Basic Guidelines for Prospecting and Technological Assessment of Clays for the Ceramic Industry. Part 2

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Abstract: Clays are irreplaceable raw materials for ceramic processing. The availability of clay deposits of suitable quality and quantity is an important competitive factor and a key issue for the economic sustainability of ceramic production. The identification of adequate sources of clay materials is an important issue that requires an appropriate methodological approach. In the form of simple guidelines, this articles reports on how to conduct clay prospecting and evaluate the technological properties of raw materials. The first part described the deposits of different types of ceramic clays, illustrating their origin, composition and geological criteria in the prospection. This second part introduces the technological evaluation of clay materials and describes the four steps to follow in clay prospecting in detail.

Keywords: ball clay, clay deposit, clay prospection, kaolin, technological properties

1. Introduction

This article introduces the basics of prospecting and technological assessment of clays for the ceramic industry. The goal is to summarize simple elements as a sort of guideline to help research on a raw material, focusing on clays that are essential for any valuable ceramic production. For this purpose, these guidelines have been divided into two papers: the first part (concerning the various types of ceramic clays, their origin, composition, and geological criteria in the prospection) has already been published [1]. The present paper illustrates the basics of technological assessment and prospection for ceramic clays.

2. Technological assessment of clay materials

Laboratory controls are very important at every stage of clay deposit exploration. In fact, on-site observations are sometimes not enough to identify the real quality of raw materials and to set the geological prospecting phases correctly. Although laboratory analyses are always considered a significant cost factor, they can be really helpful to prevent serious problems that may only become apparent during ceramic production. It is always strongly suggested to set up a simple technological laboratory (e.g., equipment for physical tests, such as firing, particle size, and plasticity analysis) near the main raw material deposits in use or near the production site. To avoid delays, this unit must be separated from the laboratory that is usually available in the ceramic factory for production controls. An example that illustrates the importance of laboratory controls is the case where shallow marine deposits transitioning to continental episodes are present in a sedimentary sequence. In outcrop, they can be similar in color and texture and therefore difficult to distinguish, even if they look completely different after firing (Figure 1). Simple technological tests are recommended for clay materials. The relevant standard methods are summarized in Table 1 [2], [3], [4], [5].

The key facts at a glance

- This article is part two of two papers on the identification of adequate sources of clay materials in form of guidelines on how to conduct clay prospecting and evaluate the technological properties of raw materials.
- Part one introduced the deposits of different types of ceramic clays.
- The second part describes the basics of clay prospecting in four steps, starting with the selection of an area for prospecting, through the search for potential mineral deposits, their investigation and evaluation, and finally a detailed investigation of the deposits.

3. International standards of mineral exploration

In the last years the CRIRSCO international organization (Committee for Mineral

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Reserves International Reporting Standards) made important efforts to promote high-quality standards of exploration and mineral deposit estimates. A detailed document called the "International Reporting Template" for the public reporting of exploration targets and exploration results on mineral resources and reserves was drawn up in November 2019; it is available on the CRIRSCO website [18]. This document includes general guidelines for different mineral categories, including industrial minerals (Figure 2).

CRIRSCO defines mineral resources as "a concentration or occurrence of solid material of economic interest" for eventual economic extraction. Mineral resources are subdivided, categorized in order of increasing geological confidence as "inferred", "indicated", and "measured". A mineral resource may be considered an "inferred resource" if estimated on the basis of limited geological evidence and sampling, or an "indicated mineral resource" if geological exploration shows quantity and quality with sufficient detail to consider a mineral deposit economic. If "detailed and reliable exploration, sampling, and testing" is sufficient to reach a final evaluation and to permit a detailed mining plan, it can be defined as a "measured mineral resource". The prospecting work permits considering a mineral resource as a probable and proved mineral reserve when the economically mineable part of it is defined with accuracy. Other interesting guidelines for mineral exploration are available on the PERC website (Pan-European Reserves and Resources Reporting Commit-

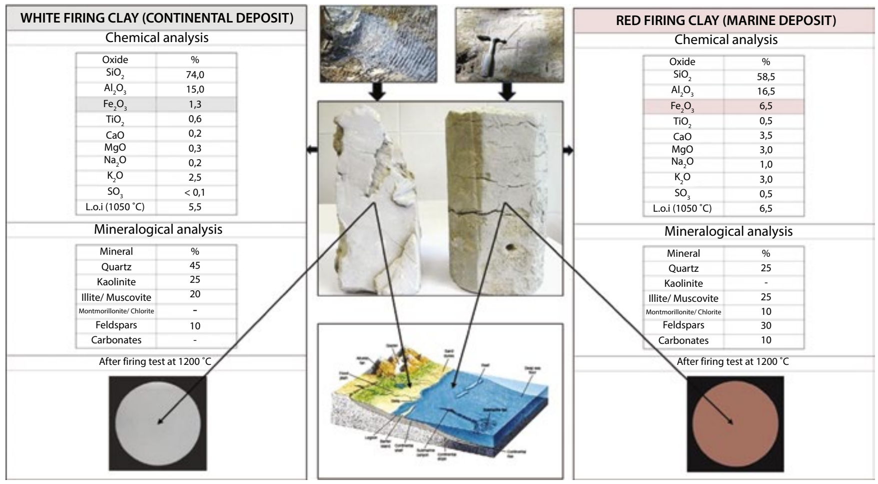

Figure 1 Differences between clays collected in the same area (northern Italy) but with different origin. (© Bertolotti)

Table 1 Standard test methods for ceramic clay materials. (© Dondi)

Property	Standard	Reference
Sampling Ceramic Whiteware Clays	ASTM C322-09(2018)	[6]
Chemical Analysis of Ceramic Whiteware Clays	ASTM C323-56(2016)	[7]
Free Moisture in Ceramic Whiteware Clays	ASTM C324-01(2014)	[8]
Wet Sieve Analysis of Ceramic Whiteware Clays	ASTM C325-07(2014)	[9]
Drying and Firing Shrinkages of Ceramic Whiteware Clays	ASTM C326-09(2018)	[10]
Specific Gravity of Fired Ceramic Whiteware Materials	ASTM C329-88(2020)	[11]
Water Absorption and Associated Properties	ASTM C373-18(2018)	[12]
Modulus of Rupture of Unfired Clays	ASTM C689-09(2019)	[13]
Filtration Rate of Ceramic Whiteware Clays	ASTM C866-11(2016)	[14]
Methylene Blue Index of Clay	ASTM C837-09(2019)	[15]
Breaking Strength and Modulus of Rupture of Ceramic Tiles	ASTM C1505-15(2015)	[16]
Liquid Limit, Plastic Limit, and Plasticity Index	ASTM D4318-17e1	[17]

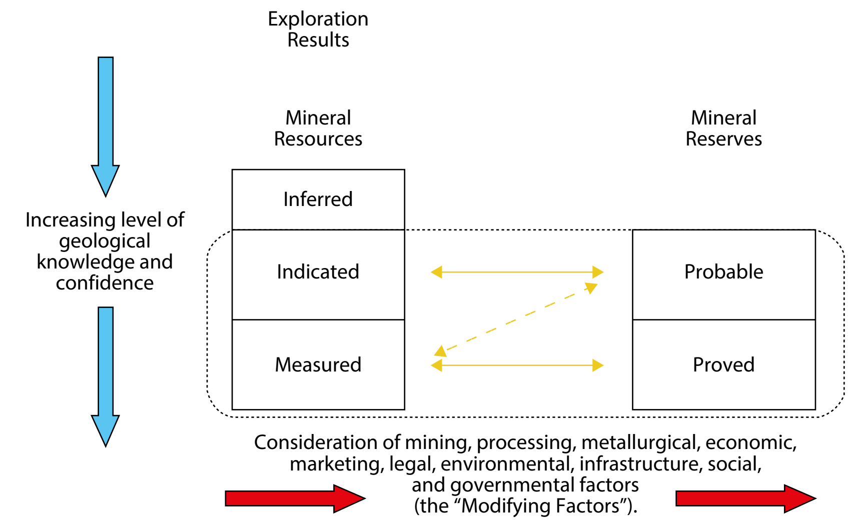

Figure 2 General relationship between exploration results, mineral resources, and mineral reserves [18]. (© Bertolotti)

tee): Standard for Reporting of Exploration Results, Mineral Resources and Mineral Reserves [19].

4. Basics of clay prospecting: the four steps

Focusing on clay deposits, for a correct evaluation it is important to organize the prospecting work in different steps, starting with cheaper exploration methods and techniques and leaving more expensive ones to the detailed final phases.

The following steps provide an increasing level of geological knowledge about each deposit and help to transform a possible mineral resource into a probable and approved mineral reserve as defined by PERC and CRIRSCO standards. Prospecting costs must always be compatible with the estimated size of the deposit and future exploitation costs. In the case of raw materials with low value per ton, such as red firing clays, prospection must evaluate not only the quality of the deposit but also its distance from the production plant and possible mining costs. On the contrary, raw materials with higher value, such as clays for white firing products and kaolins, may generate higher exploration, excavation and transportation costs. In Figure 3 the most important parameters required for prospecting clays for white firing ceramics are indicated.

Following in part the guidelines in the BRGM "Guide de prospection des matériaux de carriére" [20] and on the basis of long experience in clay research [21], the main steps of prospecting operations are (Figure 4):

1. Selection of the area for prospecting
2. Research of potential mineral deposit (strategic prospecting)
3. Study and evaluation of mineral deposit (tactical prospecting)
4. Final detailed study.

4.1 Step 1: Selection of the area for prospecting

After a preliminary localization of the area as a first step, it is important to find all available geological maps and studies previously made in the area and to collect documentation about land registry areas to confirm the possibility of future exploitation works. Before starting any prospecting activity, it is also important to be clear about all the elements that influence the final exploitation costs, such as local laws and duties, and costs for the required documents, access conditions to the area, and water availability.

4.2 Step 2: Research of potential mineral deposits

Study of existing documentation

This preliminary phase helps us to understand whether there are any interesting elements that confirm the presence of a mineral deposit and whether more detailed studies will be required to improve the geological knowledge of the area. The study of all geological work and documents regarding previous mining activity made in the area will help to identify the outcrops that are still available. The collection of topographic maps at different scales will be necessary to prepare the subsequent prospecting work. Digital georeferenced models already available will be very helpful in combination with satellite maps such as Google Earth or other more detailed images available.

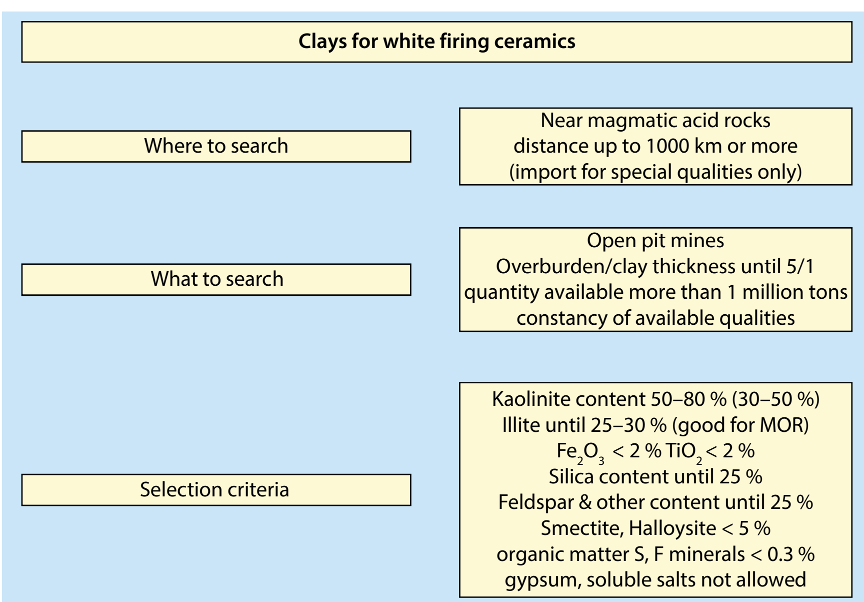

Figure 3 Most important parameters for prospecting high-quality clays [20]. (© Bertolotti)

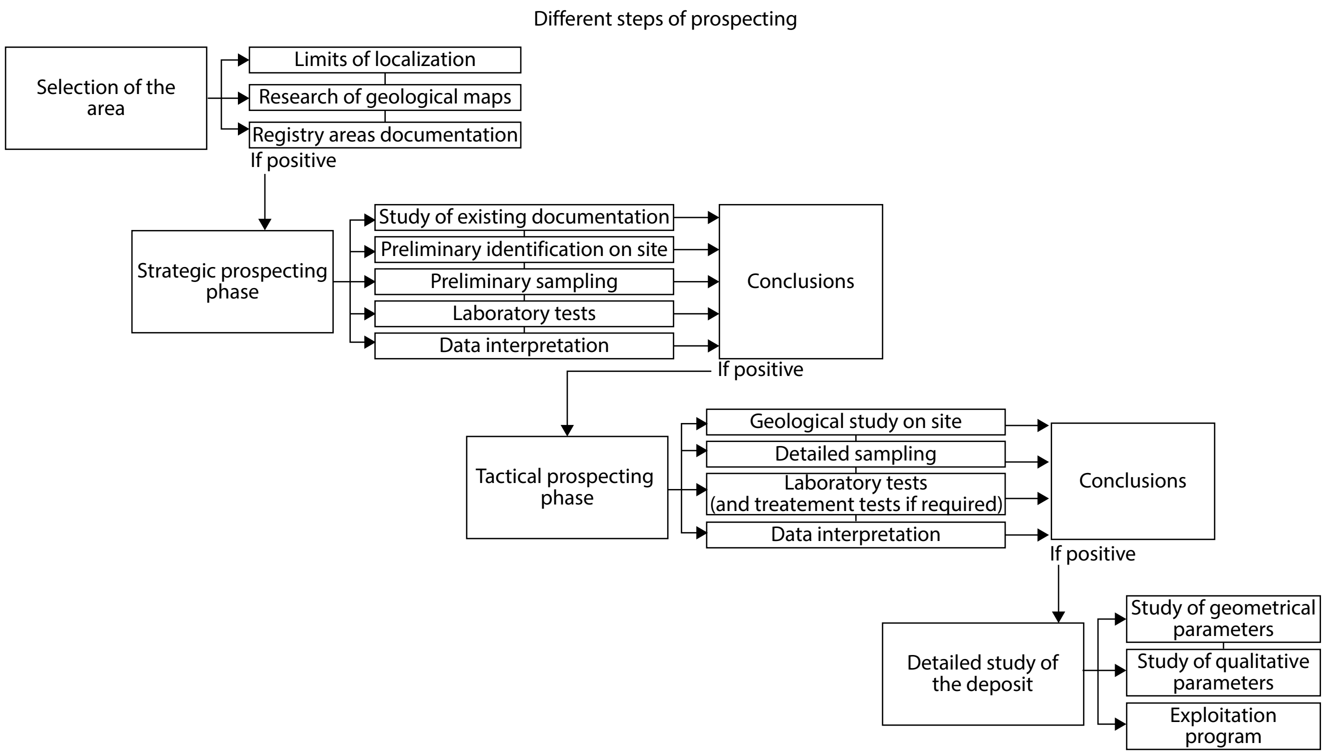

Figure 4 The main steps in clay prospecting. (© Bertolotti)

Preliminary identification on site

A preliminary overview on site of potential areas will permit to identify and study all available outcrops.

Preliminary sampling

A first set of surface samples will be collected for testing using prospecting techniques according to the budget that is available for research. Considering the high costs of core drilling equipment in preliminary phases, it is suggested to use cheaper techniques only. In the absence of evident clay outcrops, a manual auger will be very helpful to collect representative samples a few meters under soil levels (Figure 5a and Figure 5b). An auger with a motorized engine will help to reach deeper than 10 meters in soft sediments such as clay and sand (Figure 5c).

Another cheap and helpful system to collect preliminary samples can be used to excavate trenches with the help of a hydraulic excavator (Figure 6). In this case, it is possible to reach 5.0–5.5 m depth, and trench sections can also give a preliminary view of the first meters of stratigraphy.

In both cases, it is important to take samples representative of a layer thickness of at least 0.3–0.5 m to obtain grades that simulate future mining quality. About 3–5 kg of each sample can be enough, and these must be divided into two parts: one for laboratory tests and the other to be stored as an archive and saved until the end of the prospecting work. During the collection it is very important to record the GPS coordinates and make a short description of the outcrops and the raw appearance of the samples to ensure that their position will be easily found in the future.

Figure 5 Preliminary clay sampling: manual auger (A, B) and sampling with a motorized auger (C). (© Bertolotti)

Figure 6 Trench execution with hydraulic excavation for preliminary clay sampling. (© Bertolotti)

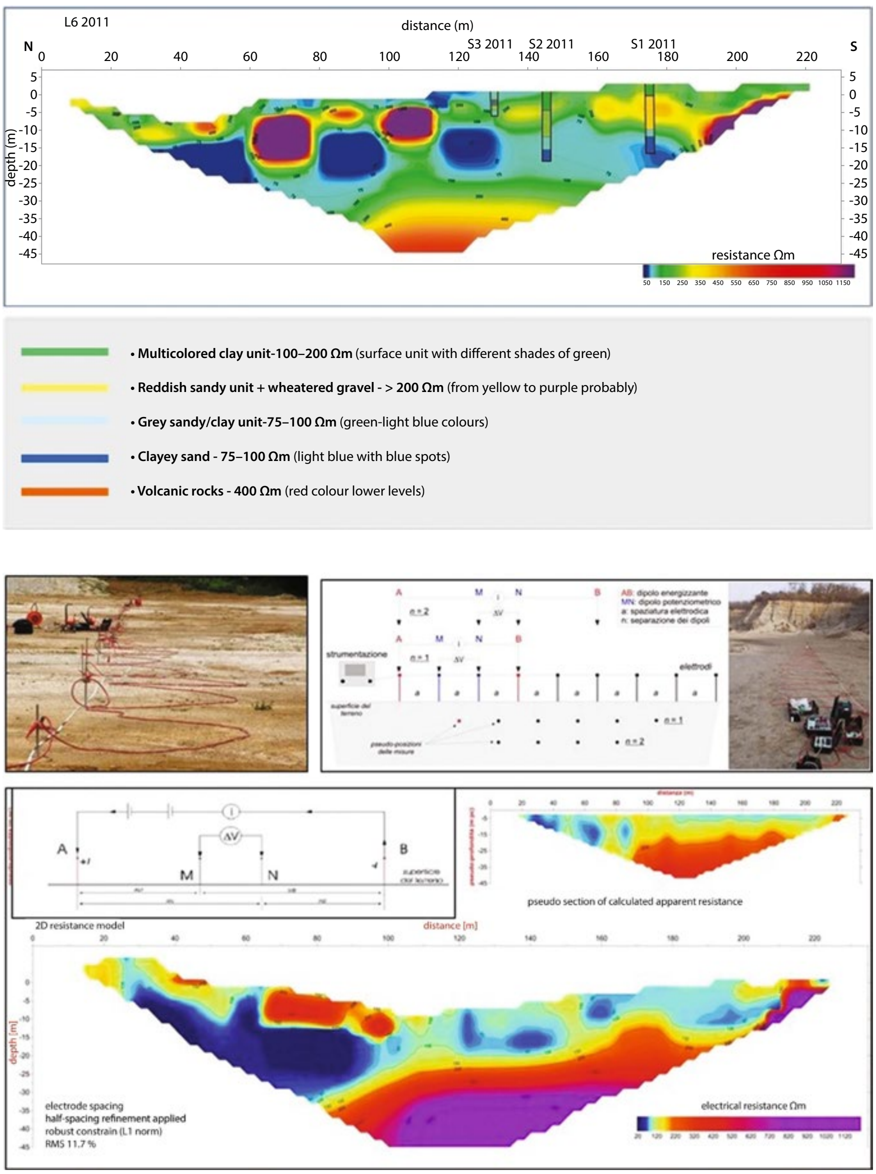

Figure 7 Example of a geoelectric prospection in an Italian clay mine and electrostratigraphic section with geological interpretation from correlation of geophysical data and geological survey. (© Bertolotti)

Test and laboratory analyses

Tests and laboratory analyses are fundamental to understanding the average quality of the deposit. In this phase, it is also important to identify the possible presence of elements that could negatively influence the final quality during mining. In the laboratory it is important to carry out the following tests:

- XRF chemical analysis with loss of ignition (if available, XRD mineralogical analysis)
- Evaluation of carbonate content (if XRF is not available in this phase)
- Particle size analysis
- Plasticity evaluation
- Firing tests in a muffle kiln.

All these data must be recorded on a datasheet with date of collection, identification code, and geographical coordinates.

Data interpretation

The preliminary strategic prospecting phase will help to reach the following results:

- A database of all available bibliographic data to clarify the geological context and indexes of mineral presence
- A preliminary lithological map of the prospected area
- Preliminary information on the homogeneity and/or variability of raw materials and a preliminary hypothesis of deposit geometry
- Information about the characteristics of prospected material made by direct observations and laboratory tests.

Conclusions

In conclusion, the strategic prospecting phase could lead to the following cases. If the outcrops show limited size without continuity in space, they cannot represent an interesting deposit. Further prospecting work will be considered only if the laboratory tests indicate a promising quality. If they show limited size with continuity in space and without an overlying thick overburden, further prospecting is required to confirm whether they represent an exploitable deposit. If it is not possible to evaluate their frequency and continuity (typical situation) because they are covered by soil and overburden, further prospecting work will be decided upon depending on the quality resulting from

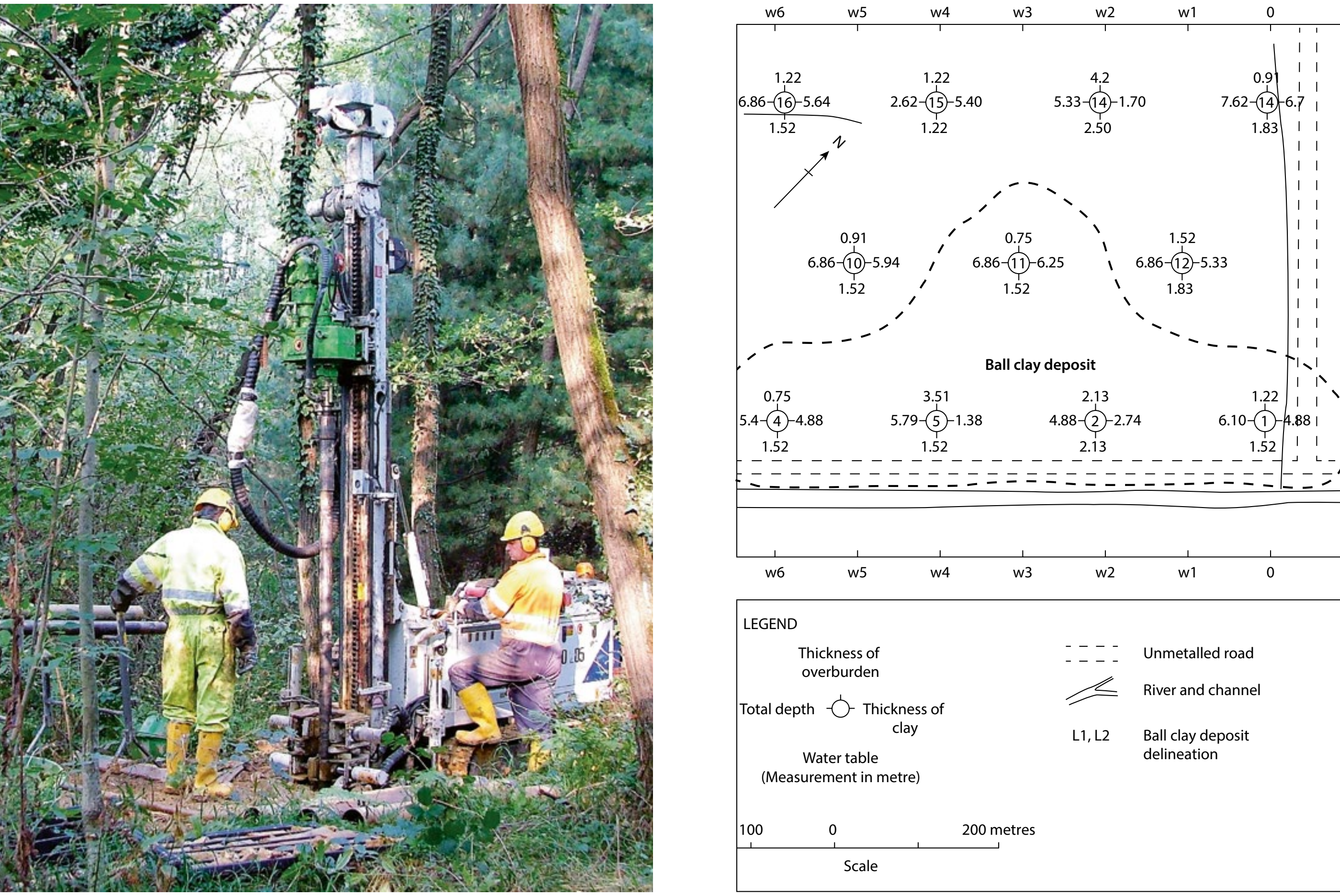

Figure 8 Core drilling operations (left) and example of a map with indication of core drilling square net made during ball clay prospecting (right). (© Bertolotti)

laboratory tests and previous information collected about the area. Negative laboratory test results or the total absence of favourable geological indexes will stop any further prospecting activity. The variable quality of laboratory results or the presence of unclear local positive indexes will require more detailed prospecting work, tightening the mesh of exploration with more accurate methods of prospecting. If only a fraction of the samples provides positive results, a map limited to the more interesting areas will indicate where further prospecting is needed to delineate the geometric contours of the area. In the case of raw kaolins, some preliminary mineral treatment tests will be necessary to understand whether the final quality will justify the investment cost of a refining plant. In the case of positive results of this phase, a following tactical prospecting step will be required.

4.3 Step 3: Tactical prospecting

This following prospecting phase will regard a more restricted area, where detailed observations and underground investigations will be required.

Geological studies on site

A more detailed surface prospecting work will complete the previous geological study of the area with a geological/lithological map at a scale of 1:10,000–1:25,000. This document will help the accurate organization of the underground research required for a better understanding of the geometry and the quality of the deposit. Geophysical prospecting (as electrical resistivity methods) could in some cases be cheaper and help understand the thickness and shape of clay deposit (Figure 7). This information will help to position drilling exploration points correctly. A geoelectric survey has many advantages. It can be quickly performed, it is economical, it does not cause damage to private property, and it is easy to integrate with geologically based GIS software. The major difficulty in geoelectric measurements is the presence of water in alternating sequences of sandy and clayey layers, which affects the accuracy of electrical measurements, and the low accuracy on small scales. Other geophysical techniques, such as gravity and seismic methods, can be applied, depending on the geological characteristics of the area. However, experience showed that only the combination of a geophysical survey with a sufficient number of core drilling points will give the correct information of geophysical results to draw a reliable three-dimensional model of a clay deposit.

Detailed sampling

In this prospecting phase, it is very important to collect representative samples of the deposit. In this case, the entire mass of the deposit must be sampled, not only the accessible surface part of it. Previous methods such as sampling with augers and excavation of trenches are accurate enough to define the real consistency of the deposit and to have a representative quality of the clays present on it. Core drilling is the only technique that permits evaluating clay levels and gives an understanding of the stratigraphy

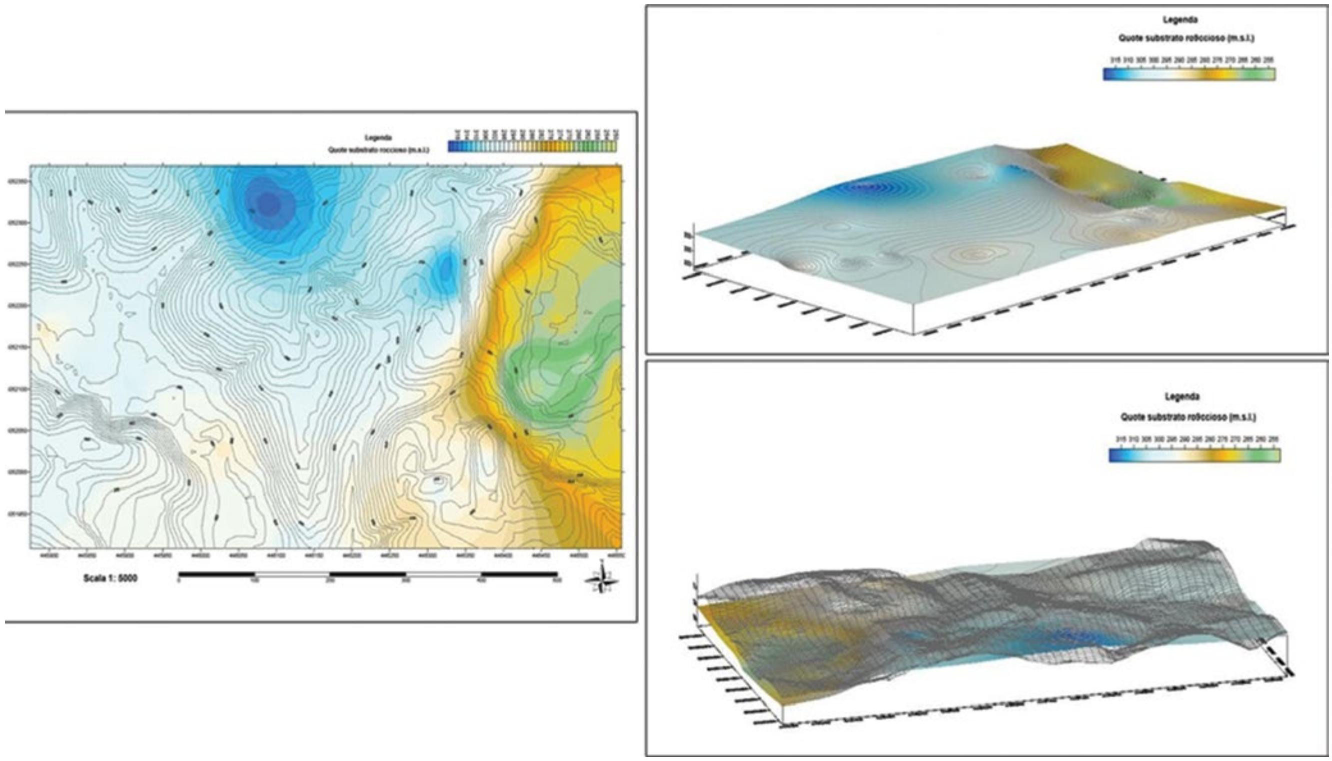

Figure 9 Example of a 3D map of a lithoid soil present under a clay deposit. (© Bertolotti)

of the deposit. Core recovery must be higher than 90 % for a correct evaluation of the quality of the material (Figure 8).

Although in many cases exploration costs do not allow detailed prospecting work, experience suggests that the drilling can be organized with a space interval dividing the area to be explored in a square net of at least 100 m (4 holes for each hectare). Samples can be collected and analyzed every 50 cm/100 cm based on the stratigraphy recognized in the boreholes. It is very important to be present during drilling operations and record all the observations regarding the progress of the work progress, for example the presence of water or coring difficulties due to the presence of stones or harder levels.

Test and laboratory analyses

During the tactical prospecting phase, it is important to carry out at least the following tests:

- XRF chemical analysis with loss of ignition (if available, also XRD mineralogical analysis)
- Evaluation of the carbonate content (if XRF is not available in this phase)
- Particle size analysis
- Plasticity evaluation
- Firing tests on a muffle kiln
- Evaluation of organic substances and sulphur compounds
- DTA/TG analysis, if available

All these data must be recorded on data sheets along with data collected, identification code, and geographical coordinates. These analyses, together with the geological observations collected on site, will allow organizing samples in groups with similar characteristics.

Laboratory tests during this phase must take into account the following points:

- Consider the main different qualities of the materials present in the deposit
- Give indications about the possible use of different qualities identified in the deposit
- Understand the impurities present in the deposit and their location
- Evaluate whether treatment tests will improve the quality of the raw materials and justify future treatment plant costs.
- With respect to raw kaolin deposits, treatment test studies are justified only if there is an important request from the local market and if the size and initial quality of the raw material was promising enough to consider such an important investment.
- In this case, laboratory tests must clearly indicate a suitable treatment process with evaluation of recovery percentage and quality resulting from the process and indicative treatment costs.

Data interpretation

At the end of the tactical prospecting phase, it is necessary to reach the following results:

- A lithological map of the prospected area
- Complete information on homogeneity and variability of raw materials and clear indications on deposit shape and geometry
- Detailed technical information about the characteristics of the material prospected.

Conclusions of the tactical prospecting phase

This important prospecting phase must be able to answer whether the material can be used in ceramics and in what type of production, and what the advantages or disadvantages of its use in ceramic formulations and its limits of acceptance are. Furthermore, it must be determined whether treatment tests will improve the quality of the material and their possible costs. Finally,

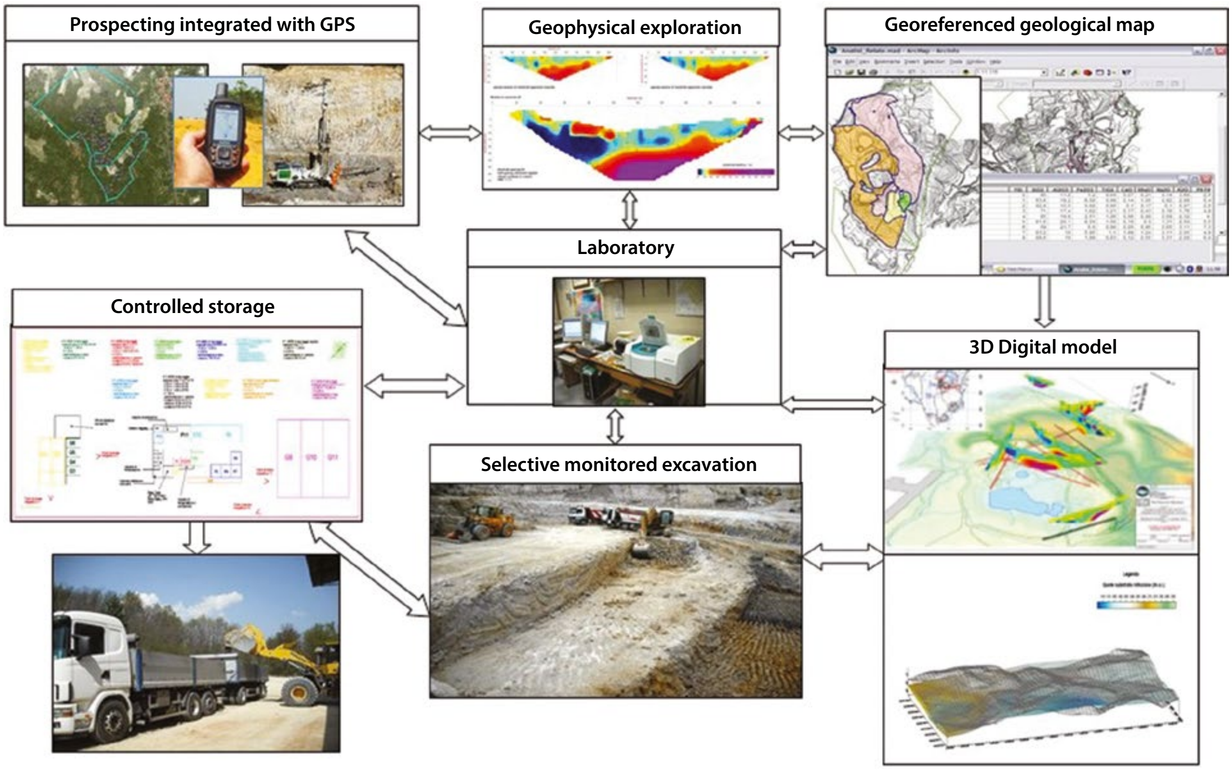

Figure 10 Prospecting techniques for the study of clay deposits [21]. (© Bertolotti)

proposals for the best future mining methods must be obtained. In conclusion, the data collected at the end of the tactical prospecting phase must be adequate to define a preliminary feasibility study and to confirm the profitability of deposit exploitation. The data must also indicate what information is still missing before the final exploration phase can be initiated.

4.4 Step 4: Detailed study of deposits

If previous prospecting phases have achieved positive results, the last step of the work is to complete the study of the deposit to organize future mining activity in the best possible way. At the end of this phase it is important to obtain a geological/lithological map with the position of exploitable raw materials and a calculated estimate of exploitable materials, overburden, and percentage of non-useful qualities. Also, complete information about raw material qualities available and treatment methods could be required. These data are necessary to program the clay mining exploitation and to evaluate the economic balance of the operation. In particular, the program of future exploitation, for example materials' movement and layout project of the future mine must be defined. Also the type of exploitation (operations and storage organization), profitability of the operation (detailed feasibility study) and a proposal of the treatment plant (type, size, operating conditions) must be established.

Study of geometric parameters

The scale of a survey can change from to 1:5,000 to 1:500 depending on the complexity of the deposit. This piece of information makes it possible to prepare the following documents:

- A digital topographic map with the positions of drilling and geophysical measurements
- A map with geophysical study results
- A map with level curves of the top of useful materials
- A map of the thickness of useful materials (isopaque map)
- A map with level curves of the bottom of useful materials
- A map of the isobaths of the phreatic table (if useful and required)

With these data, it is possible to calculate the detailed mineral reserves of the deposit and to define the conditions and the mode of exploitation of different parts of the deposit (Figure 9).

Study of qualitative parameters

Laboratory results of previous prospecting phases are integrated by a new, more detailed set of analyses with a new set of samples collected from an organized net of core drilling to complete the knowledge of the different qualities available in all the deposit. These operations will permit to draw a detailed geological/lithological map with an accurate indication of clay qualities that can be selected during the excavation phases.

Exploitation program

The last phase of the prospecting work is to synthesize all the collected data and organize it in a rational way following mining activity (Figure 10). A correct excavation program avoids any loss of material in the deposit. Sampling and laboratory controls during mining activity monitor and guide the selection of different qualities in the best way and prepare consistent and controlled clay blends.

5. Conclusions

A rational prospecting plan for a clay deposit with a progressive approach in several phases – passing from the general to the particular – allows a longer duration of the mine over time and, ultimately, an important economic saving in the mining activity. In each step of exploration, various aspects must be evaluated, with their impact on the cost of exploitation linked to the commercial value of the material, and according to the evolution and request of the ceramic market.

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