
Characterization of discontinuities in an argillaceous medium (Tournemire site): key questions related to safety assessment of radioactive waste disposal

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Abstract: The safety assessment of deep radioactive waste disposal in argillaceous medium concerns the evaluation of the possibilities and transfer processes through this geological barrier. Generally, this material is characterized by a very low permeability. However, faults and fractures may affect this medium and consequently it is important to analyse the transfer possibilities along these discontinuities. The first phase of this evaluation is the detection or survey of the fractures, and the second one is the evaluation of their hydraulic properties. A discontinuity is not a synonymous of fluid transfer, which in turn may be inhomogeneous along the same fracture.

The well-compacted Tournemire argillaceous medium (argilites and marls) is affected by some faults and fractures of natural (tectonic) and artificial (excavation) origin. The natural fractures are of different scales: major regional faults that limit blocks, secondary fault and fractured zones that affect the blocks, and local fractures and microfractures. These discontinuities are studied from the surface analyses, transversal boreholes and drifts. Geophysical methods are tested to detect these discontinuities to different scales. The present-day fluids are shown in some fractured sectors that allow us to analyse the possibilities of fluid transfer along these discontinuities. The fracture analyses show that permeability or transmissivity properties may change along the discontinuities. A decametric fluid transfer is shown along some fractures; however, their integration in a larger scale is not yet analysed. It is necessary to understand how the transfer in the near field may be connected to the possible far field transfer, or these transfers are not possible through the argillaceous medium.

1. INTRODUCTION

The safety assessment of deep radioactive waste disposal in geological formations concerns the evaluation of transfer possibilities and processes through these formations. This transfer evaluation includes the processes in the near field (excavation disturbed zone EDZ) and in the far field (non perturbed geological formation).

The argillaceous medium is a potential geological barrier for deep radioactive waste disposal due to its very low permeability and the strong capacity for radionuclide retention. In order to develop research programs concerning the confining properties of this argillaceous medium,

the French Institute of Protection and Nuclear Safety (IPSN) has selected the Tournemire site (Aveyron, France).

The argillaceous medium of Tournemire site consist of a thick well-indurate layer located between two limestone aquifers. The old Tournemire tunnel (one hundred years old) crosses

this argillaceous layer providing a good access to analyse this medium (Fig. 1). These analyses are performed with boreholes and drifts excavated from the tunnel. They concern geological, structural and tectonic, hydrogeological, geochemical and geomechanical domains. These investigations are conducted by the IPSN research group with external scientific and technical collaborations.

2. GEOLOGICAL SETTING

The Tournemire site is located in a Mesozoic marine basin on the Southern border of the French Central Massif. The sedimentary formations are characterized by three major layers of Jurassic age. In the Tournemire area the argillaceous medium corresponds to a 250 m thick sub-horizontal layer, located between two limestone and dolomite layers (300-500 m thick), where two aquifers are developed (Fig. 1). This argillaceous medium consists of claystones (argilites) and marls of Toarcian and Domerian formations (200 and 50 m thick respectively).

The Tournemire massif, bounded by two valleys of 350-400 m deep, corresponds to sub-horizontal monoclinical structure affected by an E-W striking regional fault in the northern border (Cernon fault) Fig. 1. Faults and fractures affect this massif and these discontinuities are related to different tectonic events. The present water circulation is located along the lower and upper limestones aquifers and along the major regional Cernon fault.

3. CHARACTERISTICS OF THE ARGILLACEOUS FORMATIONS

The argillaceous medium of Tournemire site corresponds to well-compacted (rock) argilites and marls composed of thin bedded clay minerals giving a typical anisotropic texture. Mineralogy is characterized by predominant clay fraction (40-50 %) of kaolinite, illite/smectite, muscovite, biotite, chlorite. The other mineral phases are the calcite (10-30%), dolomite, quartz (10-20%), pyrite, siderite and organic matter.

The argillaceous matrix shows a very low water content (1 to 5% bww), porosity between 6 and 9%, and extremely small poral space (2.5 nm) Fig. 2. Grain density is $2.7-2.8 \cdot 10^3 \text{ Kg/m}^3$ and specific surface varies between 23 and 29 m^2/s . The cation exchange capacity is about 10 meq/100g and pore water has a moderate salinity (1500 mg/l).

The permeability of the argillaceous matrix, measured in laboratory and in situ, is characterized by very weak values ranging between 10^{-12} and 10^{-15} m/s (Fig. 2). This very low permeability and the very small porous space suggest that diffusion processes essentially govern the fluid migrations in the argillaceous matrix. This very low permeability, from laboratory and in situ measurements, is in agreement with the well confining properties of this geological barrier.

The argillaceous formations are affected by faults and fractures therefore the research is focused on the understanding of the transfer mechanisms along these discontinuities.

4. FAULT AND FRACTURE CHARACTERISTICS

The Tournemire site is affected by natural fractures related to different tectonic events, and by artificial fractures associated to tunnel and drift excavations. Therefore it is a well favourable context to analyse the possibilities of transfer processes along these discontinuities.

4.1. Natural discontinuities

Two major tectonic events have affected the Tournemire region: an extensional tectonics during the Jurassic sedimentation and a compressional major tectonics (Eocene pyrenean tectonics) post-sedimentation that was structured this region. The faults and fractures related to these tectonic events are analysed in different scales : regional faults, local faults, secondary faults and fractures.

The E-W striking Cernon fault is the major regional discontinuity (80 km long) that controls the past and present water circulation (Fig. 3). This fault of Palaeozoic origin, was reactivated during the extensional and the compressional tectonics and it is characterized by a large fault zone (hectometric to decametric wide). The Tournemire fault (11 km long, Fig. 3) is a local fault related to the compressional tectonics. The “Cirque de Tournemire” and the “Brias” aquifer location are associated to this fault. In general, these major and local faults bound the kilometric blocks and control the water circulation. These discontinuities may be detected by classic geophysical methods (seismic reflexion method) showing frequently vertical displacements of several tens of meters.

The secondary faults are of several hundred meters long and affect the series into the blocks bounded by the major and local faults. These secondary faults are not clearly identified on the surface do to the small vertical displacement and generally they show sub-horizontal displacements (strike-slip). In general, these faults are associated to a fractured zone, which shows different width in function to its lithology: decametric fractured zone width in argillaceous series and decametric-hectometric one in the limestone or dolomite layers. This is the case of the fault and associated fractured zone shown in the Western drift of the Tournemire site (Fig. 4). This fault shows essentially a strike-slip displacement and consequently it is not detected by the classic geophysical methods (seismic reflection) from the surface. Therefore, it is necessary to adapt geophysical method for detected this discontinuity. In this context, 3D high frequency (150-200 Hz) seismic survey is proposed for possible detection of this fault from the surface (next seismic campaign). The upper and lower limestone aquifers flows are controlled along these discontinuities. However, in the argillaceous formations a small fluid transfer is observed in metric to decametric scale near the aquifers (upper aquifer). The origin of water associated to fractures observed during the drift excavations is not known yet. If it is related to aquifer water, the circulation along these fractures is minimum several ten meters.

The fractures, metric to decametric scale, are the discontinuities that frequently affect the blocks showing small (fault) to zero displacements (joints). In general, the fractures are filled with calcite (Fig. 5) and the fractured zones may be detected by seismic tomography. These discontinuities are organized in system of fractures, associated to secondary faults, or to single fractures. The morphology and the organization are strongly related to the type of the tectonic event. Normal faults, related to extensional tectonics, show regular or sinusoidal morphology. The fracturation related to the compressional tectonics show planes well developed, and they generally present sub-vertical geometry. Generally these fractures are more developed in limestone and dolomite series, in contrast to argillaceous medium where

these are localized along narrow fractured zones or like single fractures. Geodic cavities, which are filled with water, are related to fractures with echelon geometry (Fig. 6). Evaluation of the organization of these cavities, and their connection along the fracture systems, is very

important to analyse the possibilities of fluid transfer along the fractures. The single fractures filled with calcite show a very low permeability (10^{-12} to 10^{-14}) similar to the matrix values. However, the fractures with geodic cavities and the fractured zones are not measured yet. The first water analyses related to these fractures seem to be in agreement to connection with aquifer (C14, Isotopic analyses); however, it is necessary more analyses to validate because a contamination during the sampling is possible. The fractured zone associated to the secondary fault of the Western drift was detected from seismic tomography between boreholes.

4.2. Artificial fractures

The artificial discontinuities are associated to tunnel or drift excavation into the argillaceous medium. These are located only few meters around the tunnel or drift in the EDZ zone. In the Tournemire site three main types of artificial discontinuities are observed: a mechanical fracturation, fractures related to desaturation process, and fractures related probably to tectonic origin (past or present state of stress).

The mechanical fracturation is shown in each side of the old tunnel, more than 2 m wide zone, corresponding to a stress concentration area (Fig. 7). This discontinuities are oriented parallel to the tunnel axis and are mainly open forming permeable zones. The variation of the fracture density seems to be related to the proximity of pre-existing tectonic fractures. In the recent drifts the mechanical fracturation zone is only 0.3 to 0.4 m wide. Geophysical tests, done across this mechanical fracturation, seismic refraction and radar, show the damaged rock properties. The mechanical fracture zones may appears like permeable zones along the tunnel and drift that is necessary to take into account for the safety assessment of deep radioactive waste disposal.

Other system of the local discontinuities related to the drift excavation concern the fractures related to the desaturation process (Fig. 8). This fracturation is developed along the stratification planes (anisotropy influence). Opening and closing fracture process are shown and are related with the desaturation and resaturation of the argillites due to the seasonal variations of the temperature and humidity. A small microseismic activity, recorded in the end of the Eastern drift, seems to be related to fracture opening due to desaturation process. The same behaviour, opening and closing mechanisms, are related to some pre-existing tectonic fractures. In fact, the transmissivity properties of these natural discontinuities are modified in the EDZ due to desaturation process.

A new set of fractures developed after the drift excavation, seems to be related to the tectonic state of stress (past or present). Geometry of these fractures are in agreement to the compressional axis orientation: in this case, it is a pre-existing weak zones exhibits after the drift excavation, or this is a new fracturation related to the present-day state of stress which is characterized by a compressional axis near the fracture strikes. This fracturation is not related to the open and the closing processes. The perturbed zone affected by this fracturation was analysed from geophysical tests (seismic refraction) showing a slower P wave velocity that the one in the unperturbed zones. These fractures are open.

5. FRACTURES AND THE SAFETY ASSESSMENT OF DEEP RADIOACTIVE WASTE DISPOSALS

Two main evaluation phases concern the discontinuities that affect the argillaceous medium: the first phase is the detection or identification of these fractures or faults, and the second one concerns to their hydraulic role.

5.1. Fracture survey or detection in argillaceous medium

The well compacted argillaceous medium shows a brittle rheology during the tectonic events and consequently fractures and faults have been created similar to other sedimentary brittle rocks (limestones, dolomites, ...). However, in the argillaceous medium these discontinuities are concentrated along the delimited fractured zones in contrast to the limestones or dolomites where these are more spreaded in the large fractured zones. It is a typical rheological behaviour related to the rock lithology.

The first phase concerning to discontinuities in the argillaceous medium consists of the fracture and fault survey (identification). It can be made from detailed surface cartography (organization, kinematics analyses, ...), core boreholes oriented transversal to the main regional fracturation, or from the drifts excavated transversal to the regional structures. The non-destructive method concerns the geophysical detection. In kilometric scale, the 2D or 3D seismic reflection methods from the surface, are appropriate for the identification of the main faults with vertical displacement more than 5-10 meters. However, for the secondary faults, with mainly strike-slip displacement, it is necessary to adapt probably a most adequate seismic method. For example, using high frequencies (150-200 Hz) and denser geophone array, such as it is proposed to the identification of the Tournemire secondary faults (next campaign). In a decametric scale, the seismic tomography between boreholes or drifts may be necessary to identify the fractured zones. It is the case of the tested Tournemire fractured zone between radial boreholes. Finally, the seismic refraction or seismic record in the EDZ zone are methods to detect and analyse the discontinuities in the perturbed zones around the drifts.

5.2. Fluid transfer possibilities or blockage migration along the fractures

The second phase, after the discontinuity identification, is the analysis of transfer possibilities along these faults or fractures. A natural discontinuity is not a synonymous of fluid transfer because it is in relation to the nature of the fault or fracture plane; fracture filling or nature of the fault zone; plan organizations, plan morphologies, and scale. Some discontinuities, mainly the sealed fractures, may exhibit a permeability comparable to the argillaceous unfractured matrix (10-12 or 10-13 m/s par example). In contrast, other faults or fractures show transfer fluids, mainly where these are characterized by open geometry or cavities, destructured material with an increasing porosity, non sealed fault breccias, etc. Along a same discontinuity the transmissivity properties may change in function to the fracture characteristic changes, for example the morphology (Fig.9). This permeability change may also be into the same fracture zone. It is very important to evaluate the possible transfer organization (Fig. 9). This can be studied coupling the structural and tectonic (plan nature and organization), hydrogeological (hydraulic properties), hydrogeochemical (fluid nature and origin), and geomechanical (discontinuity compartment) analyses.

The transfer possibilities along the artificial fractures, in the EDZ zones, are related to the plan organization, fracture density, fracture coalescent, fracture openings. These artificial fractures are not sealed by mineral filling, like in the case of natural fractures. The mechanical fractures, in each side of the tunnel for example, may be permeable zones that are necessary to consider for the safety assessment of deep waste disposal. Density of the fractures related to the desaturation may be reducing in drifts where their walls have been sealing.

5.3. Fracture scale and transfer fluid possibilities

The fracture scale vs. fluid transfer is the key for evaluating the possibilities or blockage of fluid migration through the all-argillaceous medium. How are the local transfer possibilities integrated to a larger scale?. How the possible transfer in the near field may be connected or not to the possible far field transfers?. What are the transfer processes along the discontinuities?. The fluid transfers are not possible through the all-argillaceous medium?. These questions are very important to the safety assessment for the deep waste disposal. Consequently, the studies from small to the large regional scale are necessary for to understand the possibilities and the processes of fluid transfer along the discontinuities. The analyses of the discontinuities that affect the argillaceous medium of Tournemire site show a variable fracture nature that is necessary to relate to the different transfer possibilities in function of scale.

6. CONCLUSIONS

The well compacted argillaceous medium is characterized by a brittle rheology, similar to other sedimentary brittle rocks, favouring the fracture development when it is subjected to natural or artificial stresses. Natural and artificial fractures characterize the discontinuities in the argillaceous medium. The former are related to past tectonic events and the latter are associated to drift excavations. Therefore the safety assessment of deep waste disposal concerns the evaluation of the possibilities and the process of fluid transfer along the discontinuities.

The natural fault and fracture survey (identification) is the first phase for the argillaceous barrier qualification. This can be done from the surface cartography, transversal boreholes and drift analyses. Geophysical methods, mainly seismic ones, may detect the discontinuities in different scales. However, for secondary decrochant fault surface detection it is necessary to adapt a more appropriated method, for example a 3D high resolution seismic survey. The artificial fractures can be analysed from drifts, boreholes, or detected from geophysical methods, such as seismic refraction for example.

The transfer possibility along the identified discontinuities is the second phase to evaluate the argillaceous barrier. A natural discontinuity is not a synonymous of fluid transfer due to the variable properties of the fault and fracture planes. Permeability and transmissivity properties of the discontinuities are analysed as well as the possible transfer organizations. Discontinuity analyses show that the transfer possibilities are related to the nature of the fault or fracture, the organization of discontinuities, plan morphologies, the present state of stress, etc. These transfer possibilities may be vary along the same discontinuity or fractured zone. The artificial fractures, in the EDZ zones, may be related to permeable zones; however, it is necessary to analyse along the all drift or tunnel EDZ. Finally, the local transfer possibilities need to be integrated into larger scale analysis, and we need to understand how the transfer in the near field is connected or blocked to the possible far field transfers.

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FIGURES

Fig. 1. Geological cross-section of the Tournemire experimental site.

Fig. 2. Characteristics of the Tournemire argillaceous medium. Argilites and marls of Toarcian and Domerian formations.

Fig. 3. Simplified geological map of the Tournemire area (from modified BRGM map).

Fig. 4. Structural and tectonic sketch in the drifts sector of the Tournemire site.

Fig. 5. Natural fracture (tectonic origin) with calcite filling. Core scanner developed view

Fig. 6. Geodic cavities with water in fractures. Example of en echelon joints of the Eastern drift.

Fig. 7. Mechanical fractures related to the tunnel excavation (EDZ). Mosaic view (drift floor) of the East tunnel side.

Fig. 8. Fractures related to the desaturation processes. Fractures in the Western drift end (wall).

Fig. 9. Simplified sketch of geodic cavities 3D location. Example of the Eastern drift.