fluid pressure, and at not very high temperatures.

Despite the widespread diffusion of phyllosilicates, in general laboratory data obtained under simulated physical conditions as reported in the literature are poor, probably due to difficulties in the mineralogical and petrographical refined analyses, that can currently be made only at present. Among the results of laboratory research, the importance of clay minerals for deep conductivity in the presence of basic wet rocks has been reported by Glover and Vine (1995) (see table II).

4.4.2. Data from experiments in the Florence laboratory

Since 1980 the authors have been carrying out a laboratory study of the electrical behaviour of phyllosilicates (mainly frequency-dispersive phenomena), which are often associated with distortion phenomena. With regard to the HCL, we considered it of interest to select the behaviour of the 3-layer phyllosilicates, such as illite. In fact, these minerals showed a high structural-mineralogical stability, or only minor changes (polytypism) up to 350 °C and several hundred MPa (Leoni *et al.*, 1996). In view of the widespread diffusion of the illite group, we believe that this mineral can be assumed to be a *marker* of the phyllosilicate conductive layer.

Typical electrical behaviour of clay rocks was observed by using samples both from the surface and from the depth in the Pliocene basin of Siena (Italy) at simulated *in situ* conditions. The surface samples were clays (P1-2-3) and sands (S and SP02), and the ENEL-PRESCIANO borehole samples were clays (P78 and P97), 78 and 97 m deep, respectively.

The mineralogical composition of these samples was 83% clay and 17% sand (clay samples) or 20% clay and 80% sand (sand samples).

The effect of pressure on the electrical behaviour of the samples was low, because the rocks had a homogeneous distribution of the hydraulic network, whereas the effect of the temperature was linked to the vapour-liquid balance of the internal fluids. The effect of the frequency and of the current density was also important: in fact, distortion phenomena appeared at $f < 1$ Hz, and were directly proportional to current density (Losito, 1979, 1981, 1982).

Also, some old deep rock samples, that came from the Apulia Carbonatic Platform (Southern Italy) and from the KTB (south-eastern Germany), were analysed under simulated *in situ* conditions.

The samples from the AGIP-PUGLIA1 Italian borehole were Permian permeable quartz sandstones N3 and N4 (6376 and 6378 m, respectively), dolomite with anhydrite veinlets N6 (6072 m deep), and a blend of quartz sandstone and dolomite N2 (6067 m deep). Their electrical behaviour depended on mineralogical and petrographic structures (Muschietti, 1993, 1995): in fact, the sandstone had resistivity values less than the dolomite and quite independent of the pressure. It was interesting to note how the resistivity of these samples was low under physical conditions close to the natural ones (the *in situ* temperature was about 110 °C). Also, the effect of the frequency was important, because the distortion phenomena appeared at typical frequencies for clay ($f < 0.2$ Hz). The mineralogical analysis confirmed a content of clay minerals and illite-group minerals of up to 50% in pounds for the sandstones.

From these measurements it could be concluded that geological history is very important for the electrical conductivity of deep rocks. In fact, two situations were possible with conductive deep and old rocks: the internal pore fluid pressure was able to contrast the lithospheric pressure (Gough, 1992), therefore, hydrated clay minerals could survive the diagenetic mineralogical changes; and/or a low-grade meta-

morphism produced phyllosilicates, such as illite, from alterations of feldspars.

Another group of old rocks consisted of the Ordovician samples from the KTB German borehole. These were biotite gneiss N1 and N3 (3508 and 3567 m deep, respectively), and garnet amphibolites N4 and N8 (3770 and 3775 m, respectively), and indicated the relevance of phyllosilicates in CLC conductivity.

In this case, in fact, the high resistivity ($\rho \approx 10^7 \Omega \cdot \text{m}$) of dry samples was strongly modified by the pore fluid pressure (Lastovicková *et al.*, 1993), that allowed $\rho \approx 10^4 \Omega \cdot \text{m}$, if the sample was rich in phyllosilicates (*i.e.*, muscovite). This value was in perfect agreement with borehole electrical resistivity measurements (Rauen and Lastovicková, 1995).

The presence of phyllosilicates was pointed out also by temperature cycles. In fact, at $T \approx 250^\circ\text{C}$, we had ρ variations, irreversibilities, and anisotropies of the N1-N3 samples that were more marked with respect to the N4-N8 samples.

The non-effect of the Fe chemical element is relevant, because the sample (N4) most rich in Fe has the maximum ρ values. Therefore, the KTB samples could confirm the important role of foliated silicates in the electrical conduction also for old rocks.

In conclusion, by comparing laboratory and field data, we have been able to hypothesise that the conductivity of the HCL may be mainly attributed to the clay component.

5. Conclusions

A critical analysis of the data obtained from extensive bibliographical research has made it possible to focus on present-day knowledge of the high conductive layer (HCL). From this literature it can be concluded that the causes of conductivity may differ, and that they are strictly dependent on the local geology (Nover, 1995).

The key points in this research are:

1) Water content cannot be the sole cause of the low electrical resistivity of rock. In fact, laboratory experiments made on KTB and Swiss samples coming from the HCL showed a

very low hydraulic permeability, one that cannot produce good electrical resistivity, such as $1 \Omega \cdot \text{m}$.

2) Rock melting can produce low resistivities only in limited areas that are affected by very high temperatures. In fact, in the laboratory, rock melting can be attained at temperatures around 1000°C , which are present only in volcanic areas.

3) *In situ* low resistivity has been observed in areas with a low thermal gradient ($\approx 10^\circ\text{C}$ at a depth of 7000 m in the PUGLIA1 borehole; $\approx 110^\circ\text{C}$ at a depth of 4000 m in the KTB borehole) and in uplifting cold layers of tectonic windows (Switzerland and Bavaria).

4) Some laboratory experiments have indicated graphite, with or without oxides, as the cause of high conductivity, if this mineral is organised in a continuous film. This continuity can be attained with high graphite contents, or under very high pressures ($> 100 \text{ Mpa}$) if the graphite content is low. Otherwise, we can find the VHCL also on the surface, where the natural pressures are low and are unable to produce the graphite continuity. Typical areas are in Germany (Haak *et al.*, 1991), the Alps (Ádám *et al.*, 1990a), and in the Calabrian arc (Jödicke, 1992b).

It can be concluded that none of these hypotheses fulfils the required conditions for a thick, wide conductive layer inside the Earth's crust.

We believe that the high electrical conductivity of the crust mainly depends on the presence of 3-layer phyllosilicates (illite-group type). This hypothesis is based on the electrical responses of borehole samples from areas in Italy and other European countries, that have been petrographically analysed.

The hypothesis regarding the illite group is in good agreement with the following petrographical and mineralogical observations. In fact:

1) The mineralogical structure of illite is not altered by temperatures up to $\approx 350^\circ\text{C}$ (Leoni *et al.*, 1996) and by ionic exchange, in view of the absence of inter-layer water (Carobbi, 1975).

2) Illite is the main component of shale, because this mineral can be produced both by de-

cay of feldspars (that form 60% of the Earth's crust), and by diagenesis of marine clay minerals.

Therefore, widespread diffusion of the illite group minerals and their good conductivity make it possible to conclude that this mineral is the conductive marker of the HCL.

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