An integrated application of geological–geophysical methodologies as a cost-efficient tool in improving the estimation of clay deposit potential: Case study from South-Central Sardinia (Italy)

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Abstract

A multidisciplinary study attempting to improve estimation of clay deposit potential was performed using geological and geophysical techniques at Piscina Collusco, S Sardinia, Italy, a test area where a bentonite deposit outcrops. The Very Low Frequency (VLF) Electromagnetic (EM) method, a cost-effective method suitable for detecting lateral electrically resistive host rock/electrically conductive clay deposit contacts, was applied. Geophysical investigation yielded information on the lateral and in-depth continuity of the mineralisation, e.g., geometric features, strike and dip of the mineral body, and the geological–structural features of the area. Test drilling, carried out to calibrate geophysical data, confirmed that the high-conductivity zones are related to the presence of bentonite and that the clay mineral body is developed at depth. Data integration showed that higher-conductivity values are related to the highest clay contents.

Results show that this multidisciplinary approach improves resource estimation at minimum cost, and can be successfully used in mineral exploration in similar geological contexts. This could play an important role in assessing the economic potential of new industrial mineral deposits, and/or in optimising mining in active quarries. Following the interpretation of the integrated data in this case study, resources initially evaluated at 394,000 t, were found to be in the order of 3,786,000 t.

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1. Introduction

One of the most complex issues in mineral exploration is accurately evaluating the effective potential of mineral resources. In order to evaluate the economic potential of new industrial mineral deposits, and/or optimise mining in open quarries, a number of fundamental aspects must be analysed. The chemical–physical characterisation of raw materials may be performed using a number of well-known analytical techniques, such as X-ray Powder Diffraction or X-ray Fluorescence methodologies, as well as technological tests. In addition, geological–structural host rock/deposit relationships have to be considered in modelling the buried mineral body, in order to provide a reliable estimate of resources, closely related to the geometric body itself. To resolve these issues, electrical and elec-
Electromagnetic geophysical methods have been shown to be particularly suitable in investigating conductive bodies (sulphide mineralisation, graphite, clays, etc.) (Keller and Frischknecht, 1966; Parasnis, 1973).

In clay mineral exploration, significant improvement in interpretative models can be obtained using information from geophysical data, which are able to validate and constrain the geological interpretation. The electrical resistivity of clays, generally lower than that of several host lithotypes (Parasnis, 1973), ranges from 1 to 100 $\Omega$m, and that of bentonites from 1 to 10 $\Omega$m, as a function of temperature, temperature coefficient ($\Omega$m/$^\circ$C) and water content (Kaufhold et al., 2003). Consequently, a number of authors have successfully used electrical techniques for locating, mapping, and assessing conductive clay bodies (Sinha, 1980; Sands, 1993) and for in situ quality control of clay materials (Kaufhold et al., 1998). Electromagnetic techniques are also suitable for resolving these issues and are successfully applied in geological contexts displaying high-conductivity contrasts between host and mineralised rocks, e.g., in defining the spatial extent of kaolinite deposits (Ferguson et al., 1999) and in karst geological studies (Steward and Wood, 1990; Guerin and Benderitter, 1995).

The present work presents a cost-effective methodological approach, which can be successfully applied to clay minerals and, more generally, in the field of industrial mineral exploration, contributing to better evaluation of deposit potential. Therefore, this multi-disciplinary study was applied to a test area (Piscina Collusco, Sardinia, Italy), choosing the Very Low Frequency (VLF) Electromagnetic (EM) method due to its high resolution with respect to lateral variations in electrical properties (i.e., conductivity), and its cost-effectiveness. The in-depth and lateral continuity of the clay body was delineated, producing a more accurate and reliable resource estimate.

2. Geological setting and field relationships

As concerns the regional geology of Sardinia, and, in particular, the location and the geological context of the Piscina Collusco deposit, we refer to the paper by Palomba et al. (2006-this volume), in which the detailed geological setting of the island (Fig. 1) and the immediate area where the deposit occurs are shown (Fig. 2b).

2.1. Local geology

The stratigraphic sequence of the investigated area (Marmilla region, Suurgus-Donigula district, S Sardinia) is characterised, from bottom to top, by the following formations (Fig. 1):

1. Paleozoic basement (Río Mularia Unit), mainly made up of grey and black shales, metasandstones.
phyllites and metasiltites (Lower Carboniferous) (Barca et al., 1992; Barca and Eltudds, 1994); 2. Miocene (Aquitanian–Burdigalian) marine sediments, consisting mainly of marls, sandstones and limestones, interlayered with more or less argillaceous arenaceous–marly layers alternating with grey, compact limestones (Cherchi and Montadert, 1982; Cherchi, 1985; Leone et al., 1984; Assorgia et al., 1997).

The study area was affected by Hercynian tectonics (Carmigniani et al., 1986a,b, 1992), yielding folds overprinted by brittle structures (Barca et al., 1992), which were overprinted in turn by Oligocene–Miocene tectonics (Cherchi and Montadert, 1982).

2.2. Mineralisation

In the Piscina Collusco area, assays on a bentonite occurrence had been carried out in the 1970s to determine its economic potential. Although limited amounts of this material were mined and employed in manufacturing industries (Mezzetti and Gorelli, 1978), the deposit was never systematically mined. The deposit is hosted within Aquitanian–Burdigalian sediments and Palaeozoic formations (Fig. 1). The lens-shaped mineralised body outcrops over an area of about 6 ha (~600 × 100 m). At Piscina Collusco, Miocene cover, consisting mainly of limestones and minor marls, discontinuously overlies the bentonite body. The geological–structural context of the investigated area, affected by Hercynian and Cenozoic tectonics, renders the lateral and in-depth development and continuity of the body unforeseeable. In fact, the presence of a clay mineral body below the Miocene sediments is uncertain due to the Fp fault (Fig. 1), while the F3 and possible continuation of the F4 faults, which might have displaced the body, complicate evaluation of its thickness.

The deposit shows a quarry front (Fig. 1) about 100 m wide and 5 to 10 m thick (Fig. 2). From top to bottom, soil (up to 30 cm), a poor altered ash-layer (30 to 80 cm), and a polygenic conglomerate (about 60 cm) overlay the bentonite. The soil, ash-layer, and conglomerate frequently mask the host rock/deposit lateral contacts. Nodules and veinlets of calcite, which in places crosscut the conglomerate and ash-layer, are attributed to re-deposition of carbonates, caused by dissolution of overlapping Miocene marine sediments. At the bottom, about 5 m of the quarry front are masked in some places by stockpiles or stripped material (Fig. 2). The deposit has a N25W strike, probably related to Hercynian tectonics (Carmigniani et al., 1986a,b, 1992), which was subsequently overprinted by Oligocene–Miocene tectonics (Barca et al., 1992).

The original ash-lens, precursor of the investigated bentonite body, is probably associated with explosive events occurred during the Oligocene–Miocene volcanic cycle (OMC) (Maccioni et al., 1998). The OMC (32 to 13 Ma), which has a calc-alkaline latent character and is related to a NW or NWW dipping subduction zone along the paleo-European margin (Álvarez, 1972), consists of recurrent lava (andesites, minor basalts, and dacites) from 32 to 26 Ma in age, and pyroclastic (rhyolites and dacites) suites from 23 to 13 Ma in age. The origin of the investigated altered ash-lens can be temporally attributed to the latter volcanic
events, which yielded important pyroclastic eruptions consisting mainly of ash-, pumice-flows, falls and minor lava flows.

According to Maccioni et al. (1995, 1998), bentonites occur in two different deposit types in Sardinia: as in situ-altered deposits (Type I), occurring as mineral bodies interlayered within very thick subaerial rhyolitic–rhyodacitic pyroclastic sequences, and in fall-out deposits, single altered ash-lenses (Type II) far from the vents, widespread in large areas of central-southern Sardinia. These ash-lenses are generally interlayered within the Miocene sedimentary sequence, in places overlying Jurassic limestones. More rarely, they are hosted within Paleozoic formations (Carcangiu et al., 1994). The bentonitisation of Type II deposits took place in fresh water, in fluvial–lacustrine and/or marshy environments, as suggested by the presence of textures, plant relics and gradation structures typical of these transitional environments. Alteration of the ash-lenses was enhanced by permanence in subaqueous environments, the internal structural features of bodies, the permeability of the original unwelded ash-lenses, and their compositional characteristics.

In particular, the fall-out deposit of Piscina Collusco originated in a fluvial–lacustrine environment, indicated by the presence of several internal textural features, the superimposed polygenic conglomerate, and the spherical shape of the clasts. Deposition in a marine environment may be excluded due to the absence of fossils and marine sedimentation structures (e.g., graded bedding, etc.). The vertical sequence (Fig. 2) can be explained as follows: 1) deposition of a transported thick ash-lens, originating during an important explosive eruption; 2) deposition of the conglomerate in a fluvial–lacustrine environment during a short period of magmatic quiescence; 3) deposition of a thin layer of new volcanic ash-material, possibly originating from a less important eruptive event, in a subaerial or partially subaqueous environment, as is suggested by its poor alteration.

3. Geophysical investigation

The geophysical investigation was carried out using the VLF-EM technique, a quick, accurate method for detecting the presence of electrically conductive submerged bodies. Therefore, even in consideration of the absence of man-made EM induced fields in the survey area, this method was chosen, as the conductive clay deposit is hosted in more electrically resistive Paleozoic and Miocene rocks. Preliminary tests performed in the area confirmed the high-conductivity contrast between host rocks and bentonite, being a prerequisite for the application of the VLF technique.

The operational conditions of the VLF technique are well known (Paterson and Ronka, 1971; Phillips and Richards, 1975). The exploration target of this technique is to detect buried conductors using a portable instrument (a VLF receiver), which provides a measure of the in-phase (real) and quadrature (imaginary) components of the vertical secondary magnetic field relative to the horizontal primary field. The VLF technique utilises remote radio transmitters employed in submarine communications in the 15–30 kHz frequency range as sources.

VLF observations were made using a Geonics EM-16 VLF receiver. The GBR (16.0 kHz) radio transmitter in Rugby (U.K.) was employed as a source. For optimum results, the E-W direction of profiles was chosen normal to the transmitter azimuth and almost normal to the observed trend of bentonite occurrence. Measurements of in-phase and quadrature components were made with stations spaced 10 m apart.

Fig. 3 shows in-phase and quadrature component curves, as well as in-phase component Fraser (1969) filtered data. In-phase component raw data show significant anomalies extending towards the eastern sectors, while no significant anomalies are generally observed in the quadrature component, except on the western side of the P4 and P5 profiles. In any case, the imaginary component is more suitable for providing information on the electrical conductivity of shallow geological formations (overburden). Therefore, considering that the target of this work is to investigate deeper conductive layers and structures, only the in-phase component was taken into account. To facilitate interpretation of anomalies with a view to obtaining useful diagnostic information, Fraser (1969) and Karous and Hjelt (1983) filters were applied on the real component data. The Fraser (1969) filtering procedure converts the zero crossings, which occur above the conductive body, into minima peaks, which represent the high-conductivity zones. The Karous–Hjelt filter was also applied to the in-phase component data to obtain current density pseudosections along the profiles crossing the clay deposit. The pseudosections (Fig. 4a) show that the high-conductivity zones, obtained by the Fraser filtering (grey lines in Fig. 3), continue at least 50 m in depth, and probably up to 100 m.

Geophysical interpretative sections (Fig. 4b) outline the presence of a buried conductive body, generally

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1 The GBR radio transmitter in Rugby was shutdown in April 2003.
fragmented but developing eastward and in depth. The narrow subvertical high-gradient zones, between conductive and resistive zones, can be attributed to faults and/or fractures, confirming field observations (Fig. F3).

4. Sampling and methods

Chemical and mineralogical features and physical–chemical properties were determined on samples collected.
Fig. 4. (a) Current density pseudosections for P1-P5 profiles, from Kanou and Hjelt (1983) filtered data. Lighter and darker grey tones, respectively, correspond to more resistive and conductive zones. (b) Geophysical interpretative sections.
at the surface and from a drill core located in a high-conductivity zone, displaying lateral and vertical continuity.

Surface sampling was carried out on the quarry front to evaluate lateral and vertical chemical-mineralogical variations of the outcropping part of the bentonite body. The N25W quarry front was sampled along three vertical lines (Ca1–Ca2–Ca3), horizontally spaced 30 m apart. Sample points were vertically spaced 0.75 m apart (Fig. 2). A representative sample (Cm), obtained by mixing about 50 kg of material stripped from channels Ch1, 2, 3 and 4 (Fig. 2), was also studied.

A 20 m test drilling was carried out to calibrate geophysical data and compare the quality of surface and deeper materials. The drilling was strategically located on the P4 profile, where a selected high-conductivity zone displayed lateral and vertical continuity (Fig. 4a, b). The materials collected along the core, and vertically spaced 0.5 m apart, were analysed to determine the mineralogical association and physical–chemical properties and to point out possible compositional variations with respect to samples collected in the quarry front.

The collected materials had been previously ground and homogenised. Mineralogical and chemical studies were performed on whole-rock samples using the following analytical methods:

1. X-ray Powder Diffraction (XRPD) data were collected using a Rigaku Geigerflex apparatus, using Cu-Kα radiation at 30 kV and 30 mA. Mineral identification was carried out by search-match software, using the JCPDS Data Base (1985). Quantitative data, collected for core samples, were acquired using Cu-Kα radiation at 40 kV and 35 mA. Methods involving intensity measurement for mixtures of two or more components, differing in absorption coefficient, were used to quantify the minerals identified (Mirkin, 1964).

2. X-ray Fluorescence (XRF) data were collected using a Philips PW 1400 spectrometer, equipped with a Rh tube, operating at 30 kV and 60 mA. The “α factors” method was applied to correct matrix effects using an NRLXRF program on standard samples. LOI (loss of ignition) was determined by heating samples to 900 °C for 2 h.

3. Physical–chemical tests, including sand, carbonaceous contents, Cation Exchange Capacity (CEC),

Table 1
Chemical (wt.%) and mineralogical analyses and technological tests of bentonite materials

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<tr>
<th>Chemistry</th>
<th>SiO₂</th>
<th>TiO₂</th>
<th>Al₂O₃</th>
<th>Fe₂O₃</th>
<th>MnO</th>
<th>MgO</th>
<th>CaO</th>
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<td>3.04</td>
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<td>3.63</td>
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</table>
| Cal 24    | 56.36| 0.87 | 16.08 | 7.98  | 0.05| 3.76| 3.72| 0.52 | 0.53| 0.08 | 10.05| 100.00| *  
| Cal 25    | 50.27| 0.84 | 14.60 | 8.54  | 0.07| 3.37| 8.65| 0.50 | 0.62| 0.14 | 12.39| 99.99 |
| Cal 26    | 59.68| 0.81 | 15.33 | 7.24  | 0.02| 3.68| 4.25| 0.43 | 0.42| 0.13 | 8.01| 100.00| *  

**Total iron as Fe₂O₃, Sm=smectite minerals, Pl=plagioclases, Qz=quartz, Kf=potassium feldspars, Cr=crystobalite, Il=illite, Go=goethite.

*Main minerals (60<wt.%<100), * minor minerals (10<wt.%<60), *trace minerals (<wt.%), Sand and C (total carbonates) expressed as wt.%, CEC (Cation Exchange Capacity) expressed as meq/100g.
Liquid limit (LL) and Swelling index were determined on whole-rock samples according to the procedures indicated in the CNR-UNI 10014 (1964), and CNR-UNI 6716 (1970) Standard Normatives. In particular:
- sand amount (wt.%) was determined by sieving at 75 μm;
- carbonate content (wt.%) was determined using a calcimeter;
- CEC was determined by the complexometric titration method, based on the saturation of clay by Mg²⁺ ions in the presence of an excess of EDTA and titration of this excess using a Mg²⁺ solution;
- swelling index and the LL were determined for the Cm sample only. It was doped by adding, at room temperature, 2.5 to 3.0 wt.% of Na₂CO₃ to 400 g of finely ground material, previously dried in an oven at 105 °C, and sieved at 150 μm. The mixture was homogenised, dried, and left standing for 24 h. The activated material was re-ground and sieved at 75 μm. Swelling was calculated by adding 2 g of material to 100 ml of distilled water after 2-h hydration. LL was calculated on 100 g of material using the Casagrande method (CNR-UNI Standard Normative 10014, 1964).

5. Results

5.1. Mineralogy of quarry samples

The bentonite samples consist principally of smectite minerals, plagioclases, and minor quartz, which occur in different proportions and associations (Table 1). Potassium feldspars, calcite, and goethite occur sporadically; the latter two minerals were only detected at upper levels, near the limestone/bentonite contacts, and in areas where oxidation was particularly intense. Mineral distribution shows no evident horizontal zoning, whereas appreciable vertical zoning, characterised by a decrease in plagioclase and quartz contents from top to bottom of the body, is observed. Smectite content gradually increases with depth, from about 60 wt.% in the samples located just below the overburden, to 90 to 100 wt.%. Smectite content, quantitatively determined on the Cm sample, is about 90 ± 7 wt.%.

5.2. Mineralogy of core samples

Test drilling confirmed that the high-conductivity zone (Fig. 4a, b) is closely related to the presence of bentonite, which develops at depth. The reconstructed schematic stratigraphic sequence (Fig. 5) shows that 4 m of Miocene sediments overlie 16 m of bentonite material. The bentonite consists of three different coloured layers, probably in relation with different depositional volcanic episodes but closely related in time.

The Miocene cover (Fig. 5) is mainly composed of calcareous rocks, which are principally made up of calcite and quartz, along with and minor smectite and plagioclases. Quantitative evaluations show that smectite content in calcareous rocks ranges from 5 to 10 wt.%.

Although minerals occur in different proportions and associations, the qualitative mineralogy of the core bentonite samples is similar to that described in Section 5.1. Vertical variation in smectite content was estimated from top to bottom (spider plot of Fig. 5). In the hazel-brown layer (−4 to −8 m), smectite content ranges from 35 to 85 wt.% (average content: 61 wt.%). The brown layer (−8 to −10.7 m) shows a general increase.

![Fig. 5. Reconstructed schematic stratigraphic sequence of the drilled area and spider plot of smectite content, from XRD data.](image-url)
in smectite content (60 to 95 wt.%, average: 86 wt.%) with respect to the upper layer. The lowest smectite content corresponds to very thin levels (a few mm thick), occasionally crosscutting the hazel-brown and brown layers at different depths. In these levels, residual minerals like calcite, plagioclases and quartz accumulated. Therefore, average smectite content in these two upper layers has to be considered decidedly higher than the calculated averages. The grey layer (~10.7 to ~20 m), where levels bearing residual minerals are absent, shows a further increase in smectite content (80 to 100 wt.%, average: 90 wt.%) with respect to the two upper layers.

5.3. Chemical composition

Chemical analyses show that the surface materials are homogeneous in composition (Table 1). Silica slightly decreases from top to bottom, consistent with the vertical mineral zoning characterised by residual mineral depletion in the lower part of the bentonite. CaO and MgO contents (3 wt.%<CaO<9 wt.%; 3.3 wt.%<MgO<3.9 wt.%), compared to the low Na₂O content (0.4 to 0.8 wt.%) and the absence of other Mg-bearing minerals, suggest that Ca and Mg are the main interlayer cations in smectites.

Iron, calculated as total Fe₂O₃ (7 to 10 wt.% (Droop, 1987), rarely forms proper mineral phases (goethite) and generally occurs in the mixing of different amorphous oxides originating from weathering alteration phenomena.

5.4. Physical–chemical properties

Sand and total carbonate contents in samples collected from the quarry front range from 3 to 11.5 wt.% and from 3.75 to 9.5 wt.%, respectively (Table 1). The sand-rich fraction generally occurs in the upper part of the quarry front, while carbonate-rich samples contain nodules and veinlets of Miocene carbonate concretions. The Cation Exchange Capacity (CEC) ranges from 41 to 60 meq/100 g. Swelling volume and LL carried out on the representative sample, are respectively 16 cc and 320 wt.%. These values are not typical for high-quality materials, but they fall within the required limits (50 to 70 meq/100 g for CEC, 320 to 350 wt.% for LL, and 20 cc for swelling) of a number of industrial bentonite products (Passino, 1974; Cincotti et al., 2000).

Fig. 6. Surface sketch map of the deposit showing the location of the most important structural features after integrated analysis of geological and geophysical data.
Physical–chemical tests, performed on three representative samples collected from the core, show that sand and total carbonate contents are respectively 3.5 and 4.0 wt.% in the hazel brown bentonite but are absent in the brown and grey layers. CEC gradually increases from top to bottom of the deposit: respectively 55, 70, and 95 meq/100 g in the hazel brown, brown, and grey layers.

In conclusion, although each bentonite consumer has his own specifications and special demands, integrated analysis of mineralogical–chemical and technological data confirm that most samples, including the representative one, fell within the specifications of products for various industrial uses (Passino, 1974; Cincotti et al., 2000; CNR-UNI Standard Normatives 10014, 1964, 6716, 1970). These materials are suitable for several industrial uses especially for fuller’s earth, drilling mud, animal bedding and food, cement, mortar and aggregates.

6. Integrated analysis of geological–geophysical data

Integration of geological–geophysical and drilling data yields detailed information on the geological and structural features of the area, e.g., continuation of the F4 fault through Miocene terrain (Fig. 6). Moreover, geological/structural relationships between host rocks and the deposit have been delineated both on the surface and at various depths, also showing the complex geometric features of the buried parts of the bentonite body. This information is of great importance both for optimising a drilling program and planning eventual exploitation, circumscribing sectors of real interest and keeping environmental damage to a minimum.

Fig. 7. Detailed analysis of geological–structural relationships between host rocks and bentonite deposit along the P4 profile. (a) Shallow geology; (b) current density pseudosection: lighter grey tones: resistive zones, darker grey tones: conductive zones; (c) interpretative geophysical section; (d) interpretative geological section.
point out the development and variation in the geometric features of the deposit from N to S of the mineralised area, two representative sections were selected. Data and related interpretation for the P4 and P1 profiles are shown in Figs. 7 and 8.

Along the P4 profile, the pseudosection (Fig. 7b) shows three main conductive zones, outlined in the interpretative geophysical section (Fig. 7c). The western conductive zone corresponds to the outcropping part of the body (Fig. 7a). Integrated analysis of data (Fig. 7d) revealed vertical and lateral continuation of the bentonite deposit towards the eastern sector, where a more extensive part of the buried bentonite body was localised. The resistive zone in the western part of the profile (Fig. 7d) has been interpreted as the Paleozoic basement, as supported by field evidence (Fp fault, Miocene single lens overlying Paleozoic formations). Geological-structural field observations also suggest that the eastward resistive zones, with respect to the main fault Fp, can be interpreted as Miocene sediments. The low-conductivity zone, extending from about 280 to 340 m along the profile within the main conductive body, could refer either to a poorly altered part of the body or to Miocene sediments.

The pseudosection in Fig. 8b shows two extensive conductive zones and a narrow conductive subvertical zone at about 250 m along the profile. The extensive conductive zones (Fig. 8c) can be attributed to the presence of bentonite (Fig. 8d). There is a correlation between the western conductive zone and the outcropping body (Fig. 8a). The eastern conductive body may be related to the presence of a buried part of the mineralisation. The narrow subvertical high-gradient zone, in the central part of the geological interpretative section, is attributed to continuation of the main fault in depth (Fp in Fig. 1).

As a whole, integrated analysis of data shows that the geological features of the investigated area are
compatible with a horst-graben system of Hercynian age, successively overprinted by Oligocene–Miocene tectonics, in agreement with previous studies performed on nearby areas (Cherchi and Montadert, 1982; Carmigniani et al., 1992).

High-conductivity zones are closely related to the presence of the clay mineral body, the deposition of which was mainly controlled structurally or paleomorphologically. The clay mineral body, developed at least 50 m in depth, is generally fragmented and occurs either in the form of filling-up of grabens (zones limited by faults and fractures) or as single pockets, which could be related to different paleoenvironmental conditions (heteropic facies, paleo-

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**Fig. 9.** (a) Current density distribution map, from Karous-Hjelt (Karous and Hjelt, 1983) filtered data, at a depth of 30 m below the topographic surface. Lighter grey tones: resistive zones, darker grey tones: conductive zones; (b) development of the conductive body; (c) interpretative geological sketch map.
channels, and paleo-morphologies in the transitional deposition environment).

The structural features of the area and information about the areal extent of the clay mineral body at different depths can also be obtained by interpolating VLF data for each profile. The development of the conductive body at a depth of 30 m below the surface, a limit chosen as compatible with eventual mining, was reconstructed using Karous-Hjelt filtered data, contoured to obtain the current density distribution map (Fig. 9a). The zone, which shows high-current density, is related to a good conductor (Fig. 9b). Fig. 9c shows the relative interpretative geological map. This representation provides useful information for mapping the lateral and in-depth continuity of the clay mineral body, which can be useful for optimising drilling position and/or mining.

7. Discussion and conclusions

Interpretation of integrated experimental data suggests that this methodological approach can be successfully used for mineral exploration in geological contexts where host and mineralised rocks show high-conductivity contrast. In clay mineral exploration, where such contrasts are expected, this approach can substantially contribute to a better evaluation of the economic potential of deposits. In fact, the location, lateral continuity and in-depth development of mineral targets, as well as the geological–structural features of host areas, can be accurately defined using these integrated techniques. The conductivity contrast between clay deposits and host media (rocks), in absence of man-induced perturbations, leads us to conclude that the VLF-EM is a powerful, quick, and a cost-effective mineral exploration and exploitation method, which can also be considered the best technique in equivalent geological situations. VLF-EM data also provide useful information on the in-depth distribution of the current density, and hence on the spatial arrangement of buried conductive bodies. Qualitative information regarding the conductor can also be deduced, since the high-current density values are in relation with good conductive bodies. In this case study, integrated geological–geophysical data, supported by the study of the physical–chemical features of the materials, indicate that higher-conductivity zones correspond to the most argillised zones. Evaluation of the resources in the investigated deposit significantly improved with respect to the preliminary evaluation based only on acquired surface geological data. In fact, based only on surface data, resources were estimated at 394,000 t, considering 6 ha (outcropping mineralised area) × 5 m (thickness) × 2.19 g/cm³ (calculated specific weight) × 0.6 (prudential factor). The integrated interpretation of data yielded an estimate of resources, to a depth of 30 m, of at least 3,786,000 t, considering about 14.4 ha (calculated mineralised area) × 20 m thickness (bearing in mind that Karous-Hjelt filtering provides information starting from 10 m in depth) × 2.19 g/cm³ (calculated specific weight) × 0.6 (prudential factor). This calculation does not take into consideration zones which are difficult to interpret, i.e., low-conductivity zones, which could refer either to a poorly altered part of the clay body or to Miocene rocks. In these areas, direct investigations need to be carried out for a better estimation of resources. In any case, the methodological approach proposed in this study provides significant improvements in the interpretative model, effectively delineating sectors of greatest interest.

Despite being a secondary target, specific conclusions lead to the definition of Piscina Collusco as an economic-grade resource, considering: 1) the good quality of materials; 2) abundant resources; 3) absent or thin overburden; 4) proximity to the harbour in Cagliari (about 50 km from the deposit) and road conditions. Project feasibility involves a reserve estimate, evaluated on the basis of the resource estimate. In this phase, specific legal and economic criteria (environmental constraints, mining plan, mine production rate, operating and capital costs) must be considered, but these issues fall beyond the objectives of this work.

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