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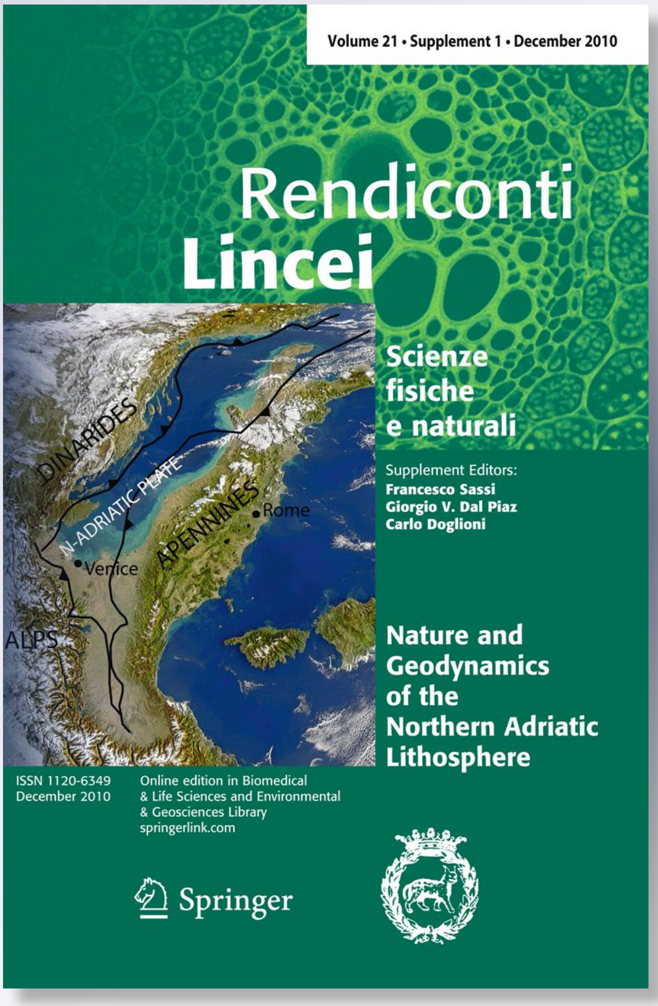

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New evidence of the outer Dinaric deformation front in the Grado area (NE-Italy)

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Abstract A well Grado-1 was drilled down to 1,108 m reaching Mesozoic shelf carbonates which occur in the structural highs in the Lignano–Grado area. The well was completed with geophysical logs in the open-hole interval from −700 to −1,108 m. The drilling bit met the nummulitic shelf Palaeogene limestone at −616.5 m and Mesozoic (Upper Cretaceous) platform around −1,007 m. About 400 m thick Palaeogene interval appears affected by open fractures which we consider linked up to a reverse fault and a tectonic duplex of the Palaeogene limestone interval is hypothesized. The feature corresponds to the outer deformation front of the Dinaric thrusts system and looks still active. Palaeogene limestone sequence is analogous to the outcrops in the northern Istria and the stratigraphy in the oil wells offshore northern Dalmatia. The drilling target was the characterization of the nature of geothermal resources in the Friuli lower plain and lagoons region, following the long-term investigations of the Department of Civil and Environmental Engineering of the Trieste University. The geothermal resource was found in correspondence of the above mentioned open fracture zone and below it, with salty hot waters at a temperature of 42°C, increasing with depth, and a flow of 25 l/s arriving to the surface with 2.8 pressure bars.

Keywords Biostratigraphy · Dinaric thrusts · Exploration well · Geophysical logs · Seismic reflection profiles

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1 Introduction

The Department of Civil and Environmental Engineering, DICA (University of Trieste) conducted several researches, sponsored by Friuli Venezia Giulia Region (RFVG)—Geological Survey and European Commission (e.g. Grado geothermal project), aimed at characterizing the geothermal resources of the Friuli lower plain and contiguous lagoons (Della Vedova et al. 2008; Nicolich et al. 2004, 2006). The integrated analyses identified the anomalous geothermal gradient areas located in correspondence of morphological–structural culminations in the carbonate basement buried beneath the Friuli plain deposits (the recent Plio-Quaternary sequences, Oligo-Miocene Alpine Molasse and Eocene Dinaric flysch).

The conceptual model proposed to explain the geothermal system considers recharge by meteoric waters from the neighboring mountain chains, infiltration to depths of 3–4 km, warming and slow up-flow and storage into the porous shelf carbonate near the Adriatic shore at approximately 700–1,000 m depth. Heat transfer by advection mainly occurs in the carbonates, whereas conduction prevails through the low permeability Cenozoic clastic deposits with heat exchange to fresh geothermal confined aquifers within the sandy-gravel layers, primarily of Plio-Quaternary age (Bellani et al. 1994; Calore et al. 1995). The quality, quantity and extent of geothermal resources were revealed and outlined by the oil industry well Cesarolo-1 (AGIP 1977), drilled in the Lignano carbonates structural culmination, by many geothermal water wells drilled in the upper sedimentary cover (Barnaba 2001; Grassi 1994) and the new 1,108 m deep Grado-1 exploration borehole. The latter enabled us to verify the geothermal conceptual model and the heating system feasibility in the Grado city (Barison et al. 2008). The synthetic stratigraphic column of the first 900 m of Cesarolo-1 well and the anomalous geothermal gradient representing the one-dimensional thermal model are presented in Fig. 1.

Geophysical prospecting was utilized in the structural setting evaluation, considering seismic profiles and wells stratigraphies and logs (Fantoni et al. 2002, 2003). Gravity measurements performed by DICA and integrated with ENI data evidenced the carbonate basement culminations in the Bouguer anomalies map (Della Vedova et al. 1988). High resolution reflection seismic profiles, recorded offshore and on land near Lignano and Aquileia-Grado, allowed to recognize the seismic facies of Cenozoic sediments and upper Mesozoic limestone. The seismic data show the main stratigraphic boundaries, unconformities, geothermal aquifer systems, structures of the carbonate platform, faults in the basement and their eventual propagation through the cover deposits (Nicolich et al. 2004; Busetti et al. 2009). All the surveys and analyses represented the base for the definition of a geological consistent location of the well Grado-1 planned to verify the conceptual model and exploit the geothermal resource (Della Vedova et al. 2008).

2 Geological setting

The investigated area belongs to the Adriatic foreland which includes the Friuli plain, Istria and Gulf of Trieste, NE-Italy. It is limited to the north and east by the south-vergent South Alpine chain and the south-west vergent External Dinarides (Fig. 2; Bigi et al. 1990). The Dinaric orogen reached its maximum growing during Oligocene, whereas the eastern edge of the southern Alpine range started developing from late Oligocene times with intense Neogene compressions of the Carnic and Friulian Alps involving also the border of the foreland plain. The External Dinarides have a large overlapping zone with the Southern

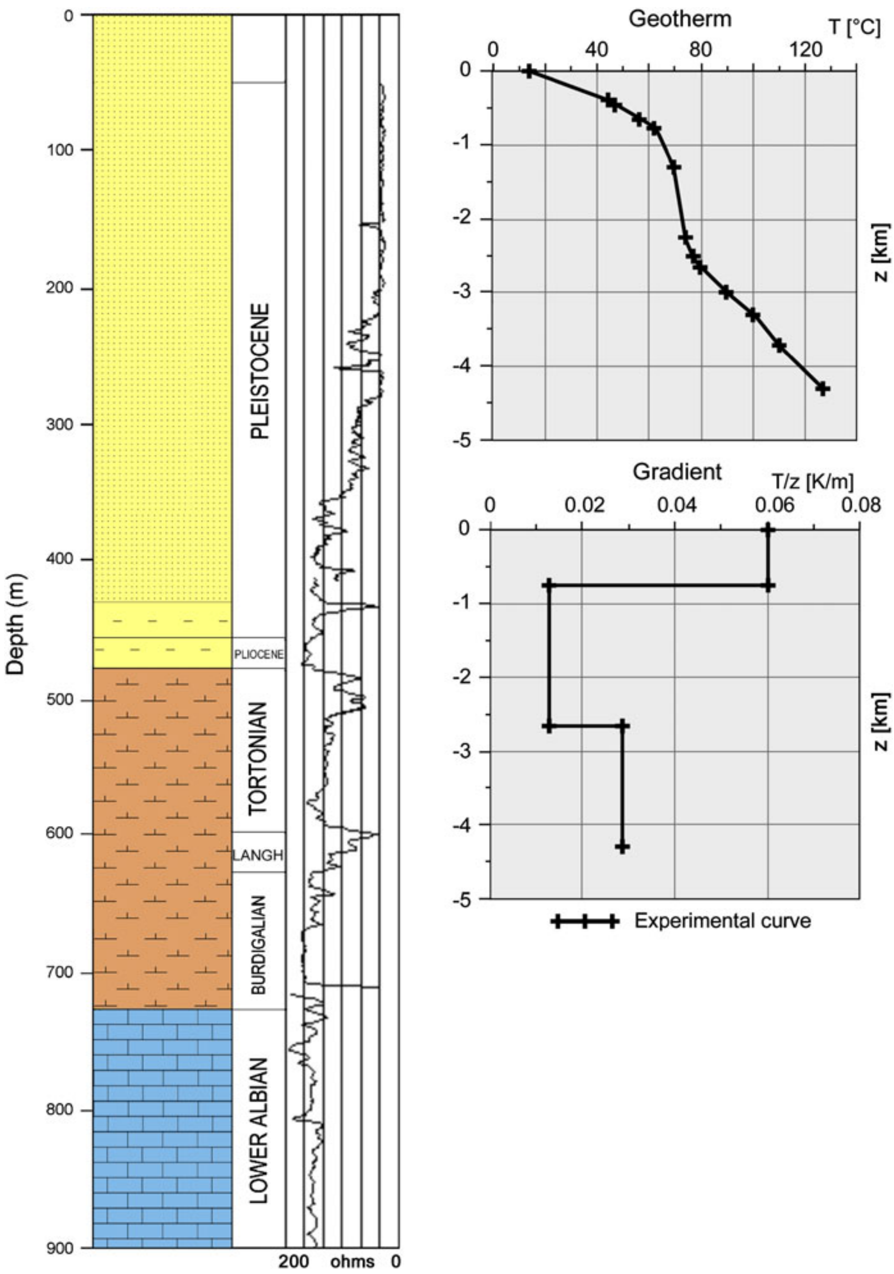


Fig. 1 Upper part of Cesarolo 1 well synthetic stratigraphy and corrected temperatures (*up right*) and gradient versus depth (*down right*). Advection phenomena are confirmed by the form of the gradient curve

Alps and the main geographic expression in the Trieste Karst, but buried thrusts were recognized by seismic profiling and wells in the eastern Friuli plain (Fantoni et al. 2002, 2003; Carulli 2006; Barison 2008). Istria represents the southern limit of the investigated

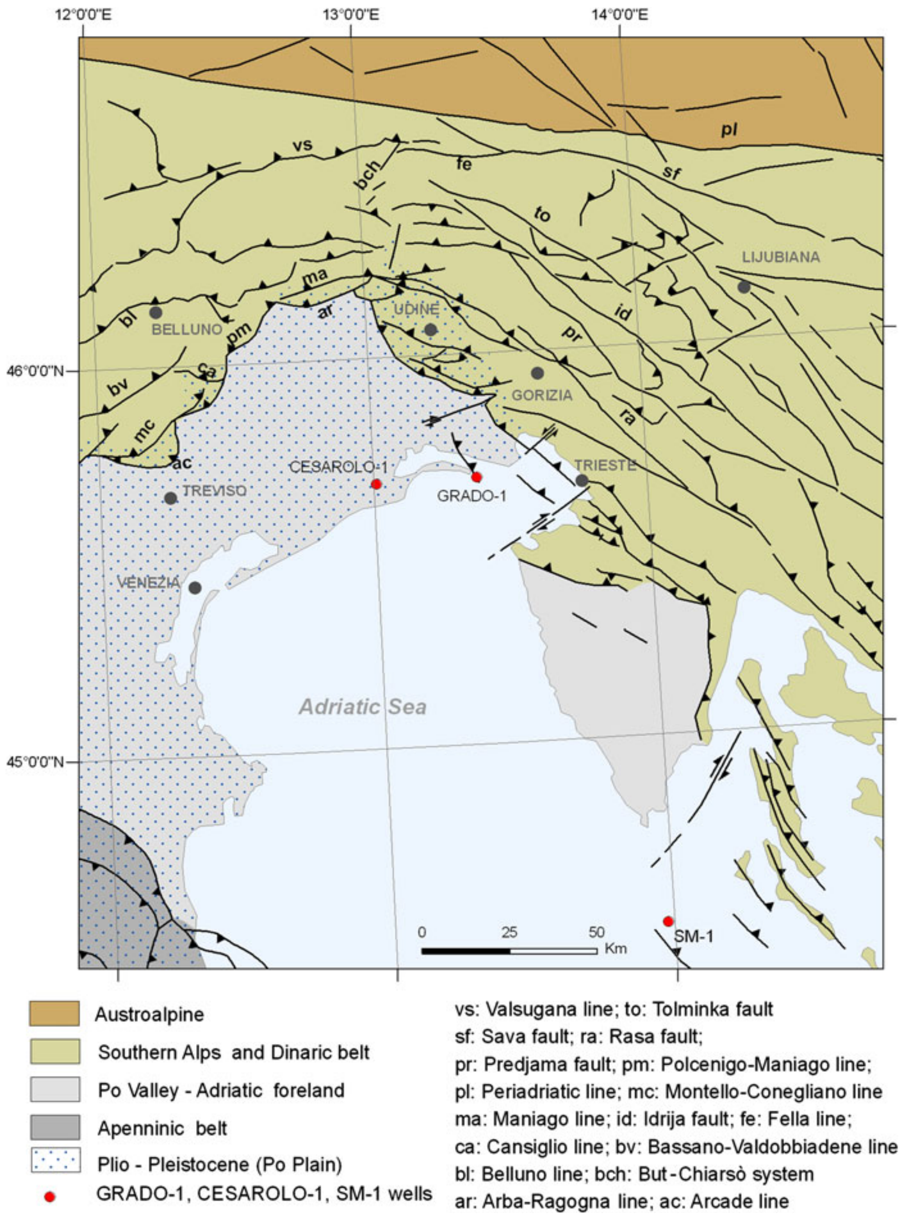


Fig. 2 General simplified structural map of the Southern Alps and the Dinaric chain

area and appears, on its western half, as a rather homogeneous and massive Mesozoic shelf domain, the stable part of Adria, which emerges from the Adriatic Sea opposing to the west-vergent External Dinarides. The S-Alpine structural evolution was characterized by intense Neogenic compression of the Carnic and Friulian Alps involving also the underground border of the foreland plain. The foreland preserves Mesozoic inherited structures after the Jurassic rifting. In fact, the present tectonic regime in the lower Friuli Plain, lagoons and Gulf of Trieste, reflects the major facies change occurring during Cretaceous between shelf carbonates and deep water pelagic sequences. The shelf to basin transition is well defined on the marine seismic sections and represents the typical reference case (Casero et al. 1990) with the slope and talus accompanying the platform aggradation up to 1,200–1,500 m with respect to the neighboring Belluno basin areas. Sawteeth platform margins with Dinaric and anti-Dinaric orientations were evidenced on land, from SE towards NW directed, presently covered by the Venetian plain recent sedimentation (Nicolich et al. 2004). The platform is apparently lined up by isolated culminations with possible shallow water seaways in between.

A pronounced flexure to NE of the top of carbonates down to more than 1,200 m corresponds to the development of the Dinaric foredeep, filled by the turbiditic sediments from the erosion of the chain (Eocene flysch). The emersion and erosion of the Mesozoic sequences is documented by a large depositional hiatus. Foremost processes dominate the central–western Istria where late Jurassic platform deposits are now outcropping (Márton et al. 2008).

Burdigallian–Langhian interbedded glauconitic sandstones and marls (Cavanella formation) of shallow water environment, fed by Southern Alps sources, disconformably transgress the peneplanated Cretaceous shelf area or the Eocene flysch, which has filled the flexure in front of the main Dinaric thrusts. From the Middle Miocene, the South Alpine chain is rapidly growing and deforming with large erosions transporting a huge amount of clastic deposits (Miocene Molasse) filling the foredeep flexure, where the carbonates are down-bended to about 4 km depth.

During the Middle–Late Miocene, the Istria shelf was again emerged and a new erosion phase took place. The Messinian erosion of the flysch formation is recognizable and marks a complex morphology with channels or valleys, terraces and escarpments on the marine seismic sections (Busetti et al. 2009, 2010), mostly evident in the western parts of the Gulf (Fig. 3).

Plio-Quaternary clays, sands and gravels unconformably covered the differentially eroded sections on the northern Adriatic Sea and Venetian-Friuli plain even if another erosive episode took place in Early Pliocene (Fantoni et al. 2002).

Figure 4 shows the isobathes of carbonate formations quoted with seismic reflection profiles and oil industry wells (Nicolich et al. 2004, Barison 2008). The flexures towards the Southern Alps and the Dinaric chain and the two structural highs in the lower plain are confirmed. The delimitation of westward extension of Eocene Dinaric flysch basin has also

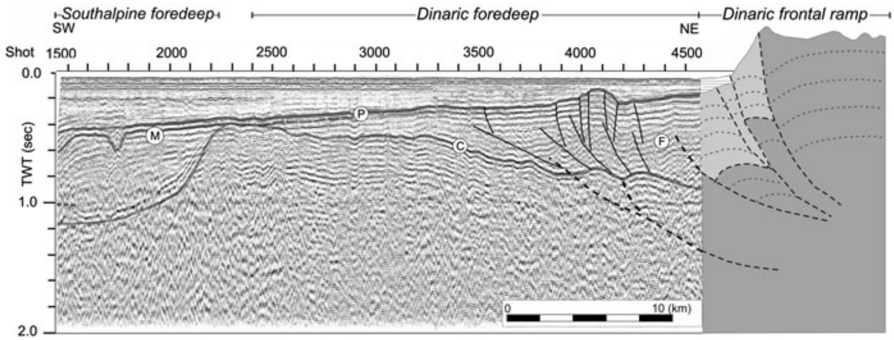


Fig. 3 Seismic line G05-4bis in the Gulf of Trieste (Busetti et al. 2009). *P* base of Pliocene marine regression, *M* Messinian erosional surface, *F* Eocene flysch terrigenous sequence, *C* top of Friuli carbonate platform. Onshore geological section modified after Carulli (2006). Location in Fig. 4

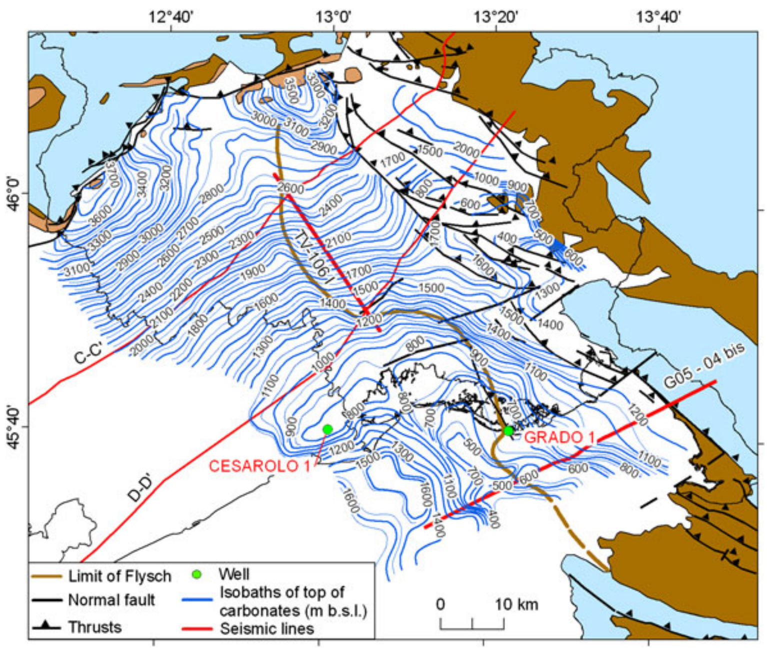


Fig. 4 Isobaths, 50-m contour intervals, of the top of carbonates in the Friuli Plain and Gulf of Trieste. The position of Cesarolo-1 and Grado-1 wells, of the lines TV-106 and G05-04bis and the western limit of the Dinaric flysch deposition (*brown line*) are signed. C–C′; D-D′ seismic profiles and geological sections (Fantoni et al. 2002; Nicolich et al. 2004). Land outcrops: *Blue* carbonates, *Brown* flysch, *Tan* Molasse)

been drawn on the map. The Grado high is NW–SE oriented apparently continuing the platform structure of northern Istria, whereas a SW–NE anti-Dinaric orientation dominates the Lignano–Cesarolo high (Figs. 4, 5). Isobaths contour map of Quaternary base was defined (Fig. 6) utilizing the water wells and high resolution seismic profiles. The map also presents Quaternary substratum (Paleocene–lower Eocene limestone, Eocene flysch, Miocene Molasse, Pliocene terrigenous and marine deposits).

An example of the seismic data quality in the Lignano structure is given by the line C1 of Fig. 7 (position in Figs. 5, 6), where Cretaceous (Albian) limestone is covered by the Cavanella drapes followed by the Molasse and Plio-Quaternary deposits. Shallow geothermal aquifers have been recognized and controlled by wells and are marked in the section.

3 The Grado-1 well

The new Grado-1 well was drilled in 2008 on the sand beach in front of the Adriatic open sea. The telescopic borehole profile starts with 20″ casing down to −30 m, ending in the hard limestone rocks with 8½″ bit diameter. The hole was left open from −692 m to −1.108 m. Two cores were collected at 791–794 m and 1.105–1.106 m, and the drill cuttings were sampled every 3–5 m.

The well was completed with the analysis of biostratigraphic data and geophysical logs to define stratigraphic–structural constraints, besides lithology, porosity, resistivity and

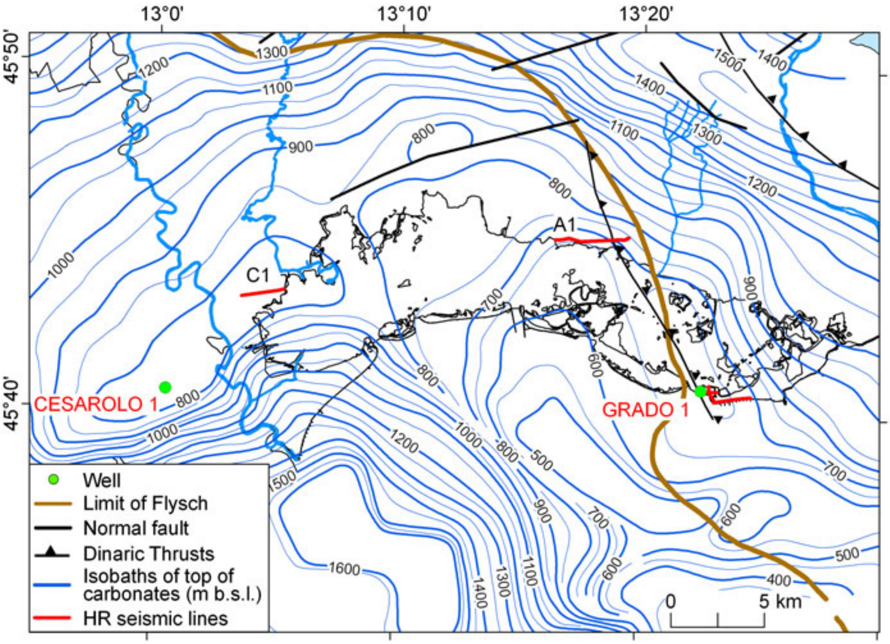


Fig. 5 Detailed map of the top of carbonates in the Lignano–Grado region. The positions of the high resolution seismic profiles C1 and A1 and other profiles in the Grado town are signed

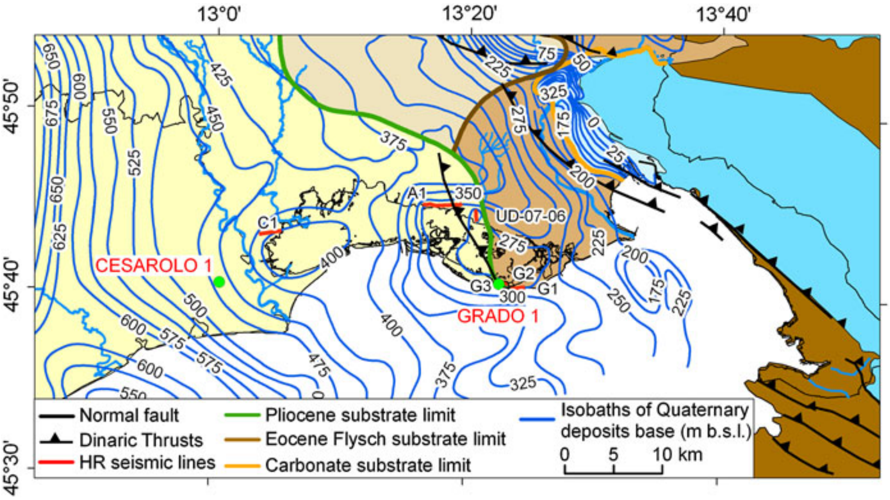


Fig. 6 Isobaths contour map of the base of Quaternary with outcropping flysch (*brown*) and carbonates (*blue*). Pre-Quaternary substratum: Pliocene deposits (*yellow*), Miocene Molasse (*beige*), Eocene flysch (*tan*) and carbonates units (*pale blue*)

elastic moduli. The biostratigraphic analysis was done on cuttings and cores with the significative contribution of R. Melis and compared to geological outcrops and other chronostratigraphic well datings. A basic stratigraphy is presented in Fig. 8.

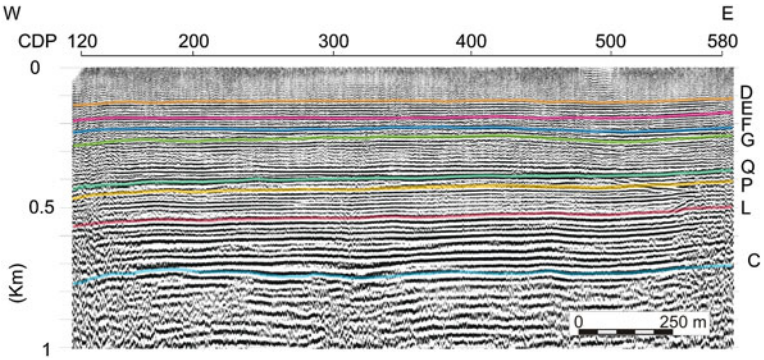
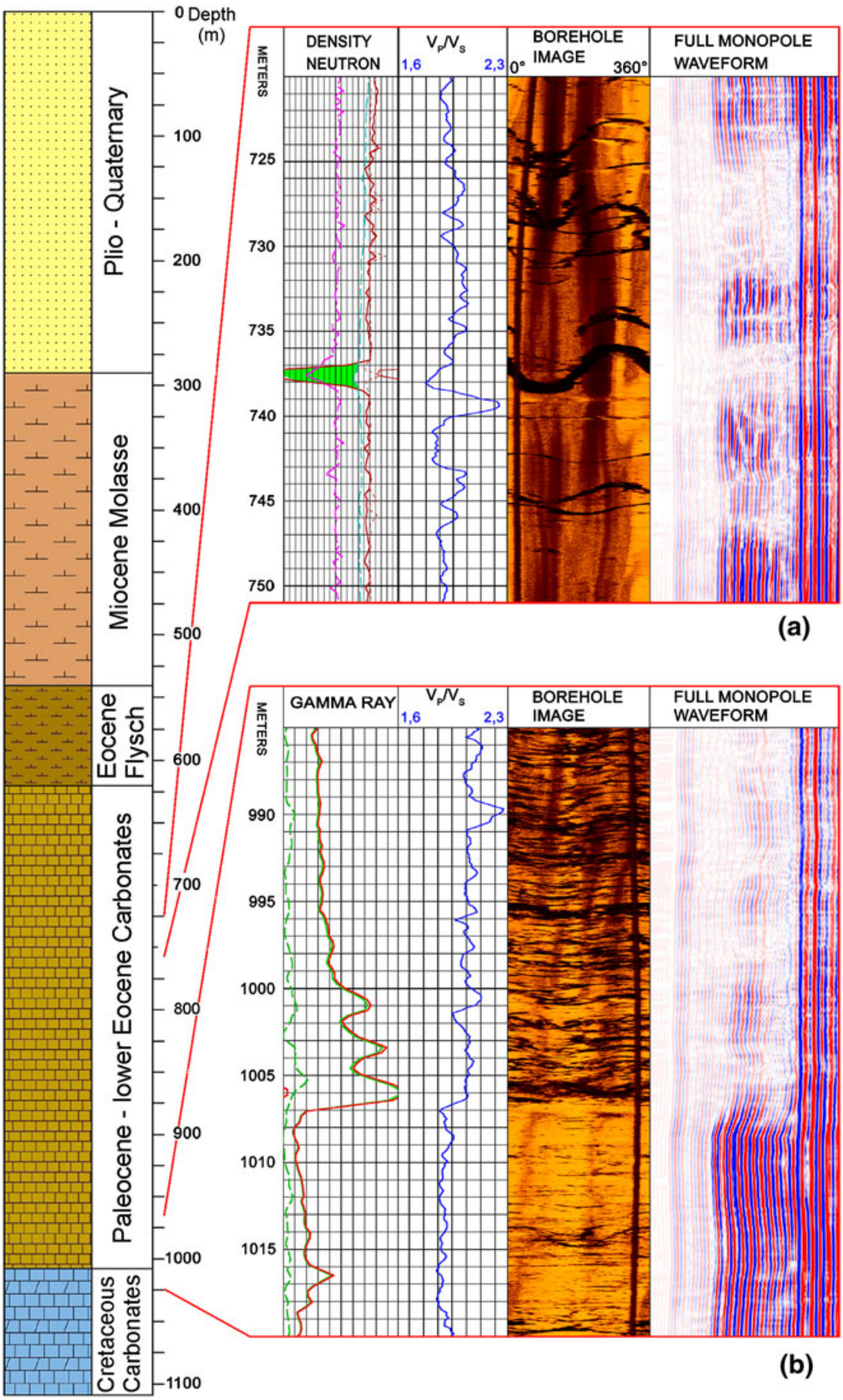


Fig. 7 High resolution seismic line C1 in the Lignano area (Figs. 5, 6) converted to depth. *D*, *E*, *F*, *G* are aquifer systems controlled by wells, *Q* base of Quaternary deposits, *P* base of Pliocene, *L* top of Langhian (Cavanella Group), *C* top of Cretaceous (Albian) carbonates

The terrigenous cover was proved to be composed by Plio-Pleistocene sediments (sands, gravels and limes), with thickness less than 300 m. A Neogene marly–sandy succession (about 250 m) follows, which is rich in external neritic faunas with less than 100 m of pelagic faunas. Palaeogene turbidites (Eocene flysch) are about 50–60 m thick composed by green marls from distal sources with glauconitic components, similar to the basal green marls recognizable in Istria at the outcropping Palaeogene carbonates contact.

Paleocene and lower Eocene shelf carbonates, encountered at −616.5 m, presents a typical Alveolinidae–Nummulitidae–Orbitolites association. This succession seems to correspond to "Haupt Alveolinen und Nummuliten kalk" investigated and illustrated on an exposed section, about 150 m thick, near Trieste (Opicina section of Castellarin and Zucchi 1966). An interesting single finding of a tiny Rudist remnant inside Paleocene should be assigned to the basal upper Cretaceous limestone (mudstone–wackestone, locally dolomitic). We speculate a possible tectonic duplex of carbonates of Paleocene–lower Eocene interval, which are exceptionally thick (about 400 m) and fractured. The logging results indicate at least three tectonic discontinuity families which are diversified according to orientation, genesis and intensity; a major sub-vertical open fracture at −736 m was revealed by a relevant circulation loss and it is interpreted as the expression of a master reverse fault plane. Logs in Fig. 8 confirm the presence of the main fracture with more than 0.5 m open hollow and Paleocene–Cretaceous contact (K/T transition). Palaeogene and Cretaceous limestones are also affected by karstic phenomena and the stratigraphic record at the contact is likely interrupted by erosion and sub-aerial exposure. The precise age determination of both units and of the hiatus is still in progress. Paleocene and lower Eocene shelf carbonates were found in the buried Dinarides, the Trieste Karst (Castellarin and Zucchi 1966), the northern Istria and offshore wells of the northern Dalmatia (Early Eocene age, Tari-Kovačić et al. 1998; Tari 2002; Vlahović et al. 2005).

Fig. 8 Grado-1 stratigraphy and well logs crossing: **a** the main fracture zone in the Palaeogene limestone at −736 m revealed by a negative pick in the neutron density log, the positive pick of Vp/Vs ratio from sonic log data, the borehole acustic image and the full waveforms attenuation (P, S and Stoneley waves) obtained by a monopole source (**a** Baker Atlas T.M.); **b** the Paleocene/Mesozoic contact at −1,007 m controlled by the gamma ray natural radioactivity log with three uranium picks near the base of Paleocene (K/T transition) ▶



0 Depth (m)
100
200
300
400
500
600
700
800
900
1000
1100
Plio - Quaternary
Miocene Molasse
Eocene Flysch
Paleocene - lower Eocene Carbonates
Cretaceous Carbonates
METERS
DENSITY NEUTRON
V_P/V_S
1,6
2,3
BOREHOLE IMAGE
0°
360°
FULL MONOPOLE WAVEFORM
725
730
735
740
745
750
(a)
GAMMA RAY
990
995
1000
1005
1010
1015
(b)

The carbonates are verified to be the most important geothermal aquifer, with a temperature of 42°C, increasing to 45°C at the well bottom and a pressure of 2.8 bars, confirming the proposed initial conceptual model.

4 Discussion and conclusions

In the Aquileia-Grado sector the seismic profile A1 (Fig. 9, position in Figs. 5, 6), part of a seismic survey executed in the area, images the top of the carbonate horizons gently folded and faulted. These reflectors indicate the Palaeogene carbonates occurring in the Grado-1 well directly covered by the Miocene Molasse. The Cavanella units are likely missing and only about 50 m of Eocene flysch was drilled, but the latter is present with 500 m thick interval few hundred meters to the east of the profile A1, recognizable by high amplitude reflectors and thrust geometries (Busetti et al. 2009, 2010). This evidence suggests the occurrence of a main tectonic deformation, documented by thrusts in the flysch successions and low angle faults in the carbonate units. Clear thrusting structures were found on seismic sections at the western tip of the Grado Island, where the new borehole was drilled confirming the presence of sub-vertical open fractures and cavities.

The normal faults within Eocene flysch sequences filling the carbonate basement flexure in front of the main Dinaric deformation front, were successively inverted with thrusts rooted in folds and low angle reverse faults in the upper carbonates units as imaged on the marine seismic sections (Fig. 3; Busetti et al. 2009). These thrusts are well documented in the outcrops in northern Istria (Placer 2005, 2007; Placer et al. 2004).

The geothermal aquifers sampled in correspondence of Grado-1 borehole, Grado Lagoon and Aquileia coast belong to the same sodium chlorinated family, although with different depths and temperatures (from 30 to 41°C). Isotopic analysis performed on several elements, ^{18}O first, reveals the presence of waters highly mineralized from an evaporitic environment or enriched in ^{18}O from the contamination of very old fossil marine waters (the presence of Tritium was not recognized). All the data from the deep Grado 1 well and the shallow wells drilling Plio-Quaternary aquifers in the above geographic area show perfectly similar trends. This suggests a common source from the deep geothermal system in the upper shelf carbonates reaching also the shallow aquifers through permeable sediments or minor faults.

All these evidences strongly support the presence of a Dinaric frontal thrust, NW–SE oriented, which was not previously known (see position and length in Fig. 5). The northward border of the Lignano–Cesarolo shelf culmination is likely located in

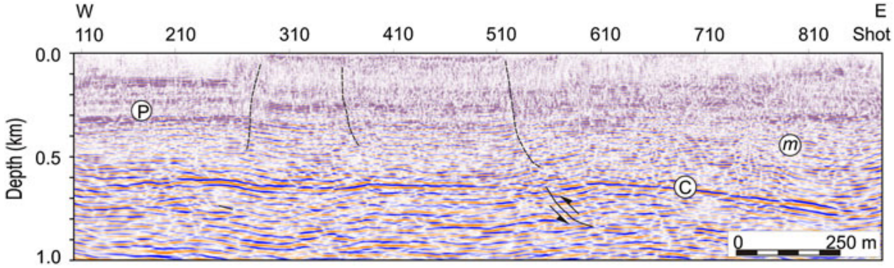


Fig. 9 High resolution seismic line A1 converted to depth at the Aquileia margin of the Grado Lagoon (Figs. 5, 6). *P* Pliocene, *m* Miocene, *C* top of carbonates

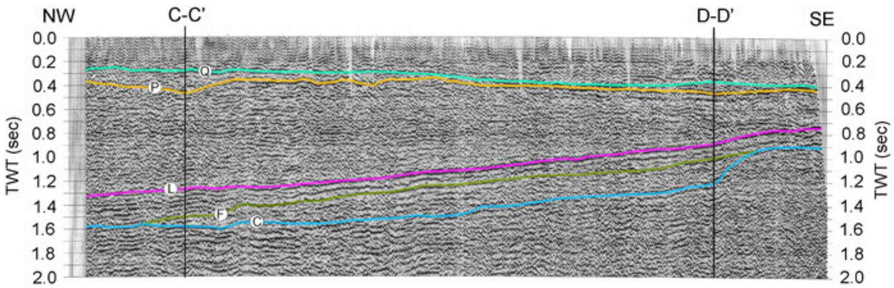


Fig. 10 Seismic line TV-106. *Q* base of Quaternary; *P* base of Pliocene, *L* top of Langhian (Cavanella Group), *F* Eocene flysch, *C* top of carbonates. Intersections with C–C′ and D–D′ sections are signed (Fig. 4)

correspondence of the scarp shown in the seismic line TV-106 (by courtesy of ENI Company and RFVG) in Fig. 10. The line (position in Fig. 4) images the platform marker, whereas, towards the center of the Friuli plain, a distinct bedding character of Paleocene (?)–Cretaceous deposits is recognizable. In this area, Casero et al. (1990) and Cati et al. (1987) hypothesized a change towards an internal shallow marine depocenter called Friuli Basin. Along this section, the flysch is not affected by tectonic deformation and is conformably covered by the Cavanella formation and the southward thinning Molasse wedge.

In conclusion, the Grado-1 well and geophysical data provide new evidences of an important regional tectonic feature, turned out to be the Dinaric frontal thrust, which involves Palaeogene and probably Cretaceous carbonates, as well as Eocene to Miocene clastic deposits fed from the erosion of Dinaric and Alpine belts. Quaternary sediments are locally interested by minor structures, up to surface (Fig. 9). The deformation front has reactivated stratigraphic unconformities and local extensive systems.

The top of the nearby Lignano platform is characterized, on the contrary, by Lower Cretaceous formations (lower Albian), directly covered by the Cavanella Group found in the Cesarolo-1 well.

The outer deformation front appears to be delimited north of Aquileia by strike-slip dextral transfer faults with anti-Dinaric direction (NE–SW) accompanying the southwestward activation of thrusts. This system of dextral faults is supposed to control the structural setting of the whole Gulf of Trieste as far as the northern Istria shoreline. An analogous tectonic situation was recognized, in the Adriatic Sea, south of the Istria peninsula, in the northern Dalmatia offshore, with Oligocene–Miocene NE–SW dextral strike-slip transfer faults (Fig. 2).

The stratigraphic sequences in the Grado area can be directly compared to those in northern Istria, where Palaeogene–Cretaceous contact crops out, and in northern Dalmatia offshore oil wells. The Grado-1 stratigraphy and logging results show a particularly good match with the data acquired in Susak More -1 well (offshore northern Dalmatia, Tari-Kovačić 1997, 1998 and SM-1 in Fig. 2). A reverse fault was found in a similar thick Paleocene–lower Eocene limestone interval, a tectonic duplex involving Cenomanian shelf units present at the base. In this area, the deposition during Palaeogene was mainly controlled by intense synsedimentary tectonic deformation of the former platform area. Carbonates (mostly Eocene in age) were deposited on irregular ramp type carbonate platforms surrounding newly formed flysch basins. This tectonic setting corresponds to the one in the Grado zone and the Gulf of Trieste as discussed in this paper.

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