Supplement of Solid Earth, 15, 1385–1406, 2024
https://doi.org/10.5194/se-15-1385-2024-supplement

Solid Earth
Open Access

Supplement of

Geophysical downhole logging analysis within the shallow-depth ICDP STAR drilling project (central Italy)

Paola Montone et al.

Correspondence to: Paola Montone (paola.montone@ingv.it)

SUPPLEMENTARY 1: DETAILED GEOLOGICAL DESCRIPTION

TSM01 borehole (Figs. 4a and 5), 133.00 m deep, was drilled at the footwall of the Gubbio normal fault, at about 150 m from the main fault surface, in the floor of an abandoned quarry (555 m a.s.l.). The borehole, below a few metres of incoherent anthropic deposits, drilled the sub-horizontal beds of the Cretaceous mainly calcareous succession, including, top to bottom the Scaglia Bianca, Marne a Fucoidi and Maiolica Fms.

In particular, it (Figs. 4a and 5) drilled top to bottom the Scaglia Bianca, Marne a Fucoidi and Maiolica Fms. In detail, in terms of depth, the lithology is as follows:

- from 0 to 10 m: incoherent anthropic overburden material;
- from 10 to 16 m: strongly fractured limestone in the upper part (10-13 fluid loss), with fragments of marly flakes, maximum clast size around 2 mm, white and light grey colour, belonging to Scaglia Bianca Formation;
- from 16 to 70 m: marly-limestone material with maximum clast size of 1-2 mm, white, light grey, pinkish grey, greenish grey colour, belonging to Marne a Fucoidi Fm.;
- from 70 to 133 m: limestone-marly material with maximum clast size of 1-2 mm, white and light grey colour, with fragments of black chert of 1-2 mm (73 m fluid loss probably corresponding to a slump layer), belonging to Maiolica Fm.

TSM02 borehole (Figs. 4b and 5), 160.30 m deep, was drilled at 632 m a.s.l. near the NW termination of the Gubbio anticline. The borehole drilled an Early Tertiary complex succession, including, top to bottom, the Scaglia Cinerea Fm. (mainly grey marls), Scaglia Variegata Fm., and the uppermost part of the Scaglia Rossa Fm., whose bedding regularly dip about 20° towards the SW.

In particular, it (Figs. 4b and 5) drilled an Early Tertiary complex succession, including, top to bottom, the Scaglia Cinerea Fm., Scaglia Variegata Fm., and the uppermost part Cretaceous-Eocene Scaglia Rossa Fm. In terms of depth, the lithology is as follows:

- from 0 to 3 m: inert overburden material.
- from 3 to 9 m: marly and marly-limestone material, maximum clast size about 1-2 mm, grey, grey-green, light grey, and pinkish-grey in colour - Scaglia Cinerea Fm.;
- from 9 to 15 m: marly, marly-limestone, and limestone-marly material, maximum clast size about 1-2 mm, grey, grey-green, light grey, pinkish-grey, and purplish-red in colour – (stratigraphic transition) Scaglia Cinerea Fm. - Scaglia Variegata Fm.;
- from 15 to 33 m: limestone-marly and marly-limestone material, maximum clast size about 1-2 mm, greenish-grey, pink, and reddish-purple in colour – Scaglia Variegata Fm.;
- from 33 to 66 m: limestone-marly and marly-limestone material with maximum clast size of 1-2 mm, pink, reddish, and white in colour, with fragments of red chert - Scaglia Rossa Fm. (upper chert member);
- from 66 to 160.3 m: limestone-marly and marly-limestone material with maximum clast size of 1-2 mm, pink, reddish, and white in colour - Scaglia Rossa Fm. (intermediate non-chert member).

TSM03 borehole (Figs. 4c and 5), 80.00 m deep, is located between Gubbio and Pietralunga at 341 m a.s.l. The borehole crosses only the Marnoso-Arenacea Fm., locally mostly composed of grey marls, with few fine-grained sandstone layers.

In particular, it (Figures 4c and 5) crosses only the Marnoso-Arenacea Fm. In terms of depth, the lithology is as follows:

- from 0 to 8 m: overburden and colluvial eluvium;
- from 8 to 80 m: marly and arenaceous material, maximum clast size about 1-2 mm, grey, greenish-grey, dark grey, and brownish-yellow, belonging to Marnoso-Arenacea Fm.

TSM04 borehole (Figs. 4d and 5), 100.80 m deep, is the most structurally complex one. It is located near Umbertide, at 313 m a.s.l. The borehole crosses the Marnoso-Arenacea Fm. characterised by alternated sandstones and marls. Next to the drilling site, there is a water pool with intense emissions of deep-origin CO_2, which is constantly monitored by INGV researchers. To prevent potential gas leaks, drilling was carried out in conjunction with the use of two preventers: the first applied to the conductor casing and used during the initial drilling phase, and the second applied to the inner casing.

In particular, it (Figures 4d and 5) crosses the Marnoso-Arenacea Fm. characterised by marly and arenaceous (sandy) material, grey, greenish-grey, dark grey, down to 101 m. Only between 0 and 8 m non coherent Holocenic deposit level has been crossed.

TSM05 borehole (Figs. 4e and 5), 118.00 m deep, is drilled near Cantiano at 379 m a.s.l. The borehole, below a few metres of Holocene colluvials, crosses the Schlier Fm. consisting of a rhythmic sequence of hemipelagic and pelagic marls and marly limestones interbedded with frequent black shales.

In particular, it (Figs. 4e and 5) crosses the Schlier Fm. In terms of depth, the lithology is as follows:

- from 0 to 7 m: Holocene deposits;
- from 7 to 118 m: marl, limestone marl, clayey marl; maximum clast size around 1-2 mm, grey, grey-green, dark grey, belonging to Schlier Fm.

TSM06 borehole (Figs. 4f and 5), 117.50 m deep is located east of Città di Castello, at 437.5 m a.s.l.. The borehole crosses the Marnoso-Arenacea Fm., locally with a mostly marly composition.

In particular, it (Figures 4f and 5) crosses the Marnoso-Arenacea Fm. In terms of depth, the lithology is as follows:

- from 0 to 6 m: transported material and eluvial-colluvial cover;
- from 6 to 117.5 m: marly-clayeous and sandy material, maximum clast size about 1-2 mm, grey, grey-green, dark grey, and brownish-yellow in colour, belonging to Marnoso-Arenacea Fm.

SUPPLEMENTARY 2: LOGGING TOOLS DESCRIPTION

For the execution of geophysical logging, wireline slim hole probes have been used. Each probe was lowered into the borehole by means of a winch and moved upward at a constant speed, with real-time data acquisition available on a dedicated computer. The logging data were only acquired in the open hole section, with the exception of gamma rays (GR), which was also performed in the cased hole. All probes are equipped with the GR which allows depth matching with all logging probes.
The following geophysical logs were performed along the shallow boreholes by Geologin srl. The logging measurements were screened and reprocessed by the Authors prior to interpretation with the logging data software WellCAD5.6 by ALT company.

a) The optical borehole imager *(OBI-QL40,* performed along TSM 01, 02, 03, 05) generates a continuous unwrapped 360° true colour image of the borehole wall using an optical imaging system. A built in high precision orientation package incorporating a 3-axis magnetometer and 3-axis accelerometer to determine the azimuthal direction and inclination. Resolutions up to 1800 pixels over the borehole circumference can be achieved which makes it ideal for lithological, mineralogical and structural analyses. The system has an integrated natural gamma sensor thereby enabling the measurement of gamma radiation emitted naturally from within the formations crossed by a borehole. This tool provides an image of the borehole using a high intensity light and rotating image through air- or water-filled boreholes. Image logs are collected with the tool centred in the borehole. The speed of the OBI is generally of 1-2 m/min. The orientation of the borehole deviation and magnetic declination can be applied to the apparent orientations of interpreted features to obtain corrected orientations of the planar features. Planar features that intersect the borehole appear as sinusoids on the magnetically oriented images, and their orientation can be computed. The strike is normal to the azimuth of the lowest point (dip azimuth) on the sinusoid and is expressed with respect to magnetic or true north. In addition, the apparent dip can be computed as the sine of the amplitude normalised by the diameter. Thus, the depth and orientation of planar features such as fractures, bedding, and lithologic contacts can be mapped. The images show fractures very clearly, as well as reflectivity of the minerals in the borehole and structures within the rock such as xenoliths or bedding planes.

b) The acoustic borehole imager *(ABI-QL40,* performed along TSM 01, 02, 03, 04, 05, 06) generates a 360° unwrapped and 3D image of the borehole wall. The tool emits ultrasound pulses towards the formation and records the amplitude and the travel time of the reflected signal. A built in high precision orientation package incorporating a 3-axis magnetometer and 3-axis accelerometer allows orientation of the images to a global reference and determination of the borehole's azimuth and inclination. The amplitude record is representative of the impedance contrast between rocks and fluids. The speed of ABI is generally of 2 m/min. The clarity of the image logs, however, is not only related to the speed but there are other parameters to be taken into account such as the transparency of the drilling fluid. The travel time is used to determine accurate borehole diameter data, which makes the tool ideal for borehole deformation description (stress field analysis and casing inspection). Unlike the OBI, this probe works even in cloudy water or drilling mud. The amplitude and travel time images show e.g., fractures, faults, veins, bedding planes, breakouts and drilling induced tensile fractures.

c) The three- arm caliper *(CAL-QL40,* performed along TSM 01, 02, 03, 04, 05, 06) records the borehole diameter using a cumulative measurement of three mechanically coupled arms in contact with the borehole wall. The standard arms of CAL-QL40 are suitable for a borehole diameter ranging from 57 mm to 406 mm. The extension arms are suitable for borehole diameters up to 736 mm. The sonde orientation and hence the hole orientation is determined by triaxial magnetometers and accelerometers yielding the deviation of the tool axis from vertical, the azimuthal direction of this deviation and the azimuthal direction of the caliper arms. The caliper arms orientation is used to identify stress induced borehole breakouts and hence the orientation of the stress field around the borehole. Desirable caliper data would be a smooth consistent diameter (in-gauge hole). Increases in diameter, especially breakouts over a m long and several cm deep, are very undesirable and might indicate collapsing areas or areas producing a lot of water.

d) The gamma ray probe (*GR-QL40,* performed along the TSM 01, 02, 03, 04, 05, 06) measures the amount of gamma radiations occurring naturally from within the formations crossed by a borehole. A scintillation Sodium Iodide crystal is used to detect the gamma rays. Gamma rays are produced mainly by isotopes of potassium (40K), thorium (232Th), uranium (238U) and their decay products. The probe converts the counts into a standardised unit well-known as gamma-API [gAPI]. The gamma ray log is widely used for the identification of lithology, clay content analyses, correlation between boreholes, cyclostratigraphy analysis and for the estimate of the natural heat production

e) The fluid temperature conductivity (*FTC-QL40,* performed along the TSM 01, 02, 03, 04, 05, 06) provides borehole temperature (°C) and fluid conductivity (µS/cm) measurements. It is capable of recording a wide range of conductivity from fresh to highly saturated water. The borehole fluid temperature measurement is helpful to detect anomalies caused by events such as fluid flow into the borehole. The borehole fluid conductivity is directly proportional to the concentration of dissolved minerals.

f) The Full Waveform Sonic log (*FWS-QL40*, performed along TSM 01, 02, 03, 04, 05, 06) is widely employed, often in combination with other logs, to provide porosity, permeability, and geo-mechanical properties (e.g., poisson ratio). This probe is ideal for cased-hole and open hole applications, such as fracture identification and cement bond logging. The FWS-QL40 implements a high energy source wave generated by a ceramic-piezoelectric transducer to excite the adjacent formation. Waves of different frequencies are developed and propagated within the formation, allowing for real time analysis of the full waveform. Under suitable borehole conditions, compressional (P), shear (S), Stoneley, and Tube wave arrivals can be detected. This tool sends out a signal that is reflected off the borehole walls and received with four receivers, of varying distances from the transmitter, which record return amplitude and velocity. It images deeper into the rock than just the surface of the borehole wall. It is good to show hard vs. soft rock and to show active fractures. It is also useful to show rock consistency. The unit of the velocity is m/s.

g) This probe (*ELOG-QL40,* performed along the TSM 03, 04, 05, 06) measures 8-, 16-, 32- and 64-inch normal resistivity (Ωm), single point resistance (SPR) and spontaneous potential (SP). Using one injection electrode and four measure electrodes, it is possible to log resistivity profiles with different depths of investigation and gain information about permeability, porosity, water quality and geological formation properties. Four resistivity measurements are recorded.

Tools	Unit	TS01	TS02	TS03	TS04	TS05	TS06
		Logged interval (m)					
Gamma Ray (GR)	cps	0.92 -132.47	1.28 -159.53	1.05 -79.95	0.85 -99.40	0.72 -116.22	1.10 -116.90
Acoustic image (ABI)	°	97.78 -132.39	92.69 -159.59	31.61 -79.87	79.67 -100.32	82.17 -117.10	62.82 -116.05
Optical image (OBI)	°	98.40 -132.04	96.20 -147.01	30.95 -79.41		79.46 -117.10	
Full wave sonic (FWS)	m/s	97.00 -132.00	144.50 -159.00	33.00 -78.00	81.93 -100.6 0	80.71 -117.48	61.34 -116.40
Elog (Resist. and SPR)	Ωm			33.00 -78.00	77.16 -100.22	80.05 -116.92	60.40 -117.40
Teperature and electrical conductivity (FTC)	°C - µS/cm	1.80 -133.34	2.11 -160.36	1.80 -80.82	1.68 -100.33	1.50 -117.03	1.98 -117.78
Caliper (CAL)	mm	96.10 -130.74	96.70 -157.86	29.35 -77.80	79.67 -100.32	82.17 -117.10	62.82 -116.05

Table S1. Depth interval recorded by downhole logging for each borehole. Minimum and maximum depth of Gamma Ray (GR), Acoustic image (ABI), Optical Image (OBI), Full wave sonic (FWS), Resistivity, Temperature and electrical conductivity (FTC).

Borehole	ICDP_ID	IGSN	Lat. [°]	Long. [°]	Elev. [masl]	Hole azimuth [°]	Hole devi [°]	Drilling depth [m]	Lithological formation (top to bottom)
TSM01	5070_1_A	ICDP5070EHK0001	43.34541	12.59775	555	N123°	0.7	133.0	Scaglia Bianca, Marne a Fucoidi, Maiolica
TSM02	5070_2_A	ICDP5070EHM0001	43.39626	12.48989	632	N027°	2.0	160.3	Scaglia Cinerea, Scaglia Variegata, Scaglia Rossa
TSM03	5070_3_B	ICDP5070EHO0001	43.38298	12.35450	341	N131°	1.7	80.0	Marnoso-Arenacea
TSM04	5070_4_A	ICDP5070EHP0001	43.30864	12.30464	313	N130°	1.5	100.8	Marnoso-Arenacea
TSM05	5070_5_A	ICDP5070EHQ0001	43.47958	12.60253	379	N140°	1.8	118.0	Schlier
TSM06	5070_6_A	ICDP5070EHR0001	43.47237	12.33275	437.5	N140°	4.7	117.5	Marnoso-Arenacea

Table S2. Details of each borehole including their name, their ID for the ICDP and their IGSN number. The IGSN means International Generic Sample Number and provides an unambiguous globally unique and persistent identifier. Lat: latitude; Long: Longitude; Elev.: elevation; masl: metre above sea level; devi: deviation.

Preparations for each borehole started with the installation of a 9 m long conductor casing, with an outer diameter (OD) of 219 mm and an inner diameter (ID) of 195 mm. Thereafter a 190.5 mm borehole was drilled up to the open section (the depth varies from one borehole to another one) with a surface casing (OD= 177.8 mm and ID=161.8 mm) and an open-hole section of 152.4 mm diameter. Seismometers and strainmeters have been deployed at the bottom of the open section of each borehole and the fibre optic only in the deeper ones (TSM01 and TSM02; Fig. 5 and Fig. S1).

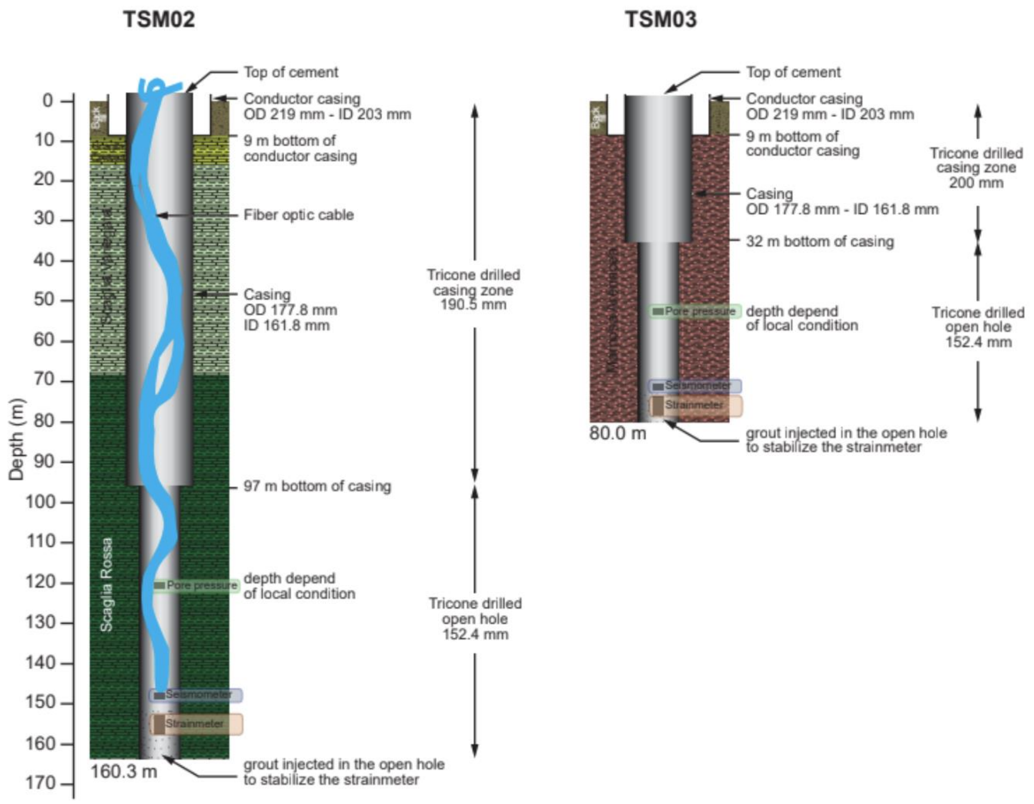

Figure S1. Drilling and instrument installation schemes (modified from Chiaraluce L., pers. com.). Seismometers and strainmeters were deployed in all boreholes, and fibre optics only in the deeper ones (TSM01 and TSM02). The figure shows TSM02 and TSM03 as representative examples of all. ID: inner diameter, OD: outer diameter.

Figure S2. Outcrops of the Marnoso-Arenacea Fm. (TSM03, TSM04 and TSM06). Geological survey provided important information on facies, bedding orientation and geological structures such as faults and cleavage. This allowed us to reinterpret the structures identified in the image logs.

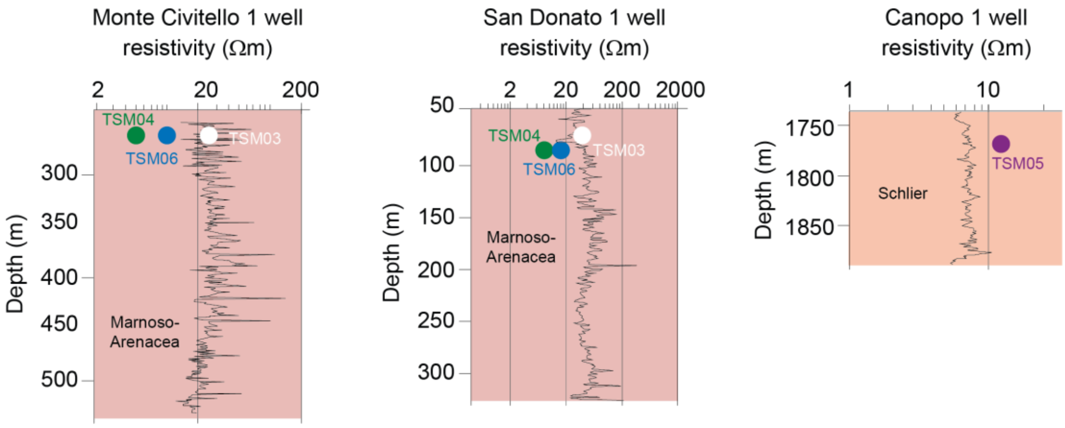

Figure S3. Comparison between the resistivity obtained from downhole logging measurements of three deep wells (Monte Civitello 1, San Donato 1 and Canopo 1) and that resulting from this study. The dots indicate the average resistivity and the bars the relative standard deviation of boreholes TSM03, TSM04, TSM05 and TSM06.