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Natural analogues and evidence of long-term isolation capacity of clays occurring in Italy

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Natural analogues and evidence of long-term isolation capacity of clays occurring in Italy

Contribution to the demonstration of geological disposal reliability of long-lived wastes in clay

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FOREWORD

When it comes to assessing the safety of geological disposal for radioactive waste, one of the major causes of uncertainty is the very long period of time under consideration. It has recently emerged, among the scientific Community worldwide, that the "natural analogues" offered by Mother Nature are probably the best support to the long term conclusions of such safety assessments (if not the only one). They are naturally-occuring evidence of processes analogous to those thought to be operating in a repository, and have developed over long periods of time.

These natural analogues are progressively providing confirmation for the many scientists of various disciplines involved in radioactive waste disposal Research and Development projects, that they are developing safe disposal options. Also, that they are building a body of evidence to which the regulators in charge of licensing the repositories of the future, and the public asked to accept them, might respond positively when the time comes.

Since 1982, natural analogues have been part of the European Community Research, in the framework of the CEC R&D programme on radioactive waste, and, more precisely, of one of its main projects, MIRAGE (Migration of Radionuclides in the Geosphere). More recently an international Working Group on Natural Analogues (NAWG) has been set up by the CEC; NAWG participants drawn from all major national and international programmes regularly discuss their experimental and modelling achievements.

It is therefore a pleasure to acknowledge the specific contribution in this field by Dr. Brondi, a NAWG participant, and his colleagues, and more generally of ENEA, the Italian Atomic authority, and Italy. It summarizes an effort of many years, conducted with tenacity and according to high scientific standards. The material presented here not only leads to an improvement of the understanding of natural phenomena in clay, but also supports the conclusion drawn from the CEC PAGIS project (Performance Assessment of Geological Isolation Systems) about the effectiveness of the geological barrier as isolating agent between man and the disposed waste.

S. ORLOWSKI
Head, Nuclear Fuel Cycle and
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TABLE OF CONTENTS

SUMMARY

This work concerns the results of the studies conducted at many sites in Italy aimed at collecting information on natural evidences of the isolation capacity of clay. Field observations allow to get the opportunity to know directly or infer the evolutive geological processes which are of concern for the waste disposal problems. As a major advantage such observations concern natural phenomena acting at the same, or at a greater, time-space scale involved in the geological disposal of wastes.

The explored situations regard the secondary permeability of clay, detected by means of natural tracers (Hg, He, hydrothermal and geothermal fluids, ...) at the ground surface or directly studied in deep civilian tunnels.
Another treated topic is the meaning of the oxido-reduction front as a control factor of the physico-chemical environment of clay as well as of the radionuclides migration.
The mechanical and thermal effects which accompany the intrusion of a subvolcanic body within clay represent an extreme worst case for a comparison of the effects on clay due to heat developed by radionuclide decay.
Finally the case of a fossil forest maintained almost inaltered by the clay cover for over 1,500,000 years is described.

All the results of the geological researches point univocally to an almost total and long lasting isolation capacity of clay formations.

INTRODUCTION

Part of recent italian clay formations are spectacularly exposed on hills and valleys slopes. Under these conditions evident traces of many genetic as well as early and late evolutive phenomena can be easily "read" directly on the ground also according to a tridimensional view. This possibility represents a real advantage in comparison to small scale observations and experiences which are currently conducted on samples, boreholes and short tunnels. Indeed field observations can be directly done at the same time-space scale related to that of concern for waste deposits. This is particularly significant in the case of the confinement of long lived radionuclides. However it is not superfluous at all in the case of low level short lived radioactive waste.

Clay formations may play at least two roles with regard to the different options considered for waste disposal:

- direct containment in the case of direct use of clay as host rock;

- isolation of a different host rock used for waste deposit.

Generally speaking geological formations must assure the long term hydrological isolation of waste deposits. From this point of view the potential development of a secondary permeability, and its consequence, due to the tectonic evolution, must be taken into consideration in site selection. The ion exchange capacity of the host rock as well as its physico-chemical conditions as a control factor of radionuclide behaviour constitute other important aspects. In relation to this second factor the position of the oxido-reduction front in a clay formation corresponds to a potential plan of separation of mobile and stable phases of transuranic elements. This front is easily legible on the field.

Modification induced by heat delivered by high level waste may be considered as a cause of alteration of the selected host rock and its properties. The importance of this alteration with regard to the required duration of a waste containment is often overestimated. Indeed a modification which is modest in comparison with the whole volume of the host rock does not significantly affect the geological

barrier. This is clearly demonstrated in a case of natural heating of clay in Italy.
Many italian clay deposits are cut by deep civilian tunnels. A great deal of information on seepage and major water outcomings into tunnels may be supplied by engineers who have worked there.

The distribution of fluids from geothermal fields and noble gas, such helium from the mantle, is a very efficient indicator of the mass impermeability of clay formations or parts of them. At the same time helium represents a potential powerful tool in the exploration of the most appropriate sites for disposal.

The long term preservation of woody trunks within clay is a striking evidence of the isolation capacity of clay with regard to the oxygen both from atmosphere and from phreatic water.

The ion exchange capacity is here excluded because data mainly derive from laboratory analyses. It must be kept in mind that in facts the variations of the oxido-reduction potential as well as the variation of other controlling factors may qualitatively modify but not cancel the ion exchange capacity of clay.

No sites reported here have been studied for disposal purposes.

1-Orcia, 2-Paglia, 3-Radicofani, 4-Valle dell'Agri, 5-Val d'Era, 6-Orte, 7-Narni, 8-Carrito, 9-Disueri, 10-Trigno, 11- Castiglione in Teverina, 12-Pasquasia, 13-San Quirico d'Orcia, 14- Orciatico, 15-Dunarobba, 16-Castelnuovo dei Sabbioni, 17- San Angelo dei Lombardi, 18-Benevento, 19- Val Topina, 20- Magliano Sabina.

Fig. 1 - Geographical position of the study sites reported here.

MASS IMPERMEABILITY OF CLAY AS REVEALED BY NATURAL TRACERS

Undisturbed clays are currently presumed to be almost impermeable. Indeed in risk analysis the migration of water along fault and fracture planes is assumed to be one of the most important ways for radionuclides to be transferred from waste deposits to the biosphere. As a matter of fact the permeability of clay related to tectonic structures is generally inferred from theoretical speculations starting from local and laboratory observations. This fact evidently limits the reliability of the conclusions which can be drawn on the actual whole hydrological behaviour of clay formations. Large scale field observations may definitively contribute to overcome this problem.

Hydrothermal phenomena

Hydrothermal waters and gases, as well as fluids and gases from geothermal fields, rising from great depths along fault planes, and other natural tracers, such as mercury and the very sensitive one, helium, may be considered as useful indirect indicators of the mass impermeability of argillaceous series. This is well evidenced in central-western Italy, where ancient and present hydrothermal activity, geothermal fields and mercury occurrences are frequently contained within the basement of clay deposits.

Field mapping aimed at locating fluid transits related to tectonic structures have been conducted in southern Tuscany and northern Latium (1), were the present Orcia and Paglia valleys correspond to a deep trench basin of Pliocene age of the horst-graben type (fig. 2-4) (2, 4).
Fault planes intersect the basement of Orcia-Paglia basin, which is made up of mixed chaotic clay and marl emerging in the horst pillars. In the eastern pillar there is an important outcrop of a mesozoic calcareous series. In the western pillar the Monte Amiata quaternary volcano crosses and spreads over the basement rocks.
The floor of the basin is situated at a depth of more than 1,000 m in the trench. The basin is filled by a prevalently clayey series. An important geothermal field underlies the basin, especially in the western part (Fig. 4) (5). Important thermal activity affects all the considered zone. The Radicofani neck, corresponding to the axis of

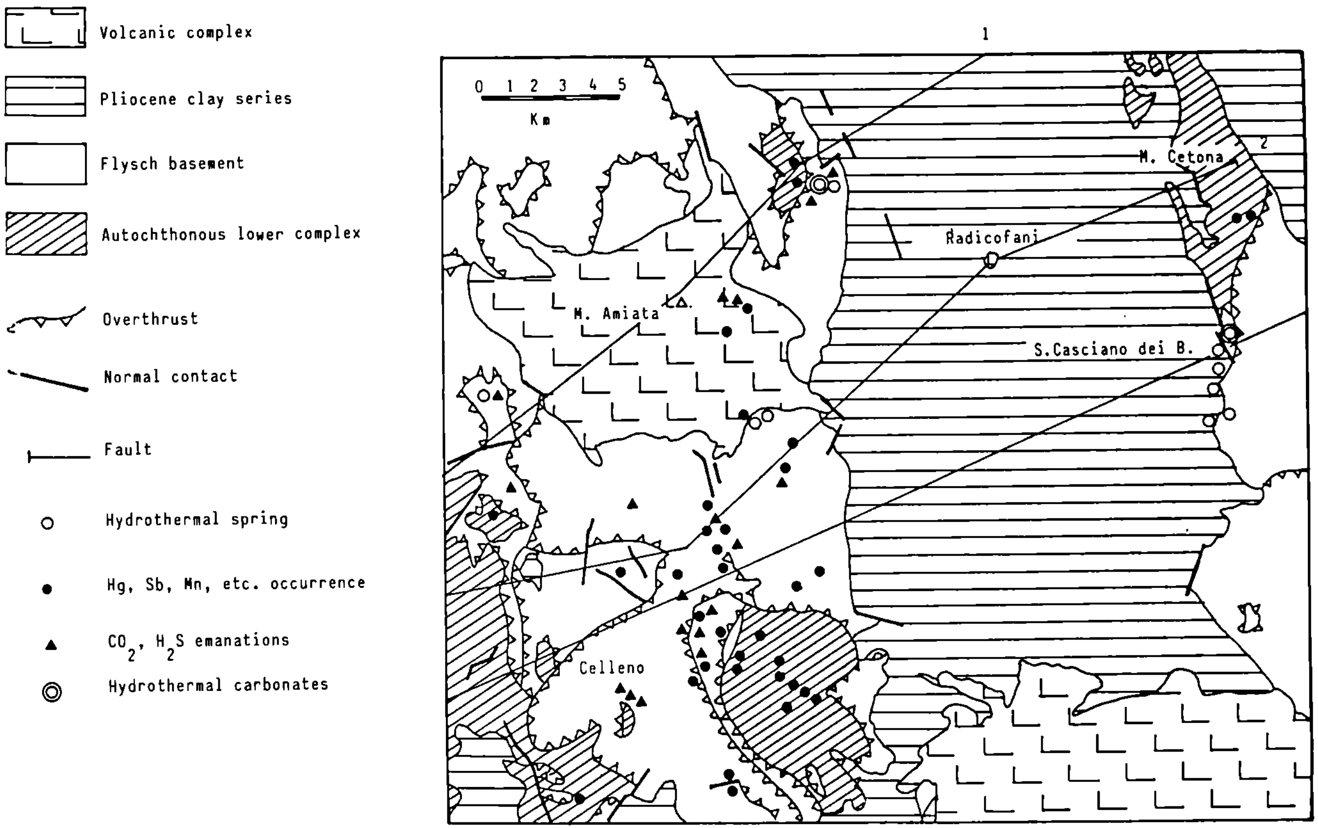


Fig. 2 - Monte Amiata zone. Sections 1-3 are shown in Fig. 3.

the graben, reveals the probable occurrence of important fractures affecting the basin floor and being prolonged across the clay series.

Hydrothermal fluids may be connected to two separate sources: very deep regional fault systems and the geothermal field.
The first source is mainly responsible for important emissions of hot water (20-52°C), which may accumulate very great deposits of carbonatic rocks (travertine), and of carbon dioxide.
The geothermal field (3) causes the uprising of very hot, high pressure fluids (150-250°C, 40-60 ata) and the thermal mobilization of the mercury geochemically contained in the deep substratum (Fig. 4). Mercury is precipitated in the form of cinnabar (mercury sulphide) in the surrounding less hot rocks or directly at the surface.
Data have been collected on the positions occupied in the basin by both hydrotermal and geothermal products. Research has been conducted on the distribution of minor cinnabar concentrations by means of alluvial prospecting (Fig. 5) (1). The main results are as follows:

a) the locations of gas and hot water emissions correspond to the boundary between clay deposits and the horst pillars bordering the basin.
b) important travertine deposits accumulate in the same locations with respect to the basin geometry.
c) the vapours of geothermal fluids are all confined within the chaotic clay-marl complex of the western horst pillar without permeating or crossing the Pliocene clay series.
d) important cinnabar concentrations and other rare minerals occur in the western horst pillar. Minor cinnabar concentrations occur in the eastern pillar.
e) numerous small and diffuse cinnabar occurrences have been recognized as corresponding to the same marginal position in the basin near the eastern pillar.
f) none of the above mentioned endogenous manifestations, apart from the very minor ones very close to the Radicofani neck, occur in the central, axial part of the basin.

The above listed data provide strong evidence for the almost complete mass impermeability displayed by clay deposits, which prevent very energetic endogenous fluids from rising to the surface from depth. These fluids may reach the surface only migrating up along the deep

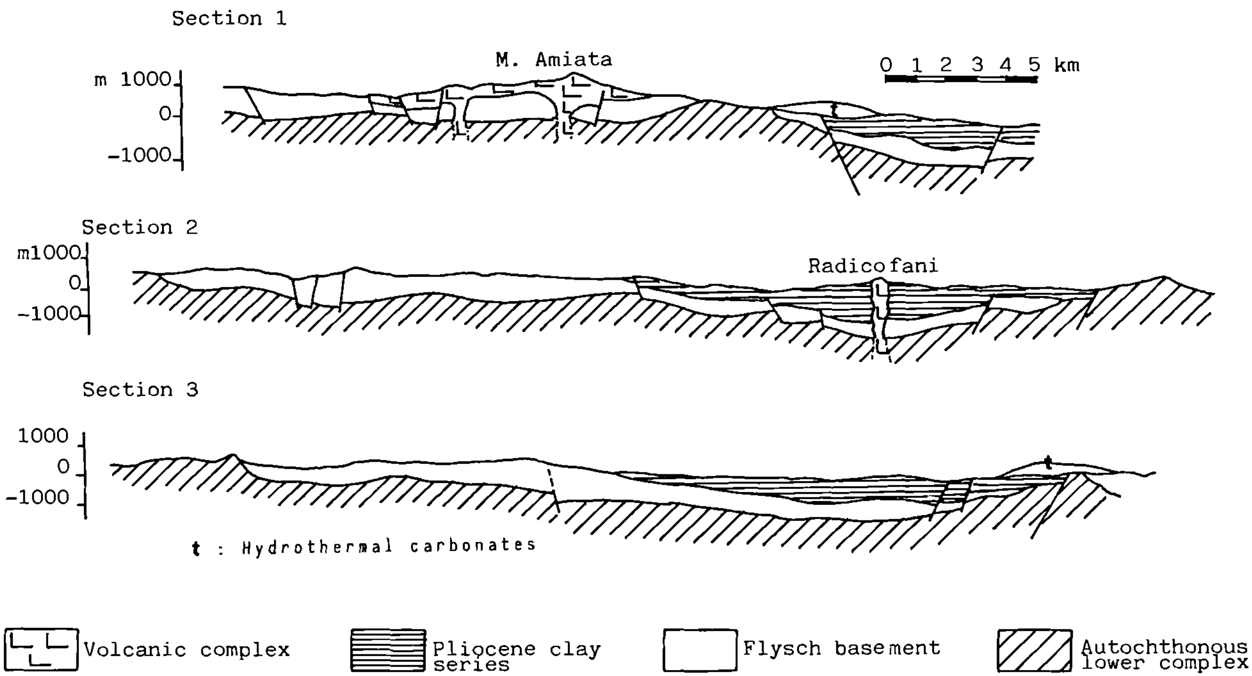


Fig. 3 - Geological cross-section of Monte Amiata zone (see Fig. 2)

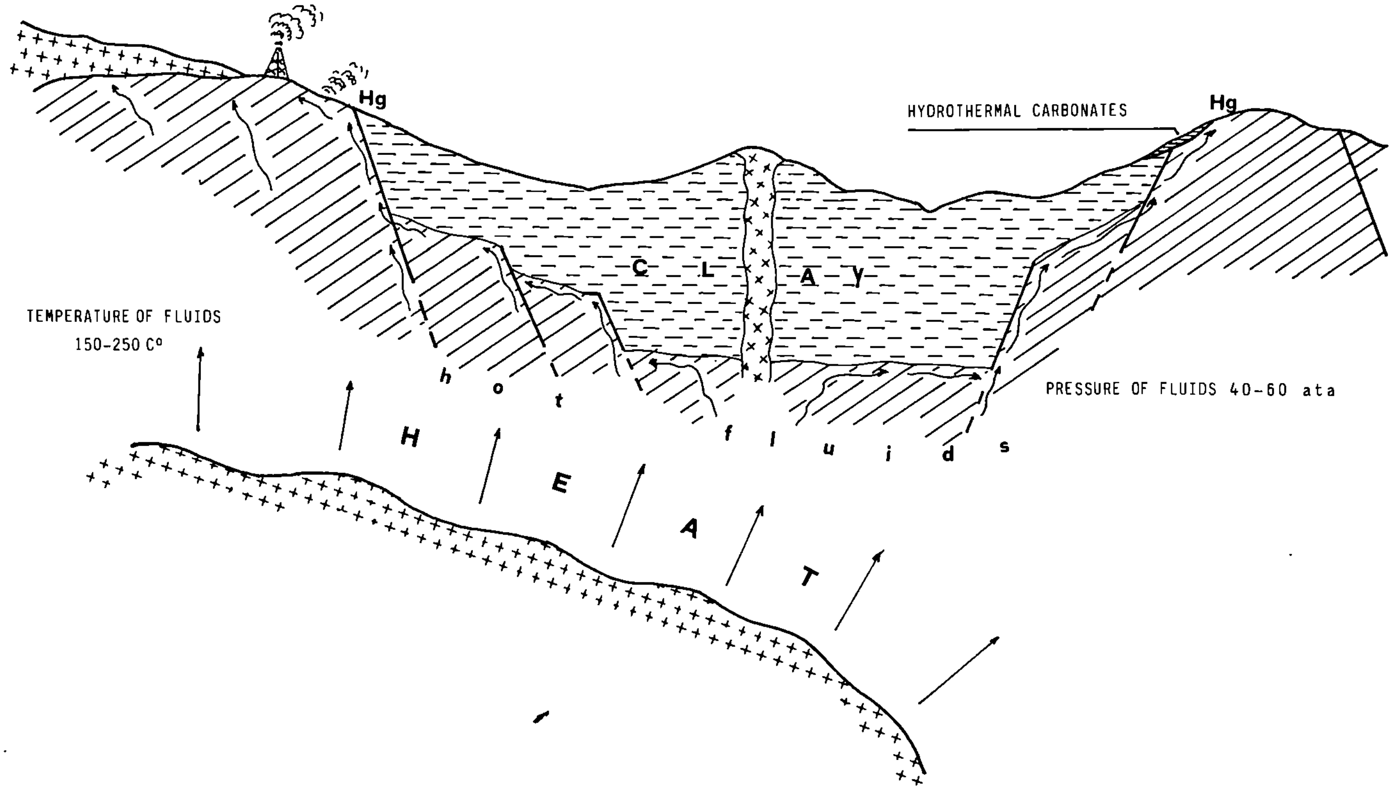


Fig. 4 - Clay as an impermeable obstacle to geothermal fluids rising to the surface. (Paglia-Orcia valleys)

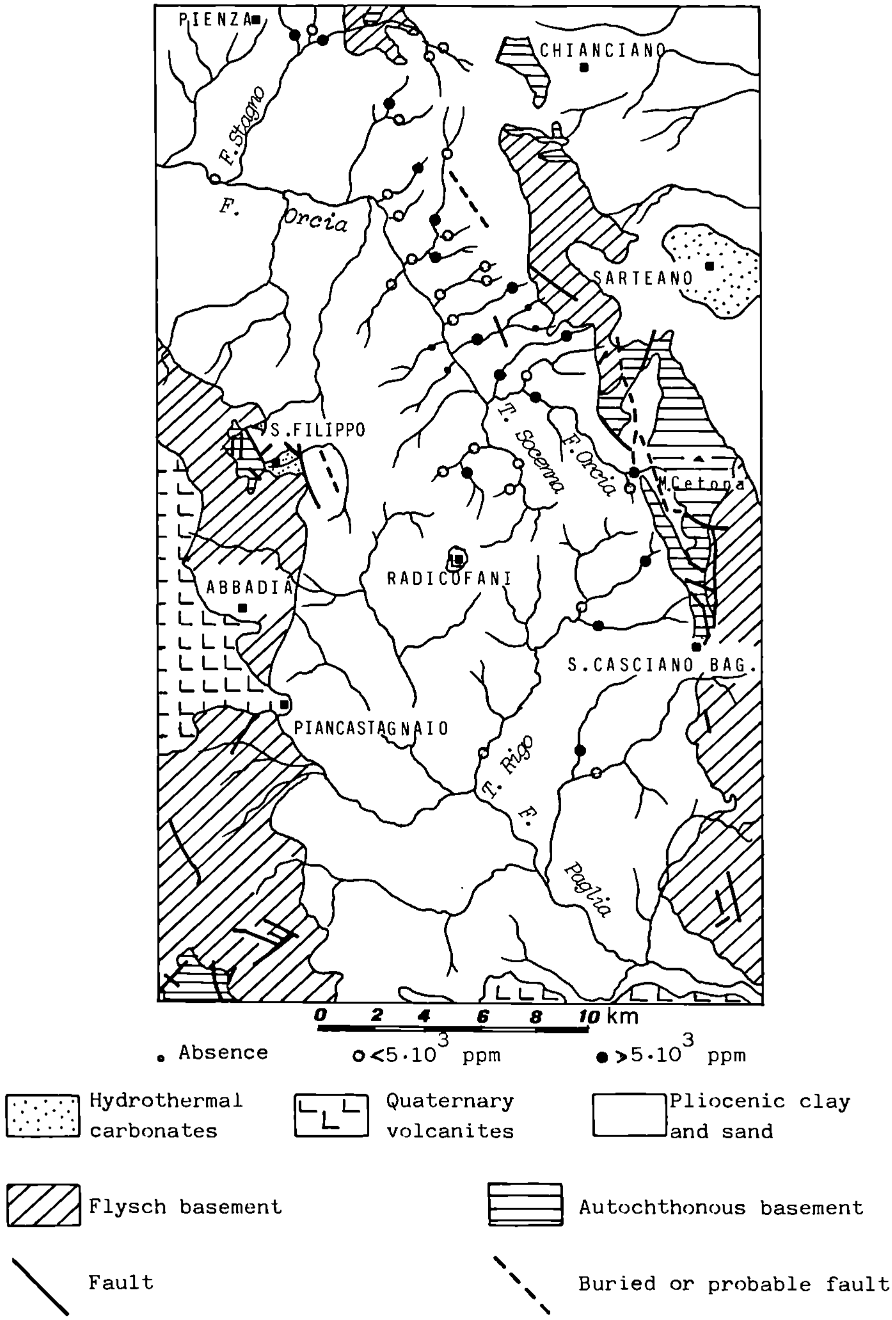


Fig. 5 - Occurrence of alluvial cinnabar (ppm) in relation to the tectonic feature of Radicofani basin.

fault planes bordering the basin, where clay tends to grow thinner and marginal interbedded sandy layers affect the homogeneity of the clay deposit and prevail on it.

Helium distribution

Detecting helium in soil represents a powerful means of revealing permeable underground structures. Helium originates in the mantle and tends to rise to the surface by migrating along discontinuities such as important fault planes. Helium displays the minimum atomic radius among the elements. Being chemically inert it doesn't react within host media and it also escapes to capture by materials provided with exchange capacity. Because of these characters helium is in absolute the most mobile element within the earth.

Impermeable bodies may hinder, limit or divert helium fluxes from depth. Where deep fault planes intersect the ground surface, the helium content in soil gases is normally higher than the atmospheric one. Many studies carried out in Italy have demonstrated that the highest helium concentrations are mostly located on the slopes of valleys, frequently corresponding to uplifted zones(6). Because of their low or practically no permeability the accumulated sedimentary, often clayey, series in the depressions may represent an obstacle to the free escape of helium towards surface. The zero or small helium concentration in the soil may therefore be due to the substantial impermeability of the underlying clay deposit. Figure 6 gives an example of differential helium concentration in soil in the Agri Valley in southern Italy (6). The smallest concentrations correspond to the valley axis, where a recent sedimentary series is accumulated. From researches in course in the Era Valley (Fig. 7) (7) in central Italy it appears that helium crosses the clay series in its central parts only in correspondence of active faults, its rise being strongly limited with fault age as demonstrated at the border of the basin. Where it is unaffected by tectonics, clay appears to be much less permeable or totally impermeable to helium. Helium being the highest mobile element its way to the surface may be impervious or completely inhibited to other natural tracers or radionuclides. This mobility may render the detection of helium distribution a very efficent tool for the individuation of the most appropriate situation of real impermeability in site selection.

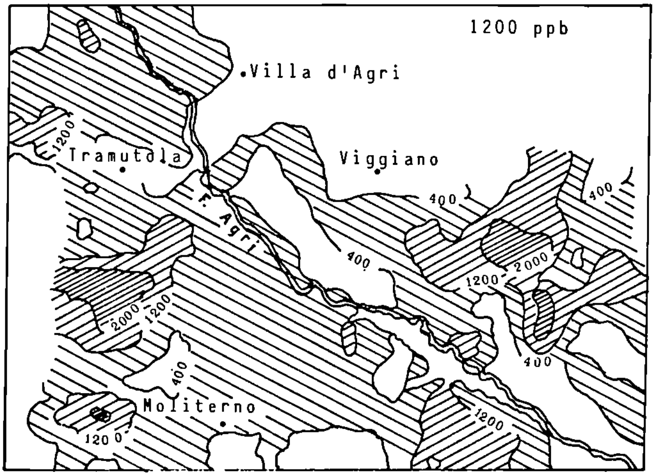


Fig. 6 - Helium concentration (ppb) in soil in the Agri valley

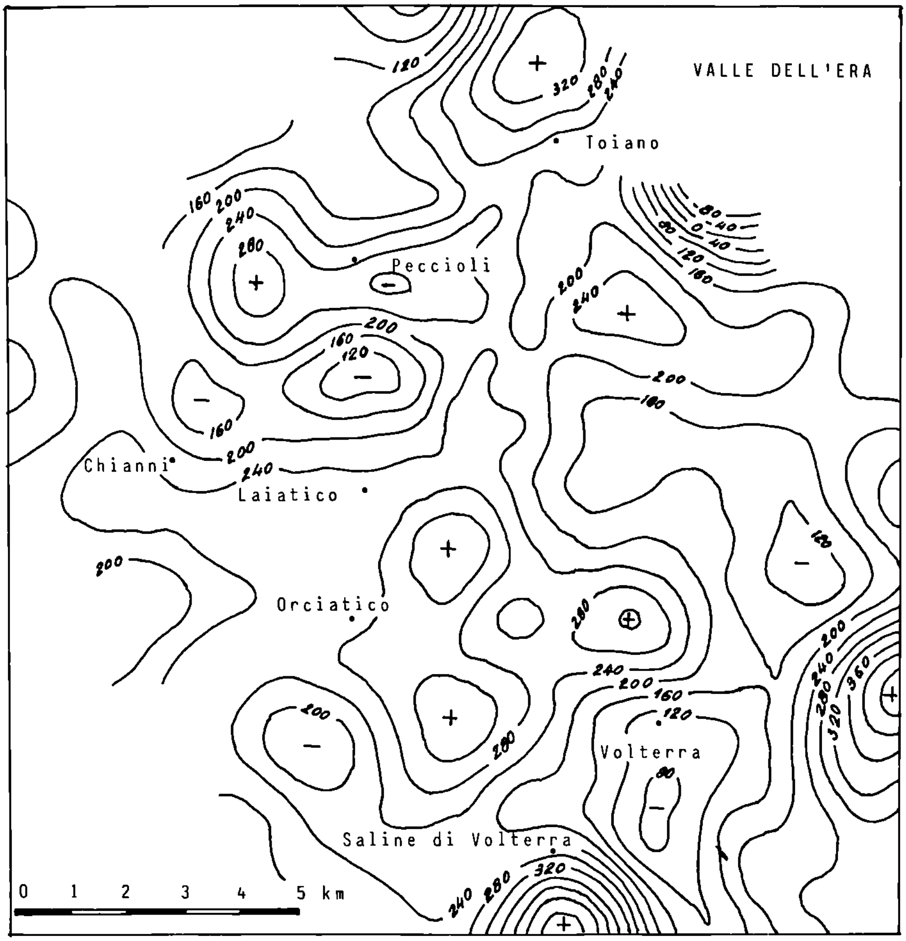


Fig. 7 - Helium distribution (ppb) in the soil gas of Val d'Era area.

SECONDARY PERMEABILITY DUE TO TECTONICS: EVIDENCE, MEANING AND REAL IMPORTANCE

Direct observations on permeability due to fracturing and faulting in clay have been done in Italy (5,8) both at the surface, and underground in tunnels constructed for many civil engineering for purposes. With regard to these latter ones each intention of exploit some of the examined situations for disposal is fully excluded.
The present paragraph illustrates some cases which can be considered representative with regard to the problem of the secondary clay permeability. It appears that the response to fracturing and the induced permeability of clay masses vary widely, owing to the interplay of many factors.
Practically all Italian argillaceous formations, regardless of age, are overconsolidated (8); only very recent Quaternay clays are normally consolidated. Except for the sediments accumulated during Plio-Pleistocene times in internal basins, most clays of this age are marine and their characteristics vary with their depositional environment.
Fault planes are not easily observable in clay under natural conditions, although some cases have been noted in quarry walls in the Tiber Valley, near Orte and Narni. Fractures, evidenced by oxidation bands, are on the contrary very frequently observable. Fracturing is indeed a common freature of all Italian, normal or chaotic argillaceous formations. Until now there has been no certain evidence of intact clayey materials.

Observations in tunnels

Systematic gathering of information on faults and fractures encountered in tunnelling work in Italy (8) has contributed to define the hydraulic behaviour of the different clay types. Some of the examined cases are reported here. Researches have been conducted on other clay series, besides plio-pleistocenic clay. Also more ancient chaotic clay have been considered.
The Laga formation is a miocenic formation formed by large amounts of clayey-silty sediments interbedded with sandy layers of variable thickness. This formation was encountered during the excavation of the Carrito tunnel of the Rome-Pescara motorway (fig. 8). The tunnel crosses westward the Laga formation in its more argillaceous facies.

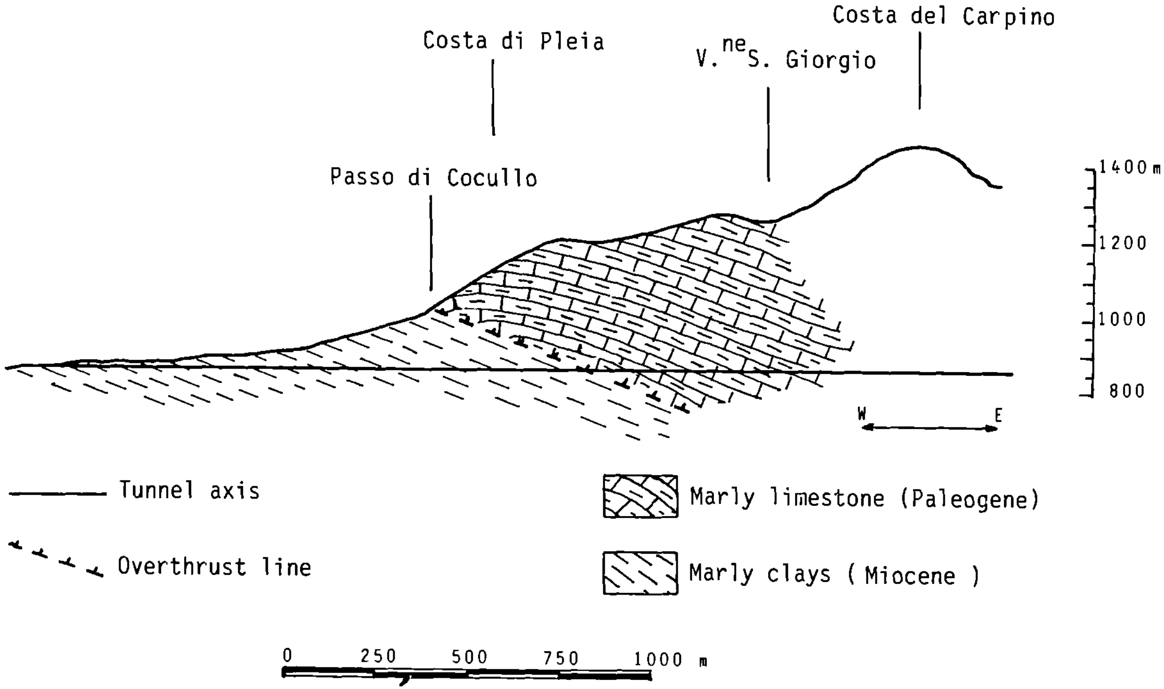


Fig. 8 - Carrito tunnel on the Roma-Pescara highway.

In this area the flysch is overthrusted by a paleogenic, water bearing, marly limestone. The whole area is affected by tectonic disturbances with well developed fractures and faults causing the observable scaly texture of clay. Despite this fact, these important dislocations did not cause any recognizable change either in geotechnical behaviour or in water percolation in clay. The excavation of the Carrito tunnel has been indeed recorded as completely dry until the clay-limestone contact. At this point the overburden is 300 m thick.

Another investigated tunnel is that crossing the Gran Sasso massif (9). Over 10 km long, the double tunnel crosses the Laga formation in a north-easterly direction for more than 3 km. Here the flysch is overthrusted by Mesozoic limestones. Marly blue clays in layers between a few decimetres and 1-2 m thick prevail, though sometimes they are silty or sandy. In the area corresponding to the major tectonic stress the formations appear extremely fractured. In the zones underlying the maximum overburden (1000 m, mainly limestone) the overlying water column is more than 600 m high with a hydrostatic pressure in excess of 60 MPa. However, tunnelling within underlying marly blue clays proceeded without difficulties and water inflow was limited to localized seepages.

Another example of this kind of investigation on clay permeability is provided by a tunnel in a Miocene argillaceous formation in Sicily. This is the outflow tunnel of the Disueri lake (fig. 9) near Gela (Caltanissetta), excavated mainly in a Tortonian argillaceous sediment which appears to be relatively free of tectonic disturbances (8).The tunnel is about 400 m long and the maximum overburden thickness is about 60 m. It was excavated when the lake was filled with water (maximum head between 10 and 15 m). As the excavation approached the lake the sediments became progressively more marly, finally becoming a diatomitic marl, which was overlain by the limestones forming the bottom of the lake. The excavation was completely dry until the limestone was entered. This case is interesting for several reasons. It was observed that the argillaceous formation is overconsolidated, bedded, fissured and under a relatively limited lithostatic load. The clays are also direclty connected, through the permeable limestone, to the lake. From a geotechnical viewpoint the formation was

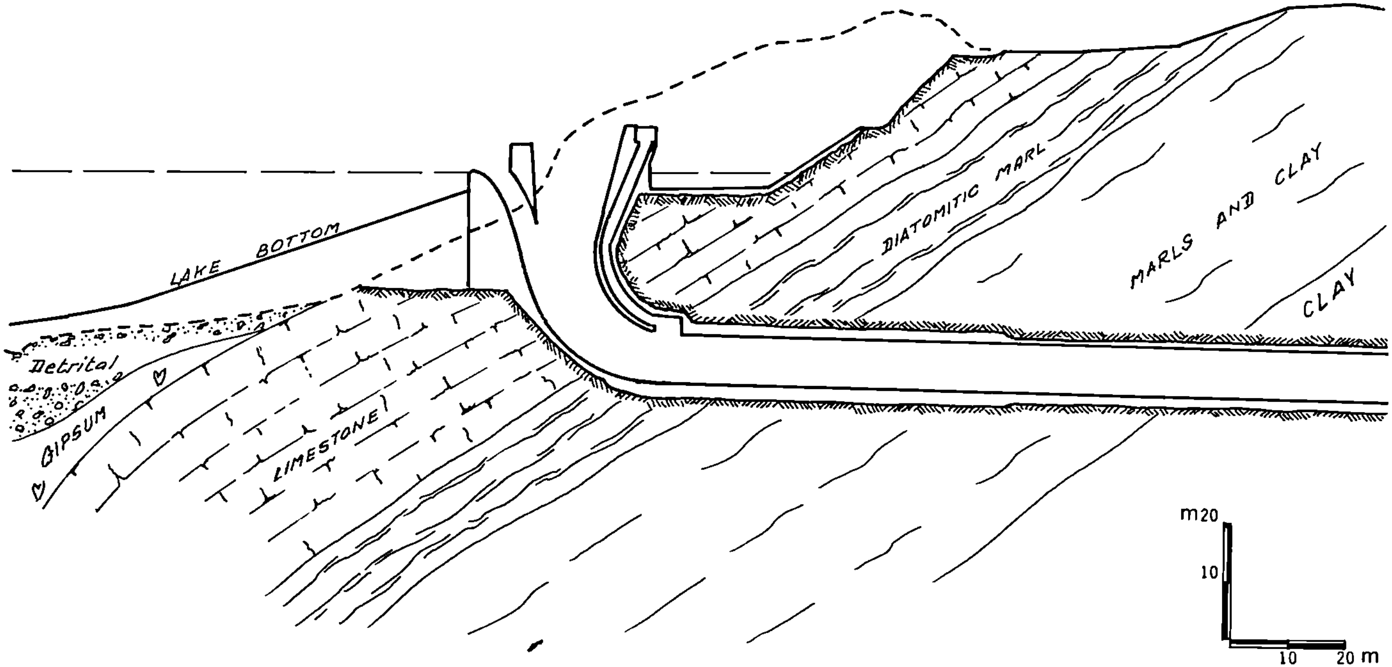


Fig.9 - Disueri tunnel in Sicily.

particularly stable: in fact, the excavation never showed convergence phenomena; the tunnel was lined many months after tunnelling had been completed.

The hydraulic situation of the Disueri tunnel can be considered very unfavourable, and flooding was feared. However, no seepage was observed either immediately after excavation or during the time preceding lining emplacement. It is impossible to know how much the observed watertightness is due to the low hydraulic head above the top of the clay formation.

On the other hands, examples of water percolation in clays are not difficult to find: at Risalaimi, near Palermo, a percolation has been observed at the contact between intact and weathered (shallow) clays. The permeability in this case is due to the proximity of the tunnel to the topographic surface. In fact as explained farther on, the surface proximity causes latent fractures to be opened and penetrated by phreatic or artesian waters.

Allochthonous argillaceous formations are widespread in southern Italy and in Sicily (8). They are generally known as "argille scagliose" (scaly clay). Despite their scaly structure unweathered "argille scagliose" are practically impermeable. As an example done, at Trigno (Molise) the permeability coefficent measured in situ with Casagrande piezometers is less than 10^{-11} m/s; this value agrees with the results of laboratory tests.

A tunnel of the Rome-Florence railway crosses the "argille scagliose" of the San Donato hill, not far from Florence. The tunnel, which is about 10 km long, was excavated for more than 4 km in the "argille scagliose" formation under a maximum overburden of about 300 m. During the excavation many faults were recognized in the argillaceous formation, as well as in other crossed formations as the Macigno sandstone and the Alberese marly limestone. In part of the excavation the "argille scagliose" showed very pronounced swelling, but this was due to water drained towards the clay by the tunnel itself. In fact, swelling occurred only where the slope of the tunnel carried water from the water bearing Alberese formation into the clays. In contrast, close to the Macigno, which is another water bearing rock, no swelling of the argille scagliose was observed, since the slope of this section of the tunnel drained the water away from the clays. It is concluded that in the San Donato area the "argille scagliose" formation is quite impermeable, even though it is intersected by many faults.

The Plio-Peistocene blue clays are the younger argillaceous formations in Italy. They are characterized by (8): (a) widespread occurrence in the whole territory, (b) a wide spectrum of mineralogical composition and (c) a very variable grain size. Most blue clays are fissured for tectonic reasons and their block jointing is a general feature, not only a surface phenomenon. In fact, this characteristic can be observed at depth during tunnelling; the only difference, with respect to near surface strata, is the absence of oxidizing bands bordering the fissures (see 4.2. section).
During the construction of the new Rome-Florence railway a number of tunnels were excavated in blue clays, overlain by water bearing tuffs, adjacent to the Tiber Valley in norther Latium and southern Umbria. One of them is the Castiglione in Teverina tunnel (8) which is 7.5 km long and was almost entirely excavated in argillaceous sediments, under a maximum overburden thickness of 160 m. In this tunnel two different behaviours of the rock were observed. At times the rock looked like a marl, with small scale conchoidal fracturing; elsewhere the clay behaved in a more plastic way and broke in regular blocks. Since the two materials have no evident differences in composition, it is supposed that their behaviours are due to different water contents. The tunnel encountered major discontinuities every 30-50 m, and sometimes partial collapses occurred. After some collapses the rock showed extremely smooth and shiny surfaces, indicating that the discontinuities were real faults. However, no water percolation from the upper aquifer was observed, either in the intact rock or along the faults.
The experimental tunnel excavated by ENEA at Pasquasia in central Sicily at 160 m depth from the surface crossed a very stiff, faulted and fractured blue clay overlain by water bearing sand. No trace of seepage or water penetration was observed.

Obervations at ground surface.

Indications of induced permeability of clay by tectonics may be directly obtained from field observations of the distribution and intersection of yellowish-ochraceous bands within the grey clay bodies at the ground surface. As explained below, faults and fractures behave differently with regard to the penetration of surficial oxidizing water into clay.

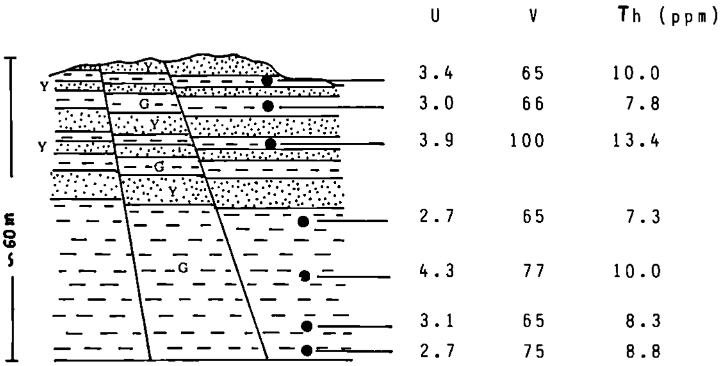
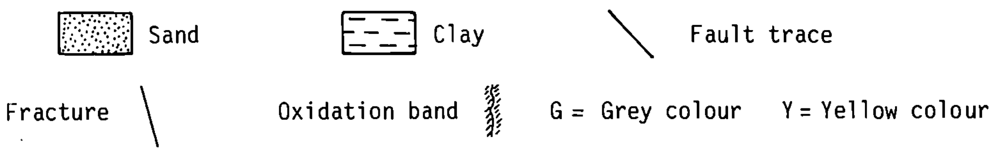


Fig. 10 - Orte clay series. No significant variation in the content of some trace elements differentiates the massive lower clay deposit from the thin upper clay levels interbedded with oxidized sandy banks.



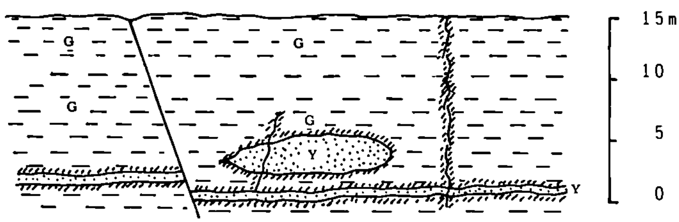


Fig. 11 - Narni clay series. Oxidation bands in clay develop along fractures and boundaries of sand lenses. No oxidation exist along the true fault.

The Orte series has normal faults running through it (fig. 10) (5). The total absence of traces of oxidation at the sides of the fault planes in the cases observed to date could indicate the clay impermeability to water and therefore the clay attitude for self-sealing.
In contrast, the many simple fractures in the main clay mass have oxidized edges 1 cm thick. This phenomenon is very commonly found in clays which are exposed to erosion as it is well illustrated in figure 11 . As a rule these fractures involve no displacement; they merely run downwards for tens of meters before coming to an end (fig. 12) (5). Networks of fractures, always recognizable by the presence of oxidized edges, intersect the vertical fractures at right angles.
The most likely explanation of the genesis of these fractures is that tectonics and orogenic uplifting cause clay deposits in Italy being broken up. The disappearence of the overlying as well as lateral masses because of erosion determines the decompression of clay, which expands in volume without a parallel expansion in mass.This causes the latent fractures to be opened, enhancing induced permeability and permitting the penetration of the clay mass by surface water.
The examples described really show that the penetration of the clay system by surficial oxygenated water is controlled by the mentioned factors.
However, as mentioned above, the discontinuity corresponding to the fault plane does not appear to be affected by oxidation.

As a general conclusion of this paragraph, the results of many observations of clay in natural conditions testify to the substantial impermeability of clay deposits under tectonic stress.
The occurrence and penetration of water noted at various levels in clay deposits may normally be attributed to easily recognizable causes, such as proximity to water bodies, connate water and surface alteration of clay homogeneity. The common assumption that the permeability of a clay formation is significantly increased by faulting and fracturing phenomena should be therefore properly brought to the real meaning and size. Indeed it seems to become effective only in the very upper part of clay masses of formations undergoing to orogenic uplift and erosion.

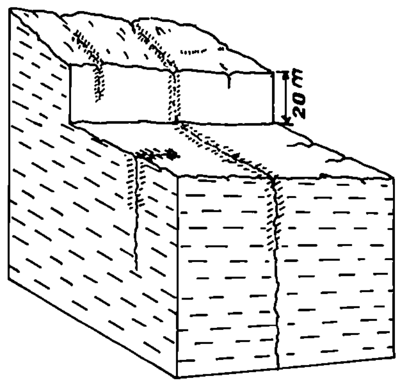


Fig. 12 - San Quirico d'Orcia quarry. The oxidation band along fractures stops some tens of meters below the surface.

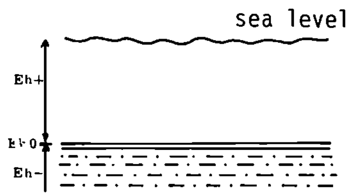


Fig. 13 - The sea bottom usually separates positive Eh values in the water from the negative ones within sediments.

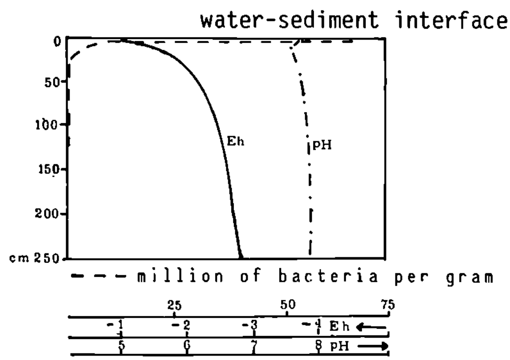


Fig. 14 - Variations of Eh, pH and bacteria count below the sea bottom.

THE PHYSICO-CHEMICAL CHARACTERS OF CLAY AS A GUARANTEE FACTOR FOR RADIONUCLIDE IMMOBILIZATION.

The oxido-reduction potential has a significant influence on the chemico-physical conditions controlling the mobility of radionuclides. Clay, and sand not permeated by oxygenated water, have very low or decisively even negative Eh values. The consequent reducing condition ensures the immobility of many radionuclides. Actinides in particular, which display a geochemical behaviour strictly similar to the one of uranium, give rise to stable forms within the geochemical environment of clay.

This fixation property is therefore one of the major advantages of clay formations as a repository for the long-term disposal of radioactive waste.

The negative physico-chemical condition is created in the first diagenesis of the sediment. The boundary between water and sediment restricts or prevents exchanges of the respective fluids and gives the two environments a high degree of mutual indipendence.

Usually the Eh=0 surface is slightly below the water-sediment boundary (fig. 13) (12).

The Eh values tend to decline lower down the sediment whereas the pH values tend to increase slightly (fig. 14) (12).

Clays are deposited in the normally oxidizing marine environment. Within the deposited sediment this physico-chemical condition is turned to the reducing one during the first diagenetic processes. This is proved by the common occurrence of iron pyrites both within the rock mass and within foraminifera shells. Pyrite minerals mostly derive from bacterial reduction of available sulfates. These Eh variations in sedimentary deposits are used by colonies of bacteria which decompose organic substances contained within them.

The bio-oxidization process becomes less efficient, due to the decreasing supply of oxidizing agents with increasing sediment depth. It seems likely that the bacterial activity does not cease altogether with depth and passing time but it is merely very considerably retarded. The discovery of living sulphate-reducing bacteria both in deep sea sediments and in fossil Plio-Pleistocenic clays in the Tiber Valley (fig. 10) (13) lends weight to this theory.

The exposure to the atmosphere and the penetration by oxigenated water may turn the reducing condition of clay to the oxidizing one. Therefore it may weaken the geochemical barrier to the potential

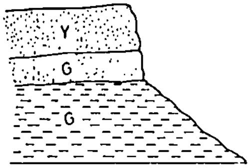


Fig.15 - Volterra. The lower part of sandy deposits still shows the grey colour inherited from the original reducing environment.

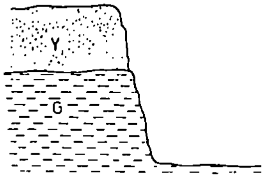


Fig. 16 - The lithological boundary frequently sharply separates the oxidized upper sands from the underlying reduced clay.

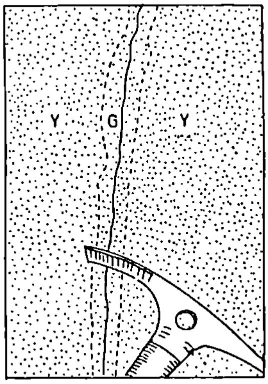


Fig. 17 - Narni. An opposite case: organic matter in the fracture, supplied by tree roots, causes the oxidized environment in the sand to be turned to a reduced condition.

migration of radionuclides. In practice, however, the limited permeability and porosity of clay restrict to some extent the likelihood of this phenomenon. Illustrations of some macroscopic examples are given below.
As demonstrated by in situ observations carried out in Italy, the oxidizing effects of the external environment on clay are somewhat limited even in cases where there is a high degreee of exposure. Indeed only for the upper few centimeters the original grey colour of clay is normally turned to yellow because of oxidation processes.
The uplifting of the clay-sand series in a continental environment and the consequent erosion processes cause oxygenated meteoric waters to penetrate the permeable sandy layers normally covering the clay series. However, as a rule, only the thickness of sand affected by the seasonal and climatic fluctuations of the water table is oxidized to any considerable degree. Below the lowest level to which the water table falls, the sand retains the original grey colour testifying that the reduced condition can still persist in the continental environment.
The natural section visible in Volterra (fig. 15) illustrates a fossil situation of this kind (12). In the frequent instances in which the fluctuation of the water table surface reaches the underlying clay, a sharp change in colour from yellow to grey indicates the boundary between the oxidized permeable sand sediments and the underlying reduced clay layers (fig. 16) (12).

The upper part of the Pliocenic series in Orte in the Tiber Valley (fig.10) is currently being subjected to geochemical analysis, with a view to the interpretation and assessment of the effects on clay of penetration by oxygenated water. Above the massive layer of exploited clay, the serie comprises layers of sand interbedded with clay. The sand is completely oxidized. The grey colour of both massive clay and even of the very thin clay levels contained within oxidized sand indicates their persistence in a reduced condition (5).
The geochemical analyses which have been carried out (fig. 10) (5,12) do not indicate significant differences between the content of trace elements of the main self-protected clay body and that one of the thin layers immersed in the oxidized sand. The same can be said of some organic substances.
The reducing nature of clay, as illustrated above, is essentially due

to the presence of organic substance in rocks of this kind and to the capacity of these rocks to retain and protect it, largely because of their impermeability. This correlation is indirectly confirmed by an example of the reverse situation observed in a quarry in Umbria. Open fractures running through a layer of oxidized sand have grey, reduced edges (fig. 17) (12). This phenomenon is caused by the presence of organic substances in the form of dead plant roots within the fractures. The progressive destruction of these substances by oxidation resulting from bacterial activity is responsible for the reducing state of the surrounding environment.

As a conclusion of this chapter, all the observations which have been made on the evolution of clay formations point to the fact that a significant alteration of physical and physico-chemical barriers would be only due to unfavourable circumstances affecting the whole geological environments of which clays are part.

THE RESISTANCE TO HEATING AND THE EFFECTIVE CONTAINEMENT CAPACITY OF CLAY AS DEMONSTRATED IN THE CASE OF THE MAGMATIC INTRUSION IN CLAY AT ORCIATICO

The metamorphic halo induced on Pliocene argillaceous sediments by the subvolcanite,of selagitic nature, of Orciatico (Tuscany, Central Italy) can be considered as an extreme effect of natural heating of clay (fig. 18,19).
A small mafic (i.e Fe-Mg rich) alkali-trachyte body was emplaced underground there about 4 m.y. ago into plastic Pliocene clays (14). This body represented a heat source which was active on argillaceous materials for times presumably of the same order as those expected for a high activity nuclear waste deposit. Such intrusion is expected to have brought some fluids in the surrounding sediments or to have induced connate fluids movements in them; certainly it caused changes into physical and mineralogical characteristics of the host formation, as evidenced by the presence of a narrow thermometamorphic halo, known as thermantite.
Despite the dramatic physical variation at the contact with the subvolcanic body, clay mantains its original characters some meters farther away. Its barrier property remains unchanged on the whole. An evaluation of the induced physical and mineralogical transformations and associated water flow and chemical migration under the thermal gradient originated by the intrusion seemed therefore particularly relevant for the problems concerning nuclear waste disposal in clays. Though available data do not allow exact evaluation of depth, many features of the Orciatico igneous body (widespread glass, highly vesicular peripherical facies etc.) point to a shallow emplacement, comparable with that usually considered for a repository. Not even exact definitions of the temperature of magma at the moment of emplacement are feasible. Only some rough evaluations can be proposed; from its distinctly magmatic composition, temperatures over 800°C may be assumed for the alkalitrachytic magma intrusion (15). These values are much higher than those, of the order of 100°C, expected around a radioactive waste container; therefore, as to the thermal aspects, the Orciatico magmatic body and its metamorphic halo can be regarded as a demonstration of a worst extreme case with reference to a radwaste repository.
The mineralogical changes induced in pliocenic clays by

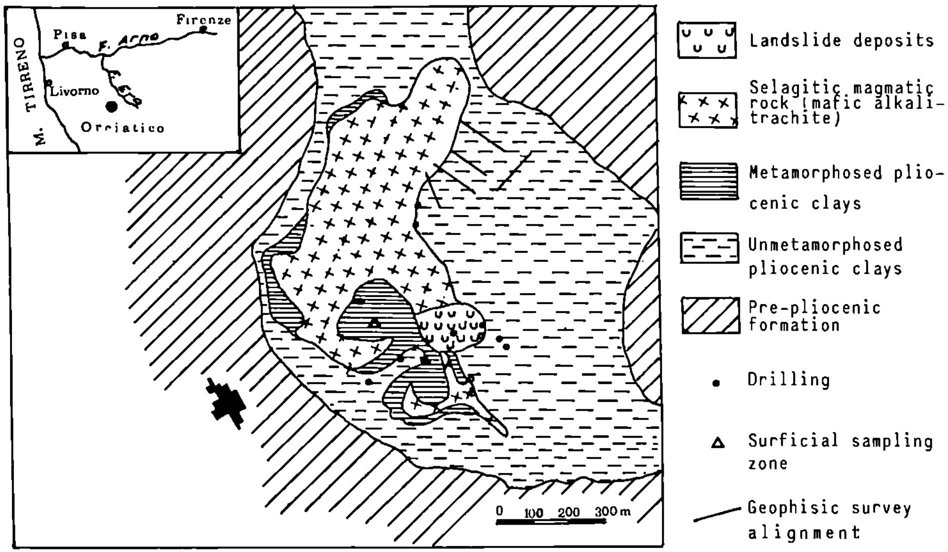


Fig. 18 - The magmatic intrusion and the thermometamorphic halo in clay at Orciatico.

thermometamorphism may be generalized as follows (fig. 20) (1): crystallization of pyroxene, Na-Ca plagioclase and biotite, in the zone closest to the contact (hornfels facies zones); (2) crystallization of albitic plagioclase, in the colder zones farther out from the contact, where Na gains still occurred; (3) crystallization of K-feldspar, most probably in more than one structural form, all over the metamorphic aureole, and in greater amounts wherever significant K-gains occurred: (4) crystallization of smectite all over the metamorphic halo, including the levels where no metasomatic change occurred.

Of interest is that in most of the metamorphism-affected zone the crystallization of the above mentioned minerals derived from reactions involving only fine sized mineral grains; only in the hornfels facies zone practically all the original sediment resulted as having reacted as a whole.

Field scale features of metamorphosed clays, their textures and microfabrics, their mineral assemblages and the dimension and distribution of veins and cracks provide grounds to make some hypotheses about the means of heat and mass transport from the subvolcanite to the host rocks. As to this problem, within the metamorphic halo two main zones can be recognized.

A first zone, 0.5 up to 1.5-3 m thick, closest to the contact, characterized by extremely compact texture, scarce fracturation and then low permeability, points to a prevalently conductive heat transfer. As to the chemical transfer the data do not allow to make any guess whether the chemicals were introduced into and passed through this first zone by ionic (and molecular) diffusion or by infiltration of fluids before the zone assumed the hornfels texture, becoming practically impervious.

Farther out from the intrusion the second zone, which includes most of the metamorphic halo, shows evidence to have been affected by heat and mass transfer linked mainly to hydrothermal fluid circulation. Notwithstanding the very low permeability commonly assigned to clays (16), several microfabric features (particularly those of the spherulitic facies metamorhic clays) indicate as probable for this zone a migration of interstitial (or "inter-cluster") water, at least in an early stage. In a subsequent stage, when conspicuous re-crystallization of the rock caused a sharp loss of plasticity, a diffuse micro-cracking could develop; this feature allowed an important convective circulation of hydrothermal fluids along

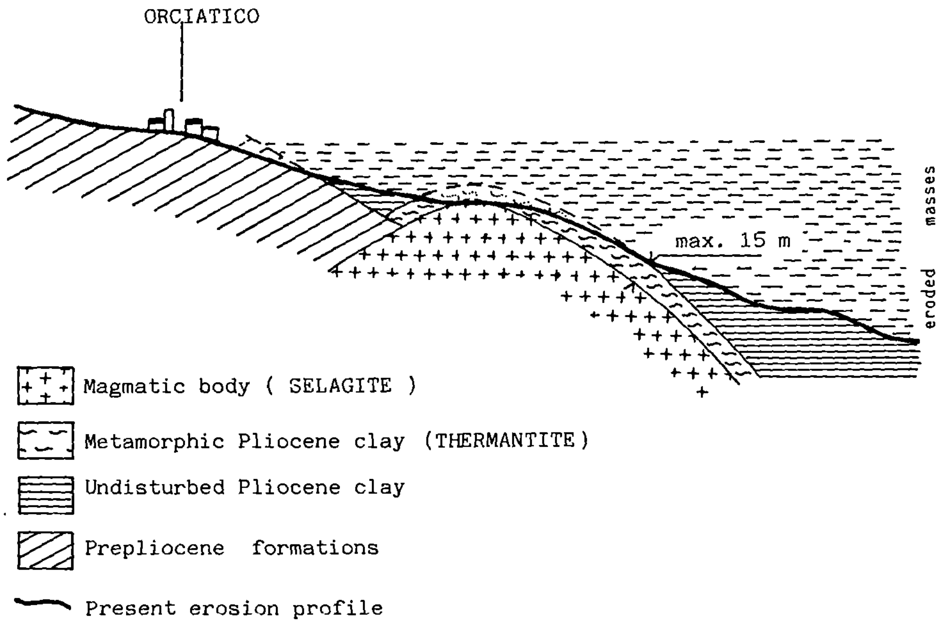


Fig. 19 - Simplified geological sketch of Orciatico subvolcanic body in clay and the related thermal halo.

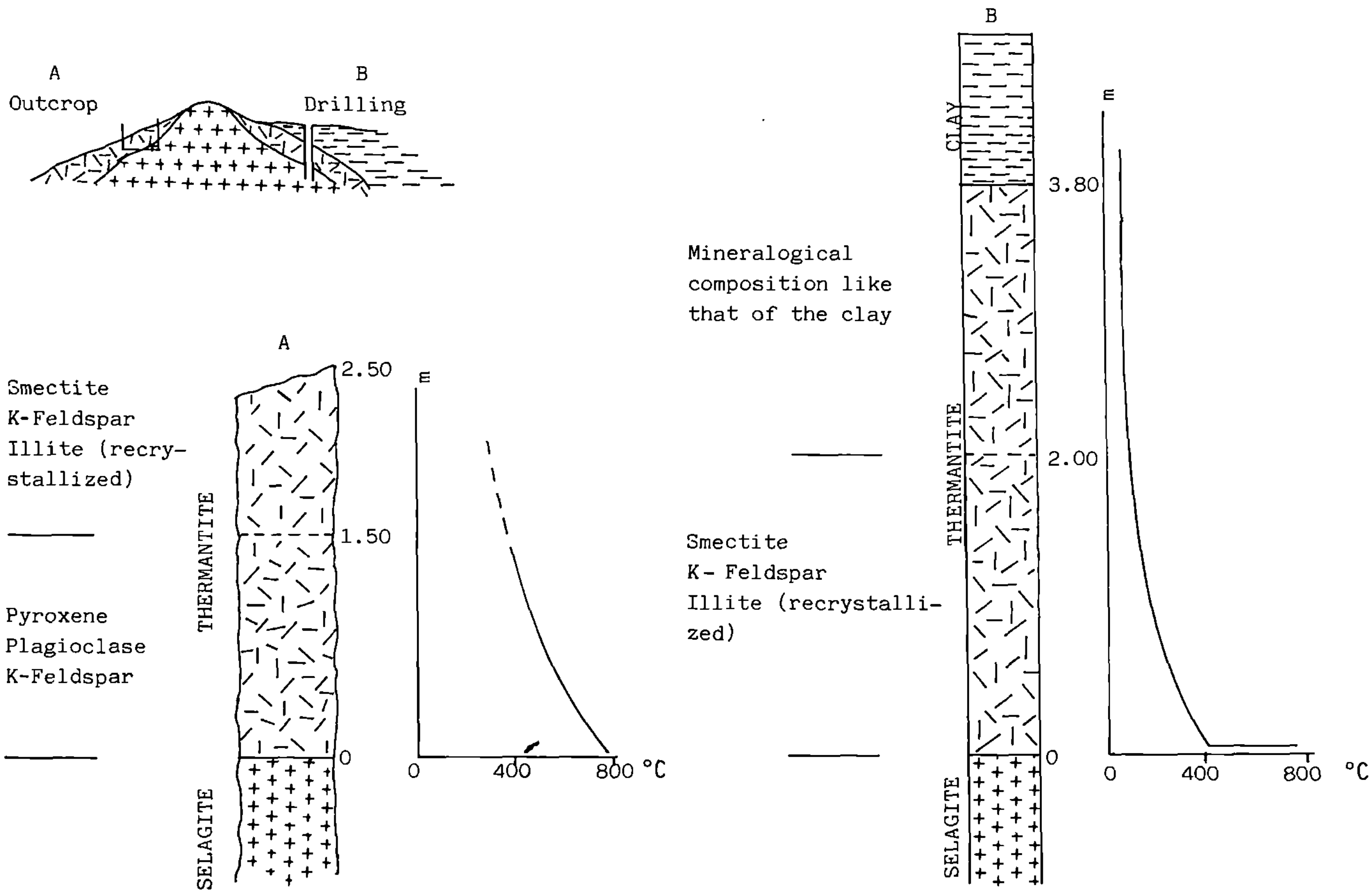


Fig. 20 - Structural and mineralogical transformation of clay at the contact with the intruded magmatic body at Orciatico

fracture pathways (14). A model of a shallow emplacement of hydrous magmas (17) gives reasons for such extensive fracturing of the host rocks, more developed in the region overlying the intrusion roof.
The same model explains the marked hydratation of the subvolcanitic peripherical facies with the consequent extensive smectitization of glass and, to a lesser degree, of Fe-Mg minerals.
Finally it should be emphasized that the metamorphosed clay appears to vary markedly depending upon profile location with respect to the magmatic body (fig. 19): 2 m at the side, 6 m up to 15 m (and probably over) on the top of the subvolcanite. These values suggest an halo shape consistent with an intrusion cooled mainly by a convective hydrothermal system (18).
As a conclusion to the Orciatico metamorphic halo study, some basic indications can be derived. They may be extrapolated by using suitable proportionality factors, to a radioactive waste repository in clays.
Around the Orciatico subvolcanite the argillaceous sediments have been affected by physical, chemical and mineralogical transformations.
(a) Physical transformations, caused by conspicuous recrystallization, mainly consist of a sharp loss of plasticity and of the formation of very hard rocks closest to the contact. Farther away clay is transformed into an indurated scaly shale.
Stresses in the metamorphosed zone caused a diffuse microcracking thus sharply increasing the rock permeability. Some features seem to indicate a permeability of the host rock not negligible even before rock fracturing, probably as a consequence of a high thermal gradient brought about by the Orciatico subvolcanite.
(b) Chemical transformation mainly consists in an important migration of higly mobile elements such as alkalis (Na K = Rb) and alkaline earths (Ca Ba Sr) resulting from hydrothermal circulation. In the Orciatico structure the zones affected by cation migration appear to extend for distances up to 15 m as for Na in one profile.
(c) Mineralogical transformations are mainly a destabilization of the original clay minerals (illite, vermiculite, chloritic intergrades and illite/smectite interstratified) leading to crystallization of smectite and feldspars.
Such a process of smectitization is particularly important; it appears to affect the whole of the halo, including the zones not modified by metasomatic changes. The relatively large amounts of

smectite explain the high C.E.C. (cation exchange capacity) observed in metamorphosed clays; in fact these values are similar to, or even higher than, the ones of non-metamorphosed sediments.

Neo-formation of smectite, which is especially remarkable among the modifications induced by the Orciatico heat source, seems to provide positive informations about thermal stability of bentonites commonly proposed for use as backfill materials in nuclear waste repositories (19). The present study data not only suggest that - in presence of water - backfill bentonites can perform as stable materials at high temperatures, but that under such conditions smectites can be even neoformed in the host argillaceous formation.

Attention must be paid to the following points.

(a) The relevant size difference between the two heat sources, which obviously affects the heat released (Orciatico subvolcanite volume: probably 10^6 to 10^7 m^3; standard radwaste repository in clays: Mol, total volume of vitrified waste 10^3 m^3 related to an electro-production of 10 GWe, 30 years (20)).

(b) The different maximum heat source temperature (800° C and over, for the Orciatico subvolcanite, 100° C for a radwaste repository (19)), which affects the thermal gradient and then, after all, the width of the metamorphic halo.

(c) The probable different importance of fluid circulation (the main cause of chemical mobilization) around the two heat sources. In the Orciatico structure the fluid circulation has been induced by a high thermal gradient, but greatly enhanced mostly by the growing of a diffuse microcracking. In the case of a shallow intrusion this phenomenon may be interpreted as resulting mainly from magmatic fluid pressure (17); it is most probably much less important around a radioactive waste repository, where mainly thermally induced mechanical cracking and hydrofracturing by expansion of pore fluids can be produced.

THE FOSSIL FOREST OF DUNAROBBA. A FURTHER NATURAL EVIDENCE OF THE LONG TERM ISOLATION CAPACITY OF CLAY. (°)

This final chapter gives information on a discovery really significant with regard to the isolation capacity of clay. During recent past years a forest has been found within clay in the Tiber Valley. At the present just a few scientific articles have been published. Most information derive from historical and journalistic materials. Nevertheless the authors consider the available elements sufficient, reliable and worthy for a presentation in this work.

The excavation of clay in the Dunarobba quarry, near Terni (central Italy), has brought to light some tens of tree trunks. The host rock is a lacustrine clay of the upper Villafranchiano; the clay was deposited about 1,500,000 years ago.

This discovery is extraordinary from some points of view:

- the trunks mauntain their original position of life, that is they are still vertically planted (subvertically in reality), rooted and spaced according to their ancient natural distribution;
- no other example of such remarkable number of fossil trees in physiological position is known in the world literature;
- in spite of the quite long period of burial the trunks are still made of wood. The lignitification process seems really not to have initiated;
- the original ligneous structure is perfectly preserved.

As to the size, the single trunk remnants may exceed 1.5 metres in diameter and 8 metres or more in height.

Much greater specimens were found years ago elsewhere in the same region. Figure 21 reproduces the case of an enormous trunk, now completely destroyed, found near Todi (23).

The botanical classification carried out for similar situations in the region (24) would indicate tropical species, such as Taxodium sp. and Nissa sp., no more living in Europe. These species could exceed the height of seventy metres. Fallen logs thirty metres long are reported in the region of the discovery (22).

The occurrence of the fossil trees, was already known during the seventeenth century to one of the most Italian famous humanists (25) as well to foreign people (26). The matter was also the object of a treatise in the same period (27). Mention is made of trees both totally or partially transformed into lignite, or maintaining

(°) Information and bibliographic materials on which this chapter is built were kindly supplied by Mrs. Rita Montani Cirinei.

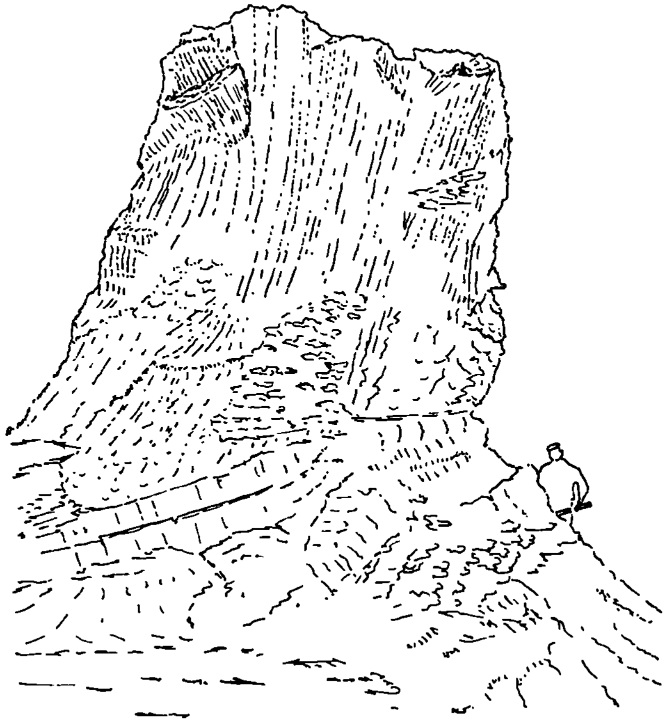


Fig.21 - This enormous trunk has been preserved for about 1,500,000 years by clay. Now it is destroyed. At the moment of its discovery it was still wooden and it maintained its physiological structure and position (Todi quarry, Tiber Valley).

their original structure and woody composition. In both cases the hydrological isolation and/or the geochemical barrier within clay assured the preservation of the organic perishable material. Some cases of observed smoke uprising from undergound were probably due to the autocombustion of lignitic bed or directly of the ligneous trunks themselves. Autocombustion of lignites is well known in a similar situation at the lignite mine of Castelnuovo dei Sabbioni in the upper Arno Valley. The combustion takes place when lignite beds are exposed to the atmospheric oxigen in the case of the erosion of the landscape.The termometamorphic alteration of clay embedding lignite under combustion testifies of a top temperature of 1200°C.
The clay banks containing the trunks at Dunarobba are overlain by sand deposits in which oxidizing water freely circulated for a long time. According to the gathered information (22), which need further support, the thikness of clay covering the trees levels doesn't exceed some metres or tens of metres. Moreover the whole environmental conditions determinated by regional uplift, erosion and circulation of oxydizing water in sandy banks, overlying or interbedded with clay deposits, should be considered as generally unfavorable to the preservation of the ligneous trunks.The fact that these latter still exist is due to the host clay, behaving as perfect isolation medium.

CONCLUSIONS

The most significant factors on which the isolation capacity of clay can be evaluated are:
- the physical barrier
- the geochemical barrier

Hereafter the results of the many observations carried out on clay widespread on the Italian territory and their meaning with regard to the above mentioned factors are summarized. The observations on natural parameters, the controlling factors, the environmental conditions of the media and the evolutive processes have been conducted on subjects characterized by the same or greater time-space scale involved with the disposal of waste. This is a real advantage with regard to the limited laboratory experiences, which are normally conducted on limited samples, during limited time.

The physical barrier is mostly constituted by the very limited permeability of clay. From a practical point of view clay may be considered impermeable. Such impermeability is generally supposed to be affected by tectonic stress. Faults and fractures consequent to tectonics are thought to give rise to a secondary permeability within clay. Obviously the creation of such structures represents a normal event in regions subjected to active orogeny, as in the case of the Italian territory. The simple fact that the studied clays, originally accumulated on the sea bottom, now form the substratum of large part of the continental landscape is an indication of the tectonic movements they underwent. Faults are very seldom observable directly on the natural ground surface where fractures are frequently evidenced by oxidation bands. They are both normally visible on clay walls in quarries and tunnels. Faults are often evidenced by sedimentary markers such as sandy and lignitic levels. Extended direct observations made at the ground level and in tunnel have univocally indicated that penetration and simple seepage of water is only limited to a few tens of metres from the topographical surface. Ochre colored edges along fractures give geological evidence of a same extent of past penetration of surface or phreatic waters with oxidizing capacity. On the contrary fault planes are always free from chemical alteration caused by such kind of water penetration in fractures. Studies are in course to ascertain if fault plains may be a preferential way of water circulation or not. Self-sealing of fault planes may be a phenomenon which develops when some sliding occurs. This could explain the different hydraulic behaviour of fault and fractures. As it appears from direct observation, the oxidized fracture is always connected with a deeper unaltered fracture. As till now observed it seems that the near-surface decompression phenomena cause the latent fractures to be opened to the penetration of ground water. The sequence of the phenomena involved is the following: tectonic stress induces faults and fractures in clay; regional movements uplift clay formations; erosion eliminates or simply diminishes the lithostatical load on fractures; near surface fractures become opened and surficial water penetrates inside.

The study of natural tracers of deep origin demonstrated that clay formations behave as an impermeable mass. The migration of carbon dioxide, mercury and geothermal fluids, in very hot and higly pressurized condition, is always confined at the edges of clay basins, in the position where both thickness and homogeneity of clay formation is weakened or disappear. The magma intrusion in clay at Orciatico is the extreme demonstration of the clay containment capacity of a dramatically active body (for both the great volume of the intrusive mass and the fluids and gases developed at high temperature and pressure). Clay is heavily modified at the strict contact with the magmatic body, but it is completely unaffected some metres away. The lack of traces of fluids or gases transit in the clay surrounding the subvolcanic body and the modified clay testifies the almost absolute impermeability of the clay itself.

Among the natural tracers of deep origin helium is the only natural element with the capacity to penetrate along fractures and faults even in zones impermeable to the other natural tracers. Actually some helium outcomes have been recognized also in the central part of a clay basin in central Italy. However large masses of clay in the same basin have demonstrated to be an absolute obstacle to the helium transit. In other terms even helium is not allowed to freely circulate within clay masses unaffected by tectonics.

The fact that a fossil forest still exist inside a clay mass surrounded by aggressive oxidizing waters, is a further evidence of the effectiveness of clay to represent a true physical, and also geochemical impermeable barrier. If exposed to oxidation, the still woody trees would have been destroyed in a short time.

The geochemical barrier lies on two principal factors: the exchange capacity and the physico-chemical conditions.

As concerns the former factor it must be kept in mind that each normal transformation from one species of clay into another (i.e. from illite into smectite) could represent a variation but not an obligatory significant decrease of the exchange capacity. From this point of view, Orciatico represents an extraordinary case of deep transformation characterized by an increase of the exchange capacity with respect to the original clay.
The normal physico-chemical conditions of the clay medium correspond to a very low or even negative redox potential (in other words to a reducing condition). Clays acquired this characteristic at the sedimentation time on the sea bottom. It accounts for their capacity of immobilizing long lived radionuclides, such as alpha emitters (Pu, Am, Np, ...). The exposition to the atmospheric oxigen and surface water may cause the reducing environmental condition to be turned into the oxiding one. Such a variation would determine alpha emitters to be mobilized.
As demonstrated by field observations, oxidation has a deep influence on sandy levels and banks overlying or interbedding clay as well as on surface fractures.
The oxidation is a consequence of the alteration due to external factors, such as uplifts, faulting, fracturing. Such phenomena do not develop under normal conditions.
In each case the altered clay is always a very few centimeters thick. The geochemical barrier is uninfluenced beyond such a thickness. On the other hand it is well known that deep waters may display a reducing behaviour as well. Therefore the reducing environment may also exist largely above the top of the clay series and it may represent a supplementary geochemical barrier to radionuclide migration. Fossil evidences of the past existance of this kind of environmental situation have been recognized in Italy.

In conclusion the physical and geochemical barrier effect displayed by clay is a general character of this kind of rock. Their efficiency may be considered greater and almost absolute in the case of deeply seated clay. Only the transportation of host clay in the surface zone, because of general uplifting with respect to sea level and consequent erosion or because of simple erosion, may affect such barrier capacity. Really the uplift may cause the direct destruction of a possible waste repository. Geochemical destabilization due to oxidation would be the simple immediate precursor of the physical

destruction. Therefore erosion really remains the principal destructive agent to be seriously considered. Minor importance must be attributed to earthquakes and hydraulic variation as well as to possible modifications induced by thermal release from the wastes. As a matter of fact in this case the geological barrier remains completely intact at short distance from the waste. The containment guarantee is undoubtely assured.
The selection of sites which would be suitable for the construction of waste repositories must be based first and foremost on a thorough examination of external factors and possible circumstances. Risk analysis is one of the means of studying the evolution processes to which the geological frame and structures of the individual sites considered are subjected. Assessments of the general and local circumstances are in any event a vital means of determining the accuracy and suitability of the analysis of the risk associated with the sites considered.

Subsiding zones correspond to the best situation for disposal, and stable zones are surely acceptable. Uplifting zones are not to be excluded in principle. However, in this case, regional uplifting and consequent erosion velocity must be accurately quantified with regard to the necessary time of waste confinement. Appropriate investigations must be carried out in order to select the most homogeneous masses, possibly not heavily affected by tectonic disturbances.
The detection of helium in soil, boreholes and tunnels may help in localizing the most reliable situations.

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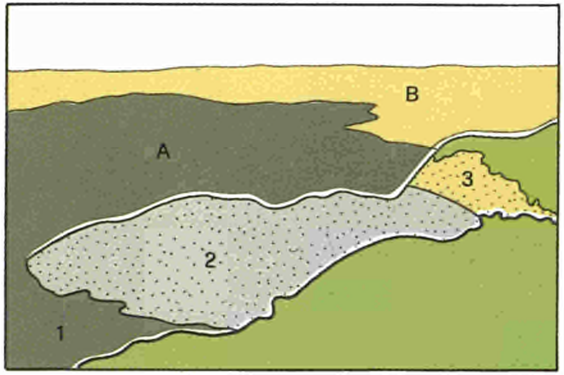
ICONOGRAPHICAL ATLAS



"Le Balze" at Volterra - Tuscany

THE LANDSCAPE OF PLIOCENIC CLAYELY FORMATIONS.

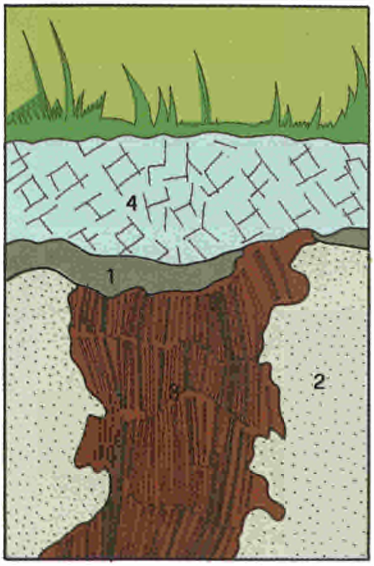
LEGEND

A - clayely landscape
B - sandy landscape
1 - reduced clay formation
2 - reduced sand bank
3 - oxidized sand bank

NOTES

On the right side it is possible to observe the recorded of a fossil hydrological situation. The separation plane between the upper yellow sand and the lower gray sand corresponds to the ancient oxido-reduction front.

PLATE I



Dunarobba fossil forest (see plate XXIII)

GEOCHEMICAL AND PRACTICAL MEANING CONNECTED TO THE GRAY COLOUR OF SEDIMENTS (SANDY SEDIMENTS PARTICOLARY)

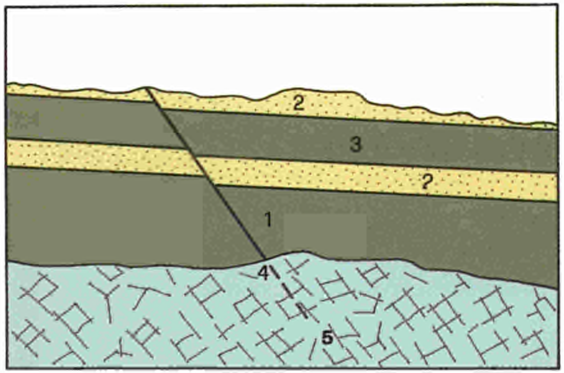
LEGEND

1 - clay
2 - reduced sand
3 - buried fossil trunk
4 - artificial debris and clay

NOTES

The picture shows a tree trunk embedded in a permeable sandy sediment in which the different colored zones (a stratum of yellow sand is present at the same level in a zone beside the one shown in the picture) assume a specific chemical-physical meaning, where the gray reduced zone is probably induced by a chemical reducing system becoming by the organic matter transformation that leaves unaltered the characteristics of trunks wood. The fundamental importance of this geological situation is the evidence that also a permeable unit displays reducing characteristics assuring a very low grade diffusion of transuranic radionuclides eventually introduced. That means a practical long term immobility considering the time life of the principal nuclides. This immobility condition may be also artificially reproduced by using appropriate sealing and backfill materials, i.e. a clay-organic matter mixture, in the man made barriers.

PLATE II



Orte quarry - Latium

PANORAMIC VIEW OF THE UPPER PART OF A PLIOCENIC CLAY FORMATION.

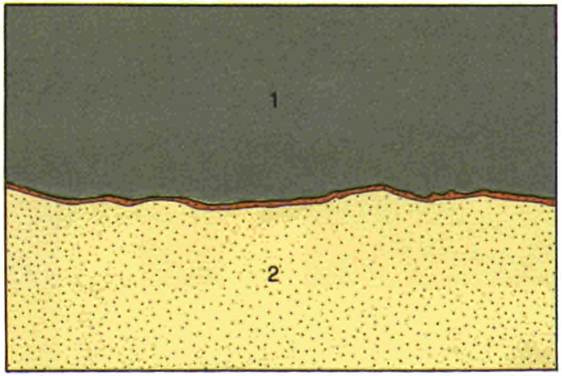
LEGEND

1 - massive lower clay bank
2 - oxidized sand levels
3 - interbedded clay and oxidized sand levels and bank
4 - fault
5 - debris

NOTES

The 3 complex corresponds to a deltaic sedimentary environment.
The 3 complex undergoes to a strong oxidation action because of circulation of meteoric water; oxidation totally affects the sandy components; clay levels appear to be unoxidized (see plates from IV to X).

PLATE III



Orte quarry - Latium

CONTACT BETWEEN CLAY AND SANDY LEVELS (DETAIL OF PLATE III)

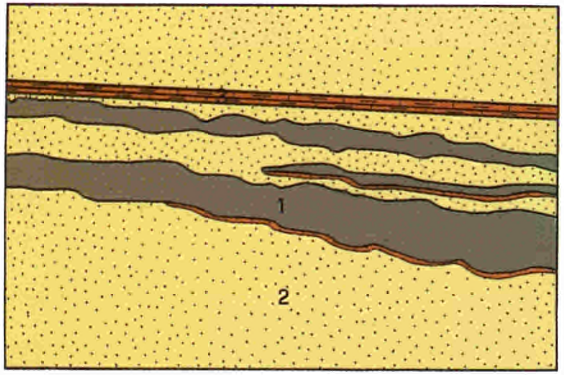
LEGEND

1 - clay
2 - sand

NOTES

The boundary between reduced clay and oxidized sand is marked by a thin ochraceous coloration in the sand due to the effect of the physical barrier to the migrating solutions as well as of the physical-chemical (redox) condition of clay.

PLATE IV



Orte quarry - Latium

INTERBEDDING OF SAND AND CLAY LEVELS (DETAIL OF PLATE III).

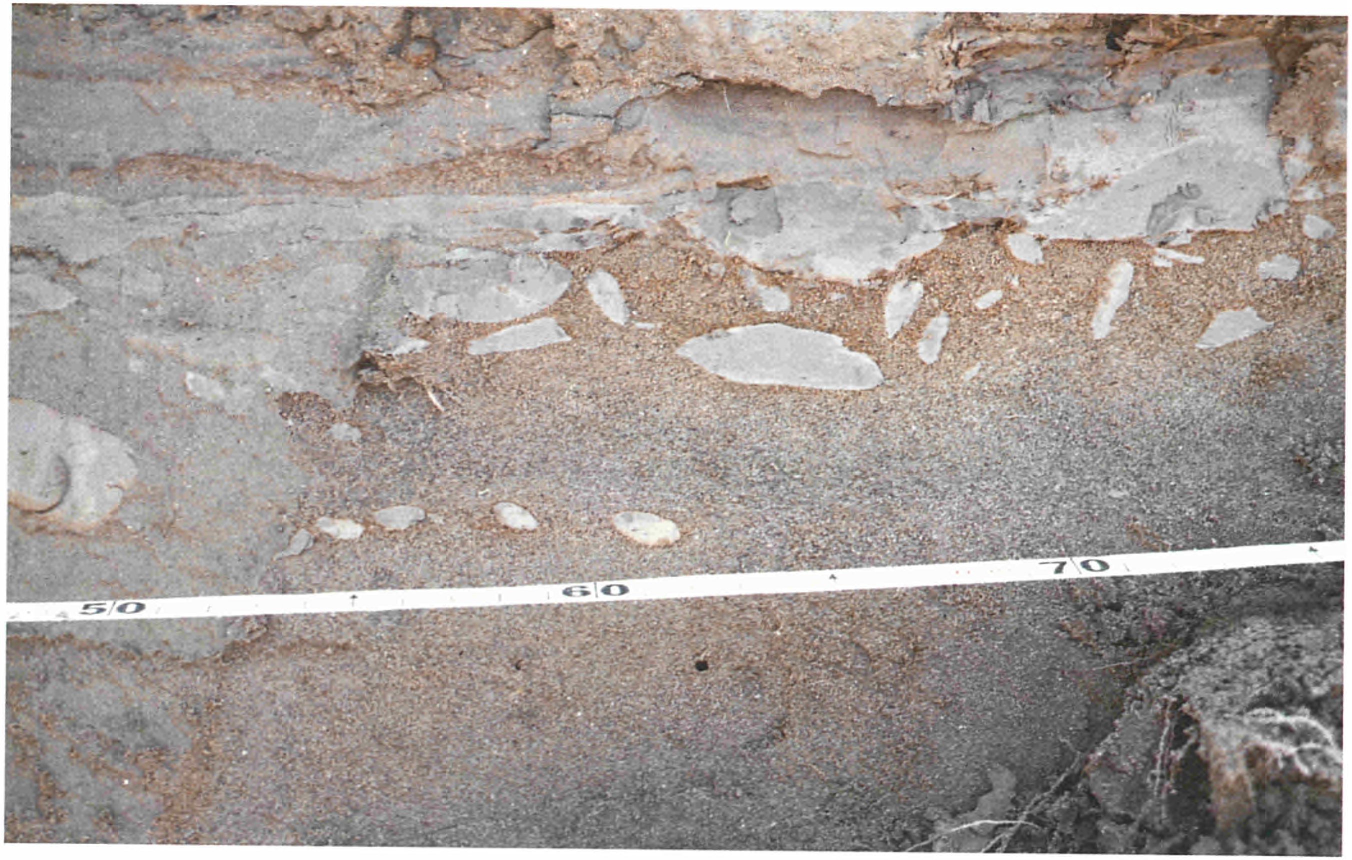
LEGEND

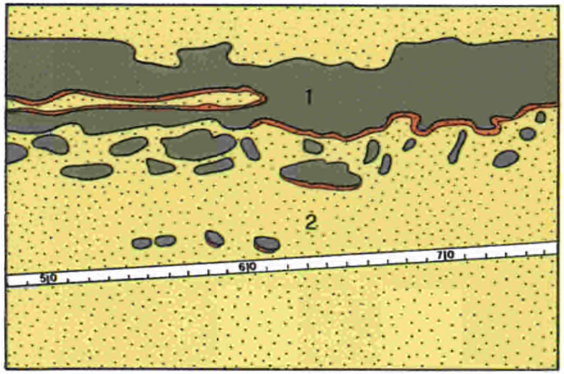
1 - clay
2 - sand
3 - marl

NOTES

The ochraceous coloration develops also at the boundaries of a very thin (about 1 cm) marl level.

PLATE V


50
60
70



Orte quarry - Latium

CLAY FRAGMENTS DISPERSED WITHIN A SANDY OXIDIZED LEVEL (DETAIL OF PLATE III).

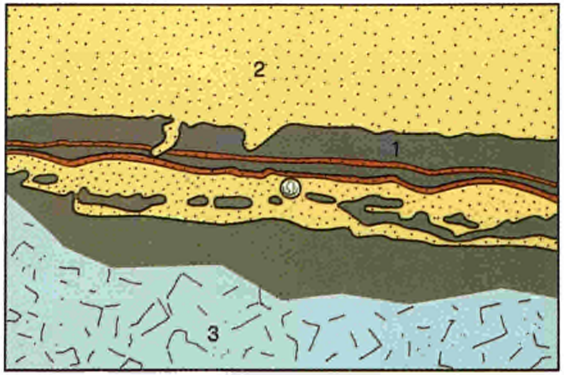
LEGEND

1 - clay
2 - sand

NOTES

Very little clay fragments maintain their original reduced character within the surrounding oxidized sand.

PLATE VI



Orte quarry - Latium

INTERBEDDING OF SAND AND CLAY LEVELS IN A DELTAIC ENVIRONMENT (DETAIL OF PLATE III).

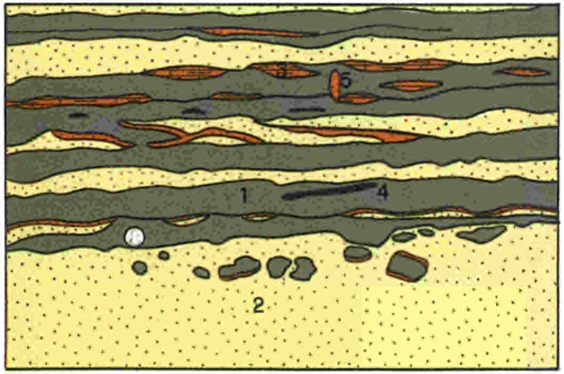
LEGEND

1 - clay
2 - sand
3 - debris

NOTES

An extremely thin and regular sandy level, contained within clay unaltered is oxidized. It is in hydraulic connection with the sandy complex embedding clay levels.

PLATE VII



Orte quarry - Latium

INTERBEDDING OF SAND AND CLAY LEVELS IN A DELTAIC ENVIRONMENT (DETAIL OF PLATE III).

LEGEND

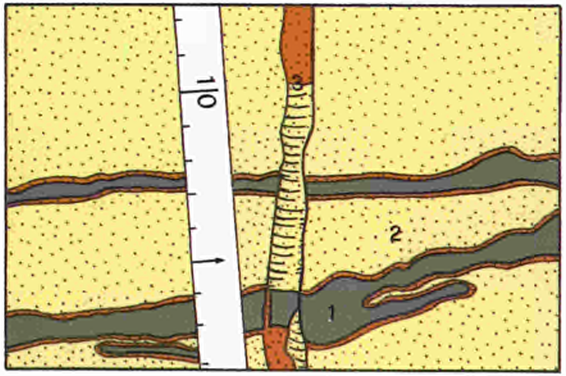
1 - clay
2 - sand
3 - marl
4 - coal and woody relics
5 - worm burrow

NOTES

Oxidation affects marl lenses as well as all sandy components, including sand contained in worm burrows crossing clay. Clay is unaltered. Coal and wooden fragments are protected by the low permeability and by the reducing environment of clay.

PLATE VIII


10



Orte quarry - Latium

WORM BURROW CROSSING INTERBEDDED CLAY AND SAND LEVELS (DETAIL OF PLATE III).

LEGEND

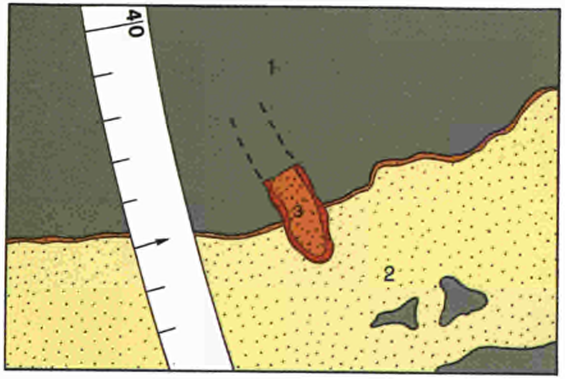
1 - clay
2 - sand
3 - worm burrow

NOTES

Worm burrow crosses both clay and sand levels causing hydraulic connection among sandy bodies separated by clay levels.
Grain size within burrow cavity is coarser than in sand level. Its permeability is therefore the highest in the whole system.

PLATE IX


40



Orte quarry - Latium

WORM BURROW CROSSING A CLAY-SAND BOUNDARY (DETAIL OF PLATE III).

LEGEND

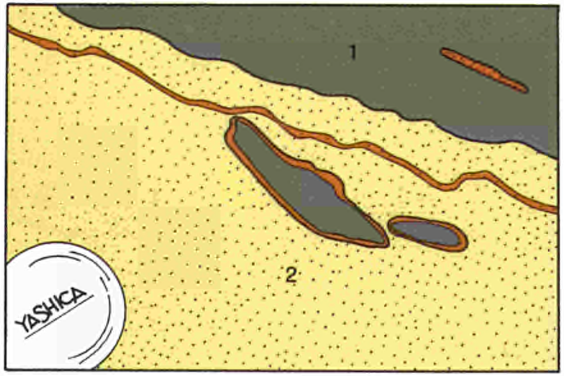
1 - clay
2 - sand
3 - worm burrow

NOTES

The sand within burrow is strongly oxidized. An intense ochraceous colorations evidences the different permeability grade occurring also between the sand filling burrow and the less coarse grains of sandy level.

PLATE X


YASHICA



S. Angelo dei Lombardi quarry - Campania

SILTY CLAY FRAGMENTS DISPERSED WITHIN A SANDY OXIDIZED LEVEL.

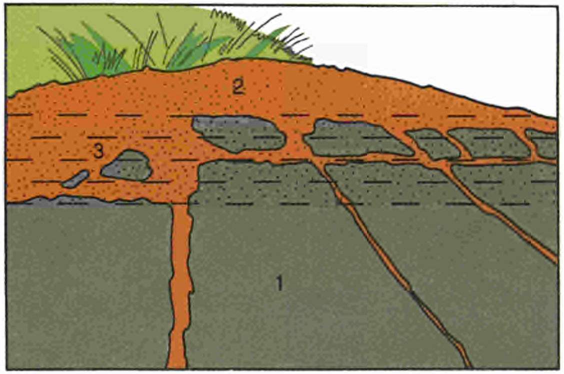
LEGEND

1 - silty clay
2 - sand

NOTES

The ochraceous coloration in this case affects the rim of the silty clay both in the fragments and in the bank. Part of the silty clay bank can be slightly oxidized starting from the boundary with sand.

PLATE XI



Val Topina road cut - Umbria

OXIDIZED BANDS ALONG FRACTURES IN CLAY.

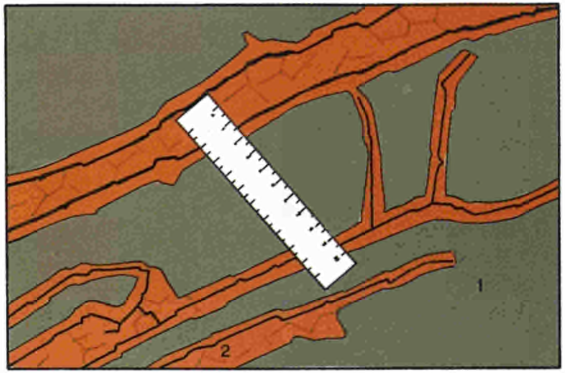
LEGEND

1 - clay
2 - surficial soil and sediment
3 - silty clay

NOTES

The oxidation of surficial soil and sediments develops along the near clay fracture network.

PLATE XII



Benevento quarry - Campania

FRACTURE OXIDATION IN CLAY.

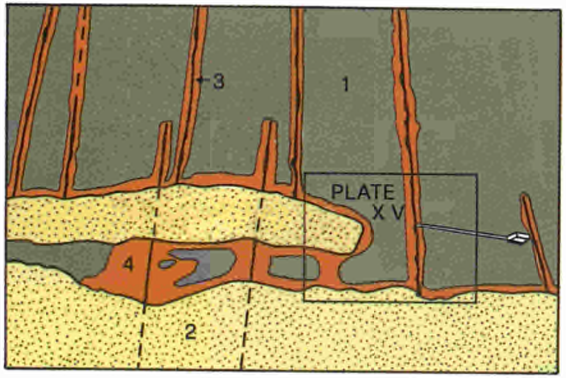
LEGEND

1 - clay
2 - oxidized halo

NOTES

The oxidation along principal and secondary fractures spreads within the clay body for a width of centimetric order.

PLATE XIII



Narni quarry - Umbria

OXIDATION ALONG FRACTURES IN CLAY AND CONNECTED SANDY LENSES AND BANKS.

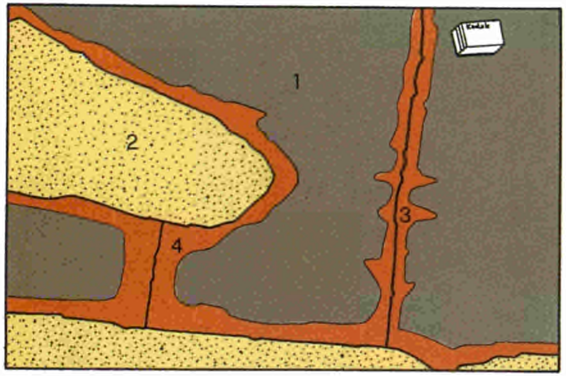
LEGEND

1 - clay
2 - sand
3 - oxidized halo
4 - oxidized clay

NOTES

The fracture network in clay and the permeable sandy bodies constitute a continuous hydraulic system. Oxidation from upper soil or from underlying sandy bodies permeate the whole system, clearly affecting the clay rim both in correspondance of fractures and at the contact with sand.

PLATE XIV



Narni quarry - Umbria

OXIDATION ALONG FRACTURES IN CLAY AND CONNECTED SANDY LENSES AND BANKS (DETAIL OF PLATE XIV).

LEGEND

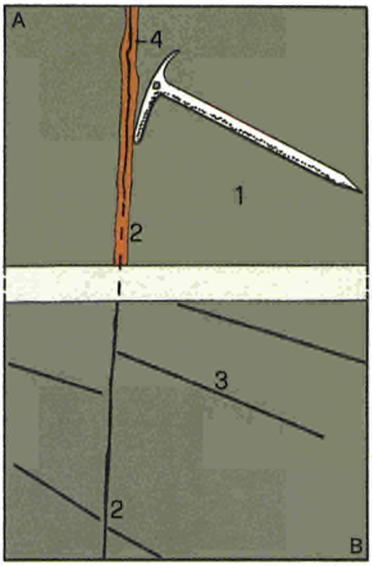
1 - clay
2 - sand
3 - oxidized fracture halo
4 - oxidized clay

NOTES

The hydraulic continuity and the connected oxidation within sand and clay is well evidenced.

PLATE XV

S. Quirico d'Orcia - Tuscany -



REAL PENETRATION DEPTH OF OXIDATION INTO THE CLAY MASSES.

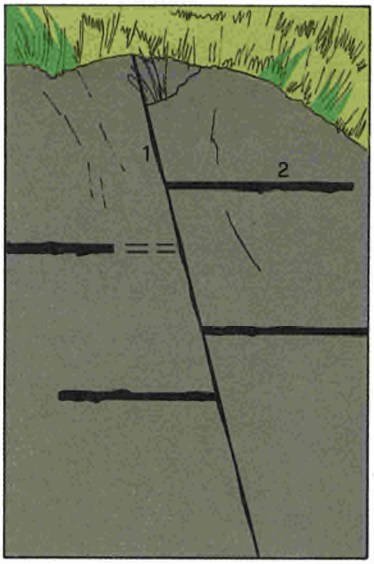
LEGEND

A - upper part
B - lower part
1 - clay
2 - primary fracture
3 - secondary fracture (decompressional feature: see G, PLATE XXI)
4 - oxidized halo

NOTES

The oxidation generally spreads along fractures in the upper part of the clay bodies until a depth of no more than some tens meters from land surface. In this case the unoxidized fracture of B part of the plate is located at about 20 meters from the land surface.

PLATE XVI



Magliano Sabina quarry - Latium

EFFECTIVE WATER FLOW ALONG THE FAULT PLANE.

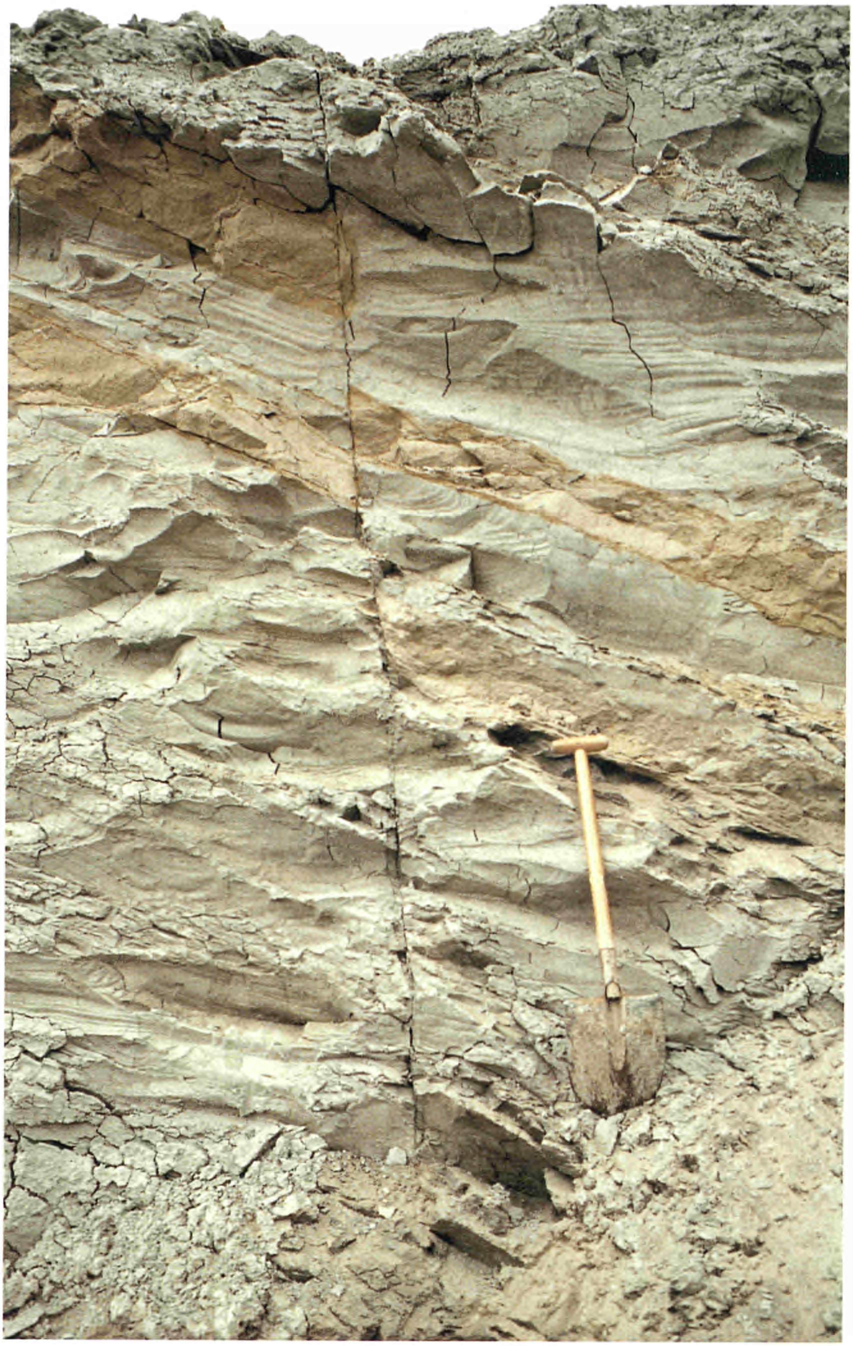
LEGEND

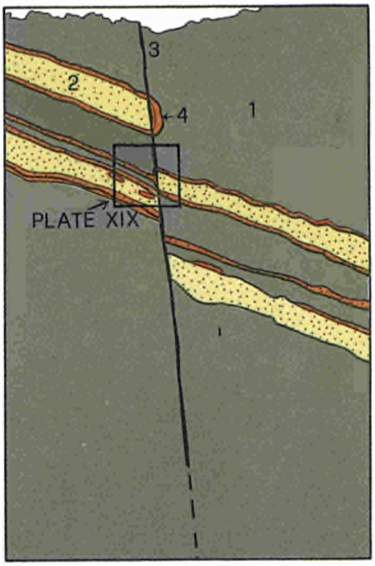
1 - fault
2 - lignitic bed

NOTES

No traces of oxidation occur along the fault plane, as in all the observed cases (including Orte: PLATE III). The absence of the oxidation should exclude any water penetration. Therefore, in comparison to fracture, fault plane appears to behave differently with regard to water penetration and oxidation processes.

PLATE XVII





S. Angelo dei Lombardi quarry - Campania -

EFFECTIVE WATER FLOW ALONG THE FAULT PLANE.

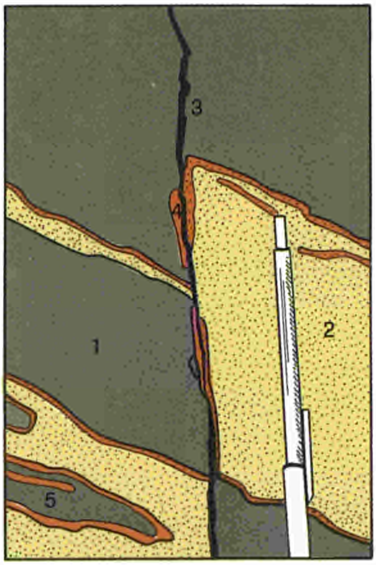
LEGEND

1 - clay
2 - sandy level
3 - fault
4 - oxidized halo

NOTES

Fault is well evidenced by the displacement of interbedded sandy levels.
Clay near the fault plane is not oxidized.

PLATE XVIII



S. Angelo dei Lombardi quarry - Campania -

EFFECTIVE WATER FLOW ALONG THE FAULT PLANE (DETAIL OF PLATE XVIII).

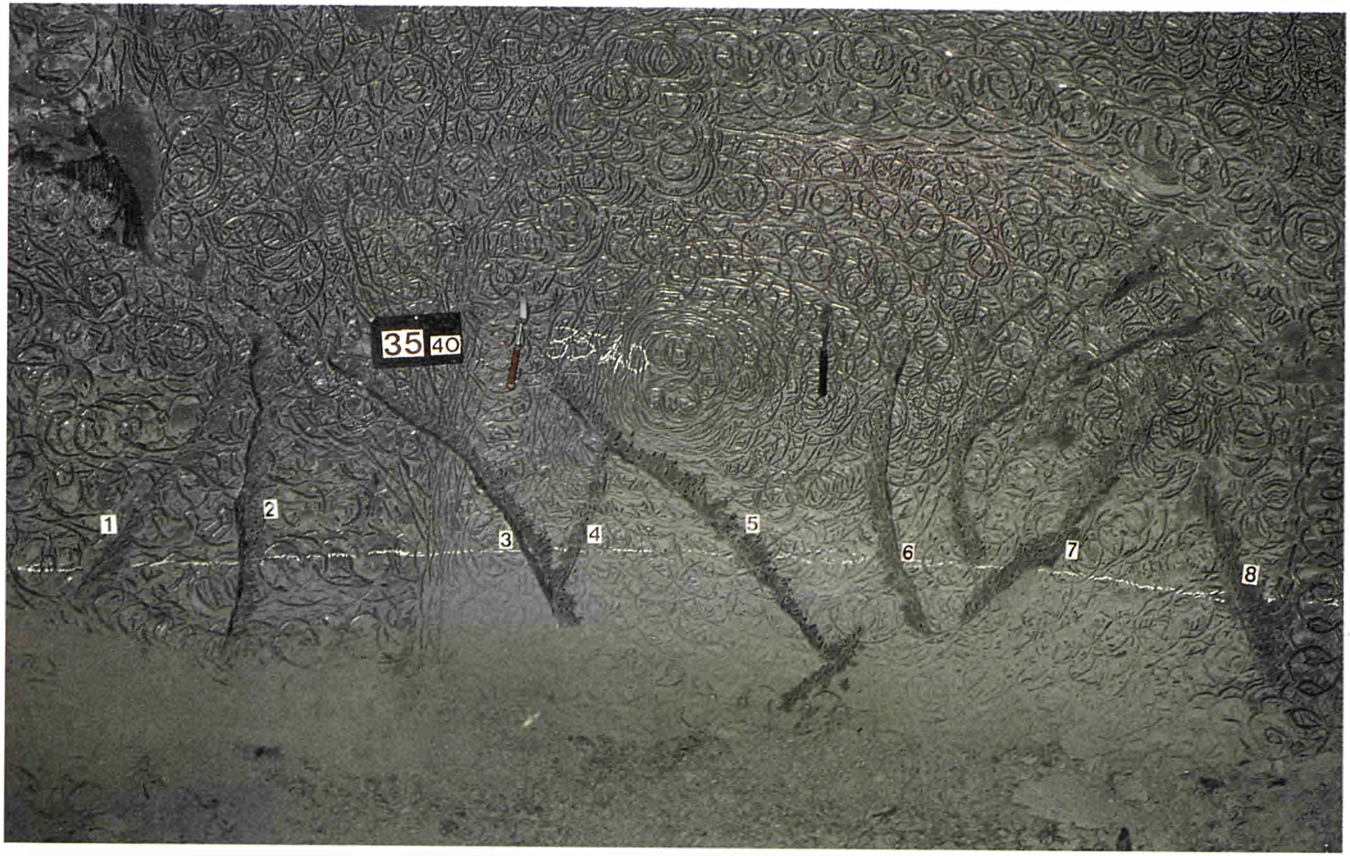
LEGEND

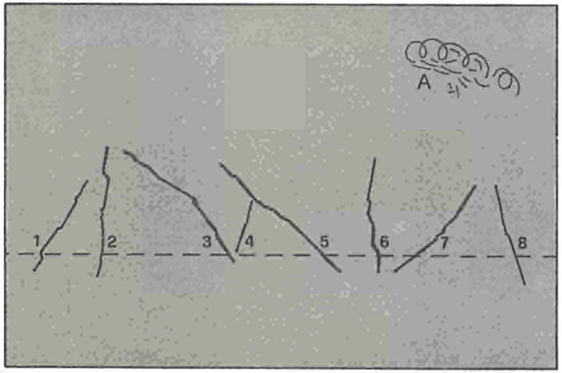
1 - clay
2 - sandy level
3 - fault
4 - oxidized halo in clay
5 - oxidized rim of clay fragments

NOTES

Clay aside fault plane (4) is affected by oxidation only in correspondance of the cut oxidized sandy level (2), permeable to surficial water. Possibility of water penetration along fault planes is apparently excluded.

PLATE XIX


35
40
1
2
3
4
5
6
7
8



Pasquasia mine - Sicily

EFFECTIVE WATER FLOW THROUGH A FAULT SYSTEM AT DEPTH (-160 M FROM LAND SURFACE).

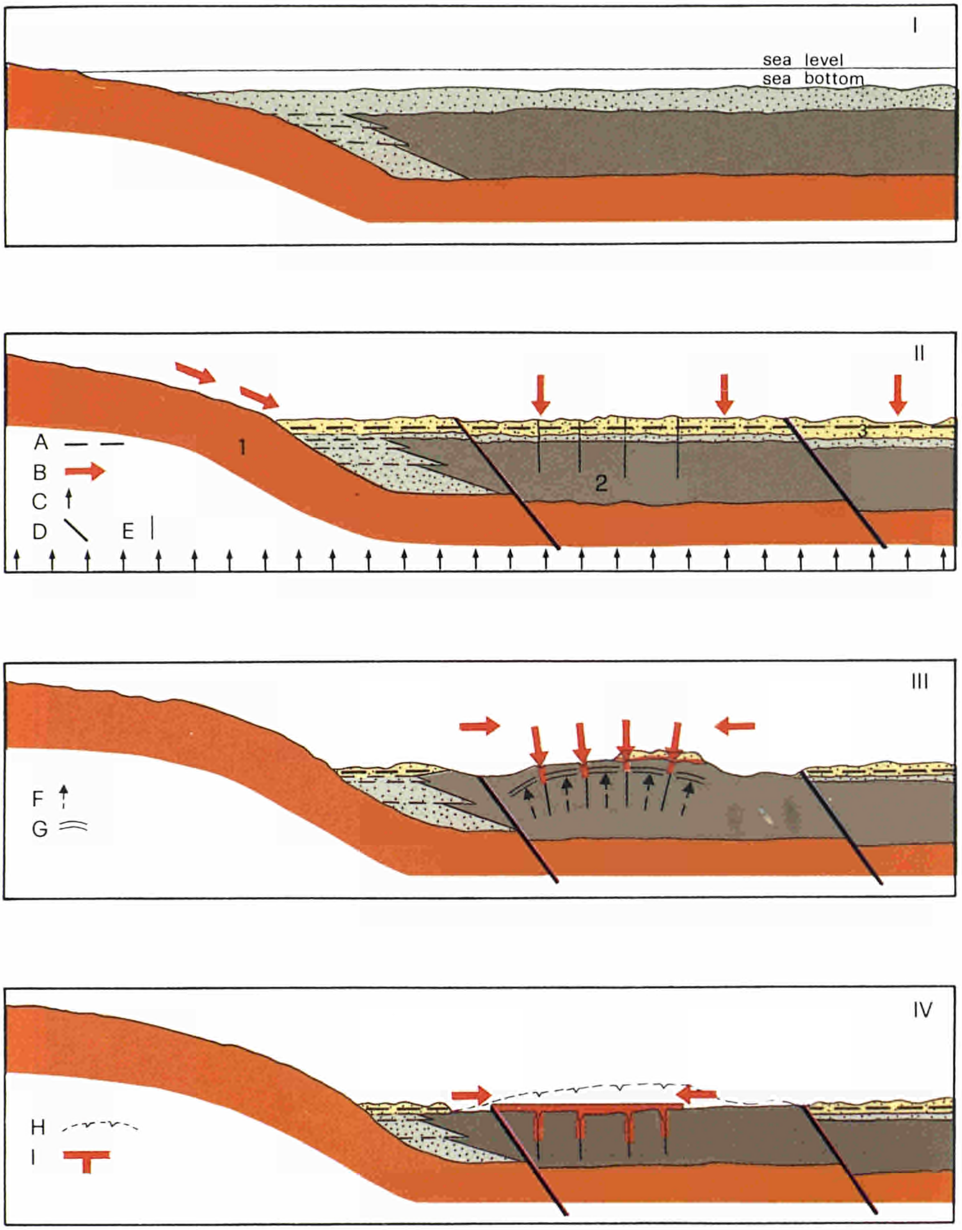
LEGEND

A - excavation trace
1, 2 .... - fault plane trace

NOTES

Several fault traces appear on the excavation front in the underground tunnel. The lacking oxidation account for a complete hydraulic isolation from the overlying (100 m above) ground water reservoir.

PLATE XX


I
sea level
sea bottom
II
A
B
C
D
E
1
2
3
III
F
G
IV
H
I

INTERPRETATIVE SCHEME OF FRACTURE GENESIS AND RELATED OXIDATION PROCESSES IN CLAY

LEGEND

A - water table
B - migrating oxidizing water
C - orogenic uplift
D - fault plane
E - latent fracture
F - unloading uplift
G - decompressional feature
H - upper profile of the eroded masses
I - oxidation process
1 - bedrock
2 - clay
3 - oxidized sand

NOTES

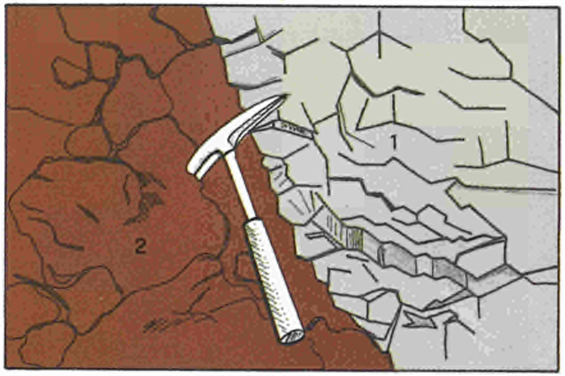
I In the post depositional phase the physical-chemical environment of clay and sand evolves toward to the reduction condition.

II The orogenic uplift induces the development of faults and connected fractures. The marine series emerge and undergo to first erosion and to first circulation of surficial oxidizing water.

III Because of intense erosion clay is unloaded of the overlying lithological masses. The unloaded clay masses undergo to uplift and to volumetric expansion without a parallel mass increase, causing latent fractures to be opened and decompressional feature to be created. First oxidation process along fracture begins.

IV Penetration of oxidizing water into the fracture systems proceeds with the landscape erosion.

PLATE XXI



Orciatico - Tuscany

EFFECTS OF NATURAL HEATING ON CLAY.

LEGEND

1 - thermometamorphosed clay
2 - magmatic body intruded into clay

NOTES

The magmatic body intruded into the clay deposit. Initial temperature was 800 °C. The cooling time lasted some thousand years. Clay was transformed into an indurated rock at the contact (1); its clay minerals were transformed into other different clay mineralogical species (clay to clay) in the 2 to 14 m span from the contact. Beyond 14 m clay is wholly unaltered. Clay behaved as perfect isolating medium with regard to the mechanical and thermal stress caused by the dramatic magmatic intrusion.

PLATE XXII

Dunarobba quarry - Montecastrilli - Umbria

THE FOSSIL FOREST PRESERVED BY CLAY.

(Picture kindly supplied by Marina Cirinei, art director for the visualization and planning destined to the promotion of the cultural and commercial exploitation of the environment)

LEGEND

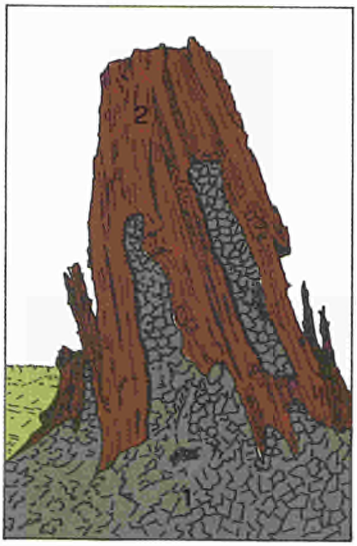
1 - clay
2 - sand
3 - oxidized clay

NOTES

The forest developed at the edge of the ancient tiberin lake during the Villafranchiano period. The age is about 1,500,000 (from 700,000 to 2,000,000) years. The trunks mantain their original position of life. The forest has been preserved because of the constant and absolute isolation from meteoric oxidizing water exerted by clay. Clay indeed acted on the plane of the hydraulic isolation of the tree trunks as well as maintaining the anaerobic condition.

PLATE XXIII

Dunarobba quarry -
Montecastrilli - Umbria



A FOSSIL TRUNK IN LIFE POSITION.

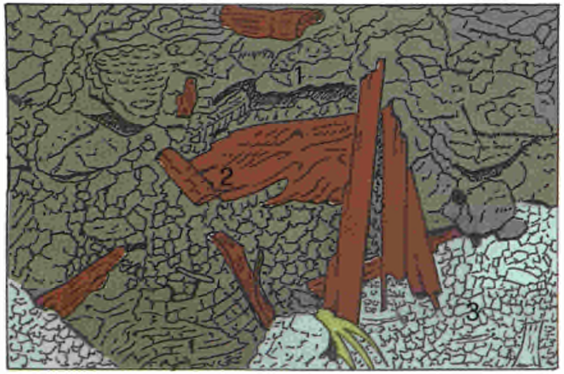
LEGEND

1 - clay
2 - fossil trunk

NOTES

Fossil tree trunk, three meter tall, in physiological position. Relics of protective clay still fill the trunk recesses.

PLATE XXIV



Dunarobba quarry -
Montecastrilli - Umbria

FOSSIL WOOD PIECES EMBEDDED WITHIN CLAY

LEGEND

1 - clay
2 - fossil wood piece
3 - debris

NOTES

Clay levels contain great amount of wooden pieces besides trunks in life position.

PLATE XXV

Dunarobba quarry -
Montecastrilli - Umbria

THE FOSSIL FOREST PRESERVED BY CLAY.

(Picture supplied by Marina Cirenei see plate XXIII)

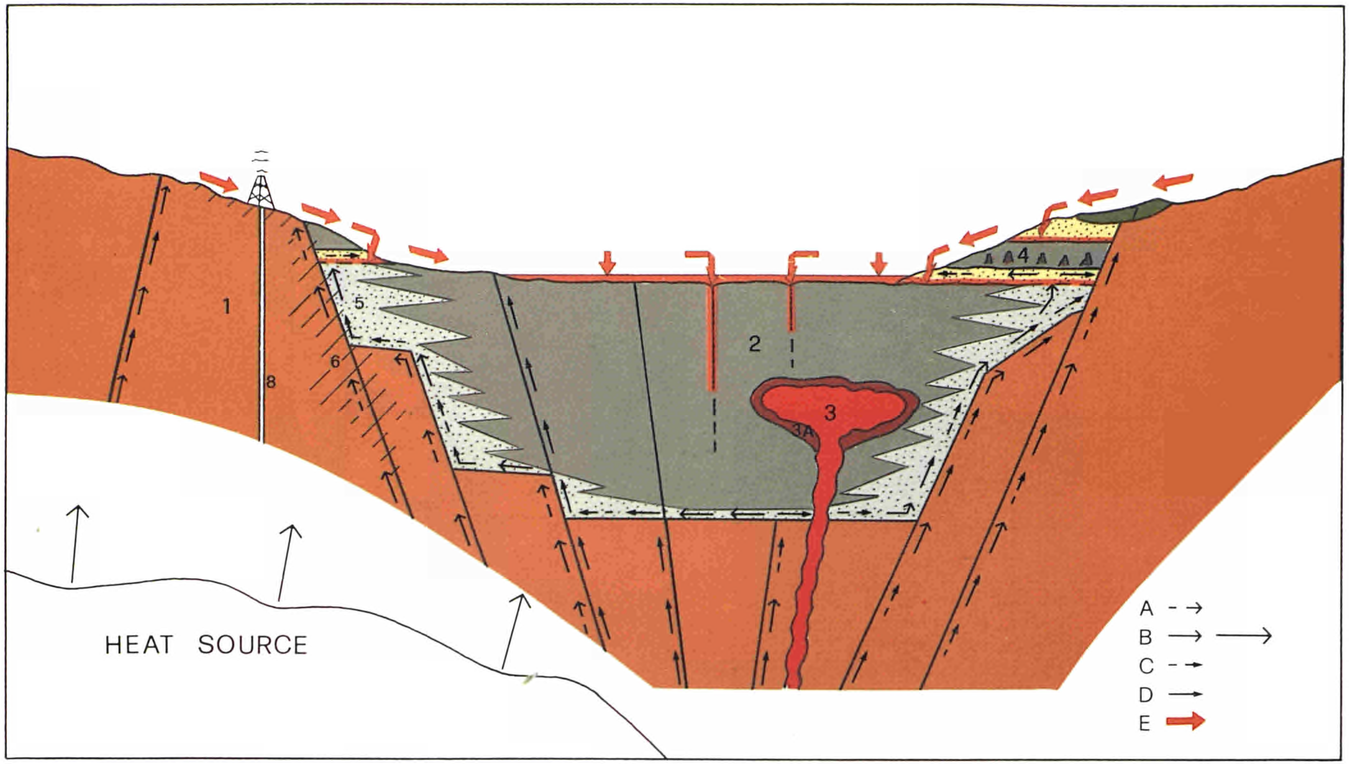
LEGEND

1 - clay fragment
2 - tree trunk

NOTES

The trunks still maintain a perfect wooden feature.
The almost absolute isolation capacity, exerted by a very few meter cover of clay, preserved trunks from every type of alteration for a very long time.

PLATE XXVI


1
2
3
3A
4
5
6
8
HEAT SOURCE
A
B
C
D
E

SYNTHESIS OF THE NATURAL DEMONSTRATION FACTORS OF THE MASS IMPERMEABILITY AND THE ISOLATION CAPACITY OF CLAY.

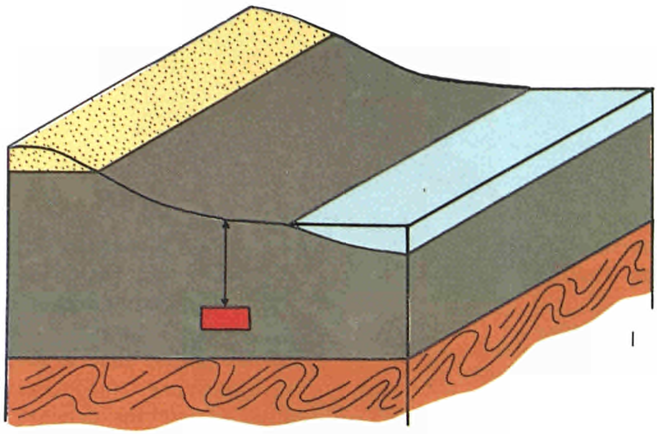
LEGEND

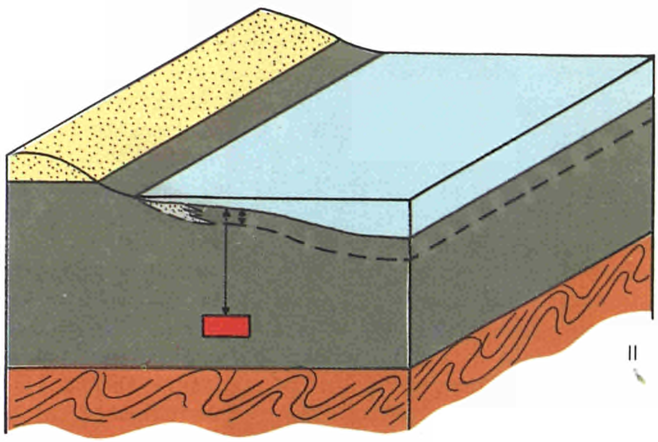
Migration of:
A - mercury
B - geothermal fluids
C - carbon dioxide
D - helium
E - meteoric water

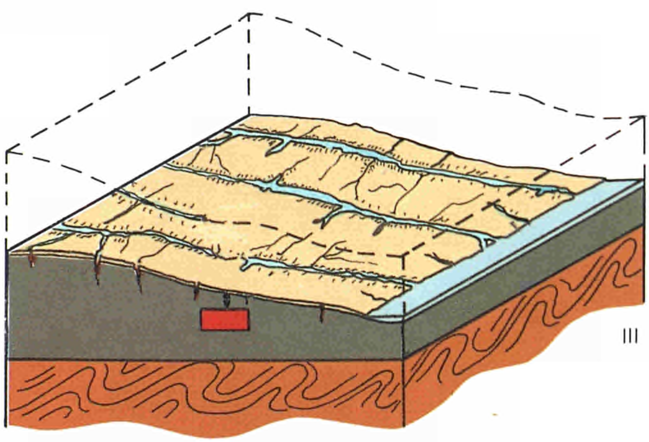
1 - basement
2 - clay formation
3 - magmatic intrusion
3A - thermometamorphic halo
4 - fossil forest
5 - reduced sand deposit
6 - mercury concentration
7 - travertine deposit
8 - geothermal exploitation

Mercury (A) mobilized by deep heating sources and geothermal fluids (B) migrating upward along regional fault planes are deviated aside from the clay mass. The same trend is shown by carbon dioxide flow (C) regionally coming from depth. Mercury (6) and travertine deposits (7) occur only at the marginal part of the clay basin. Only helium (D), the most mobile element on the earth, coming from the mantle, may cross clay along some recent fault planes. Outside recent fault planes clay is impermeable even to helium.
Clay demonstrates to be a perfect isolation medium with regard even to a magmatic intrusion (3), which is completely confined in spite of the exerted extreme mechanical and thermal stress. Clay is a perfect isolating medium able of perfectly preserving for long time a perishable material such as wood and structure of a fossil forest (4). Meteoric water (E) alterating the original reduced physical-chemical condition of clay can penetrate along surficial fracture in clay only for some tens meters. No trace of alteration by meteoric water has been observed along fault planes in clay. If clay is or not permeable along the fault plane is a present matter of study. Sand deposits (5) maintain their original reduced physical-chemical condition below the minimum level raised by oscillating water table.

PLANE XXVII


I


II


III

PERSISTENCE THROUGH TIME OF A WASTE DEPOSIT IN CLAY.

The intrinsic isolation capacity of clay has been demonstrated by means of natural evidences. Therefore the safety of a waste repository built within clay chiefly depends upon the general geological evolution. Three cases are possible:

I The waste repository is constructed in a geologically stable condition. The normal geomorphological evolution does not significatively affect the deposit safety.

II The waste repository is constructed in a subsidence geological situation. The deposit isolation and safety are increased by the new added sediments.

III The waste repository is constructed in a situation of regional orogenic uplift (or of accentuated sea regression). The erosion rate of the landscape must be accurately calculated and compared with the necessary isolation period of the waste repository.

PLATE XXVIII

European Communities — Commission

**EUR 11896 — Natural analogues and evidence of long-term isolation capacity of clays occurring in Italy
Contribution to the demonstration of geological disposal reliability of long-lived wastes in clay**

F. Benvegnù, A. Brondi, C. Polizzano

Luxembourg: Office for Official Publications of the European Communities

1989 — VIII, 101 pp, num. ill. — 16.2 x 22.9 cm

Nuclear science and technology series

EN

ISBN 92-825-9096-8

Catalogue number: CD-NA-11896-EN-C

Price (excluding VAT) in Luxembourg: ECU 8.75

This work concerns the results of the studies conducted at many sites in Italy aimed at collecting information on natural evidence of the isolation capacity of clay. Field observations allow the opportunity to get to know directly or by inference the evolutive geological processes which are of concern for waste disposal problems. Such observations concern natural phenomena acting at the same, or at a greater, time-space scale involved in the geological disposal of wastes.

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