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The relationship between the open fractures and mineralized fractures in Oligocene sandstones of Leghorn coast (Tuscany, Italy) – the hydrogeological relapses

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Abstract

The Oligocene-Miocene turbidite sandstones of fore-deep in the Northern Apennines form a very great aquifer that originally, before the reduction by Plio-Pleistocene erosion, is extended over an area of 60 000 sq/km (minimum) to 1.5 km–4.5 km tickness.

The spatial relationships between the open fractures and mineralized fracture (veins) in the outcrops of foredeep's sandstones (*Macigno*) along the Tuscany coast, between Leghorn and Piombino (Northern Apennines), are analyzed and discussed.

Also is discussed a conceptual model that allows a virtual surface of separation between an upper zone in open fractures and a fracture in the lower zone mineralization. The position of this surface than the topography surface, depends on the difference between the velocity of erosion and the velocity development of open fractures by reduction of the lithostatic load, during the exhumation of the system.

The lack of the open fractured zone, below this surface suggests that the deep water circulation into the Macigno sandstones along the coast area, depends exclusively on the connection between the major faults and the primary discontinuity (stratification).

Based on the results of fracturing analysis of the coastal *Macigno* the authors aim to extend the research to internal areas, and in particular to the ridge of the Northern Apennines, where the foredeep's sandstones are well developed and continued.

1 Introduction

The North Apennine fore deep sandstones of Oligo-Miocenic age represent a rock formation of great hydrogeological interest, for which the aquifer storage characteristics have not been assessed yet.

These sandstones comprise a silica turbidite system of an estimated mean regional scale thickness of ∼2000 m. These sediments accumulated in a strongly subsiding elongated depositional basin, located at the front of the North Appennines chain, which was in the process of structuring and migrating towards the Adria plate foreland (Ricci

Lucchi, 1986).

In a 10 My time period, the migrating to foreland North Apennine fore deep alternatively activated, gradually accommodating the turbidity flows originating from the dismantling of the Alpine chain crystalline units and sedimentary cover (central-western Alps).

The activation and closing phases of the fore deep depositional system are diachronous and the top and bottom biostratigraphic ages of the sandstones led us to conclude that when the Miocenic (post Aquitanian) fore deep activates, the Oligocenic and Oligo-Aquitanian fore deep (corresponding to the whole ligurian-thyrrenian sector of the North Appennine chain) is already entirely deactivated, and the sandstones are buried underneath the chain units originated in the back land (Ligurian Units).

At the Miocene-Pliocene boundary, as a conclusion of the geodinamically controlled fore deep's depositional history, a huge slab of sandstone originated. This sandstone was originally continuous across the northern Apennine, from the ligurian-thyrrenian coast to the padano-adriatic margin.

This sandstone table was estimated to be approximately 1.5 km to 4.5 km thick, 200 km to 250 km wide and 350 km to 400 km long; as such it consisted of a rock mass ranging from 105 000 km^3 to 450 000 km^3, prior to its tectonic shortening.

2 The aquiferous of the *Macigno* sandstones (Tuscan Nappe, Northern Apennines)

The Northern Apennines fore deep turbidite system, lithologically generally comprising well-cemented heavily fractured sandstones of few metres thick strata, with very thin silt bands, potentially constitutes a major fractured aquifer of which hydrogeologists should assess the real potential

Focusing on the Oligo-Aquitanian fore deep sandstones, these comprise the Tuscan Nappe's *Macigno* Formation, outcropping with remarkable continuity in the Apennines's ridge, occupying its western (ligurian) side, and being generally set as a monocline

dipping towards north east.

West of this area, the *Macigno* Formation outcrops with discontinuity in large inliers underneath the internal Ligurian Units (Elter, 1975).

Due to their north eastern dipping, the sandstone strata along the Apennine ridge facilitate the conveyance of infiltration waters towards the padano-adriatic margin, whilst in the western zones the outcropping or buried at variable, often shallow depths *Macigno* Formation represents a water reservoir where the interaction between the geometry of the strata and the fracture pattern controls a more complex hydraulic circulation.

When not weathered, the *Macigno* sandstones are normally well cemented and its internal circulation is controlled almost entirely by planar discontinuities, both primary (stratification surfaces) and secondary (tectonic fracturing).

The stratification consists which graded sandstones strata of variable thicknesses between few decimetres to several metres alternates with thin pelitic bands of thickness ranging from few millimetres to few centimetres.

Tectonic fracturing pattern is organised in complex systems originating from polyphased brittle deformation, both compressive or strike-slip and extension occurred during the mio-pliocenic and pleistocenic evolution of the northern Apennine chain.

Variable geometry, high-angle systems of joints are present, often conjugate, and many faults, both strike slip and dip slip (ranging from vertical/high angle to low angle). At the bend of major isopach folds, fracture cleavage is well developed.

In general, within the Tuscan Nappe *Macigno*, the brittle deformation is dominant, due to its elevated structural position and lithological characteristics. The permeability and subsurface drainage patterns of the largest and most continuous north Apennine aquifer system are a function of the brittle deformation and the degree of connection of the primary discontinuities. As such, the enhancement of the knowledge on the hydraulic conductivity given by the interconnections between fracturing and stratification it is deemed important for the assessment of groundwater resources occurring within the Tuscan Nappe *Macigno*. However, given the scarcity of structural data on brittle deformation, only limited to the investigation of major regional faults, a suitable assessment of the *Macigno* sandstone's hydraulic conductivity is prevented.

Decreasing of transmissivity with depth, caused by the decreasing density and progressive closing of fractures as a consequence of the increasing lithostatic pressure, represents an issue upon which literature does not show much disputed opinions. The attempts were made in order to quantify this phenomena with theoretical mathematical models (Scesi and Gattinoni, 2007); however, the validity of these models was not backed up by field studies due to the obvious difficulties in measuring fracturing at depth.

Whilst it is known that the open fracturing at increasing depths radically progressively reduce the dimensions of the flowing fractures as a consequence of the increasing lithostatic pressure, the spatial relationship between the open fracturing and the mineralised fracturing, in form of arrays of veins, mainly quartz or carbonates, are not enough investigated. Mineralised fractures behaves, very more than the open fracturing in depths conditions, drastically decreasing the rock mass hydraulic conductivity, on leaving to this the major faults element. This issue affects the planning of the rock mass structural study aimed to the assessment of its hydrogeological potential.

Whilst the study of vein systems is fairly well developed from a structural point of view, for the information provided by the vein minerals orientation on the spatial position of the tensional strain field which caused the fracturing, structural surveys and studies aimed to the assessment, definition and distinction of rock masses affected by open or mixed fracturing from rock masses affected by mineralised arrays of veins only, are missing.

2.1 The fracturing of *Macigno* outcrops of coast between Leghorn and Piombino (Tuscany)

The Tuscan Nappe *Macigno* Formation outcrops located along the coast near Leghorn and approximately 80 km further south in the Piombino area (Fig. 1), offer suitable observation and analysis occasions on mineralised fracturing and its lateral and vertical

distribution within the tidal zone.in both locations, at an elevation of approximately 10 m a.s.l., corresponding to the plants free steeply sloping rock cliff, the common fracturing (joints and minor faults) is only represented by mineralised systems, being the open fracturing is totally missing.

At this elevation, the absence of open fracturing is also evidenced by the lacking of plane surface rock elements with sharp edges coincident with the fracture surface intersection. Dihedral angles with their acute and obtuse bisectors lying on the stratification surface and intersection orthogonal to the stratification surface, expression of a strain field with horizontal $\sigma 1$ (maximum compression) and $\sigma 3$ (maximum tension), active at the time of the initial phases of the multiphased deformation process on the *Macigno* Unit, are also lacking.

The absence of the open fracturing does not permit the detachment of rock elements, neither by hand or with the hammer. The fracture surfaces are only made of the intersection between the rock outcrops or by the veins exposed by selective erosion (Fig. 2) and higher than the sandstone matrix. Although the density of the fracturing network is very high, the outcropping surface (always rounded) almost never corresponds to a fracturing surface and almost always corresponds to an erosional surface.

The Tuscan Nappe *Macigno* Formation outcrops located along the road linking the villages of Castagneto Carducci, Sassetta and Suvereto in the interland zone of Piombino (Fig. 1) represent the opposite of the situation described above. In these outcrops, the fresh rock beneath the superficial weathered soil is characterised by an extensive brittle free deformation, with open fractures always present defining unit rock elements bounded by planar surfaces and sharp edges which are easily detached from the rock mass by hand or hammer (Fig. 3). Mineralised veins are very rare and secondary to the high density open fracturing (joints and minor faults). The observation of major faults is difficult at these locations, due to the lack of suitable vertical outcrops. The extensive free fracturing system of these sandstones is strongly interconnected with the stratification surfaces, thus defining a hydraulic pattern predominant on the hydrogeological role played by single flowing fractures or faults.

The Tuscan Nappe *Macigno* Formation outcrops located along certain road cuts nearby the coastal area (Romito-Calignaia location, in Leghorn coast) show intermediate characteristics compared to the two locations mentioned above, where free fracturing and mineralised fracturing coexist, the first one cutting off the latter.

In the Rio di Calafuria and Rio di Calignaia riverbeds sandstone outcrops (Leghorn coastal area), the mineralised fracturing is, again, the only one present and this is only developed along the watercourses alignments.

The walls of the disused quarries located immediately uphill of the Via Aurelia on both the Rio Calignaia river banks are another example of location where the relationships between free fracturing and mineralised fracturing are preserved within the *Macigno* sandstone occurring in the Leghorn coastal area.

The diagonal alignment of the quarry wall compared to the hill slope allows the assessment of the type of fracturing at a few superficial locations, where it was observed that open fracturing, estimated approximately twenty metres thick was only developed in the upper zone whit respect to the topographic surface (Fig. 4). Underneath the quarry area located further away from the topographic surface, as observed in the previously mentioned coastal outcrops, the open fracturing is missing and the mineralised veins are spread and major faults are evident, cutting off the continuity of the sandstones with mineralised fractures.

3 Conclusions

The considerations on the relationship between open fracturing and mineralised fracturing (vein systems) are related to local areas and, as such, it is not appropriate to state general conclusions or derive numerical correlations. However, based on the field observation, it is worthwhile attempting the definition of a provisional conceptual model, as detailed below.

The total absence of open fracturing in the coastal outcrops and its systematic, dominant presence in the road cuts and quarry outcrops, could indicate the existence of a

virtual surface separating an upper (external) zone with open diffuse fracturing from an under (internal)zone with mineralised fracturing.

This virtual surface would intersect the topographic surface at an elevation above the recent and current land-seawater interaction band, thus exposing the mineralised fracturing zones within the land-seawater interaction band, subject to the seawater mechanical erosion and in progressive regression. This virtual surface would successively be "punctured" by erosion in correspondence to the alignments of the water courses, thus making the mineralised fracturing areas outcrop within tectonic inliers (Fig. 5).

This model is therefore assuming the erosive process in the land-seawater interaction band and the water courses alignments to be faster than the development of the open diffuse fracturing, thus stopping the migration of the mineralised fracturing in upper zone and therefore the development of open fracturing.

This conceptual model implies that:

- where the erosion process is slower than the development of open fracturing, the bottom surface of the open fractured zone (OFBS) is to be located underneath the topographic surface.
- where the erosion process is faster than the development of open fracturing, the bottom surface of the mineralised fractured zone (OFBS) is to overlie the topographic surface.

As such, this conceptual model implies the position of the Bottom Surface of the open fractured zone (OFBS) to shift in time and space with respect to the topographic surface, according to the erosion and fracturing development velocity differences.

This provisional model also presume that the rock mass releases, in a defined and not instantaneous time, the tectonic stress accumulated during the deformation history stored within the minerals crystalline lattice but not at the rock mass scale (Weinberger et al., 2010), thus developing a fraction of open fracture systems, only when the lithostatic pressure decline under a critical boundary.

Road cuts and quarries located above the OFBS would intersect the open fracturing systems – released at surface by the decompression of the lithostatic pressure – which may or may not coexist with the mineralised fracturing systems, depending on the degree of veins (carbonate) solution

The mineralised fracturing systems located beneath the OFBS would display the existence of fossil hydraulic circuits, abandoned following the migration of flowing water towards the surface, after the clogging of the open fractures network – created within the rock mass since the beginning of the deformation process when the tectonic pressure was greater than the hydrostatic pressure – by means of salts precipitation.

Should this provisional structural model for the *Macigno* sandstones occurring between Leghorn and Piombino (Leghorn coastal area) be confirmed and extended at a regional scale would remarkably affect the studies on the structure of the deep hydrogeological circuits of the major northern Apennine bedrock aquifer. Particularly, structural geological surveys would aim mainly to the geometric and cinematic characterisation of major faults (Fig. 6), being these the only tectonic discontinuities capable of conveying groundwater at depth, thus ensuring the connectivity with the planar primary discontinuities and the aquifer system permeability.

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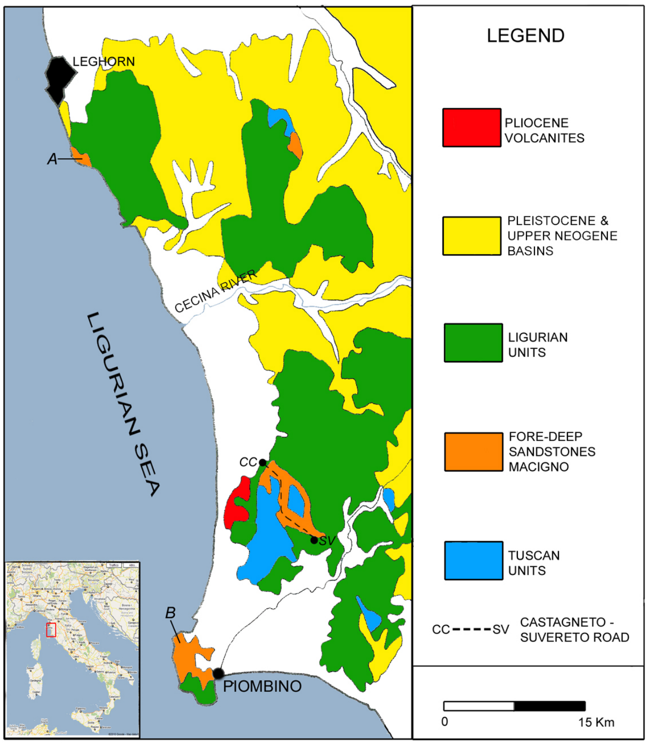

Fig. 1. Geological sketch map of Ligurian coast between Leghorn and Piombino (Tuscany).

Fig. 2. In the sandstone's outcrops *(Macigno)* near the level sea, are present only mineralized fractures.

Fig. 3. The sandstones *Macigno* along the road Castagneto Carducci-Sassetta-Suvereto. In this outcrops are present only open fractures.

Fig. 4. The red line (OFBS) divided an open fractures zone (over the line), from a mineralized fractures zone (under the line). Quarry of Rio Calignaia near Leghorn.

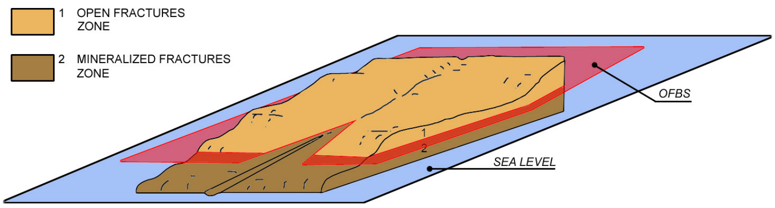

Fig. 5. The position of the surface between the open fractures zone and mineralized fractures zone with reference to the sea level and to the topographic surface.

Fig. 6. A fault,with cataclasite, in *Macigno* sandstones near sea level, with fractures mine ralized only.