Apennines subduction-related subsidence of Venice (Italy)

Eugenio Carminati and Carlo Doglioni
Dipartimento di Scienze della Terra, Università La Sapienza, Roma, Italy

Davide Scrocca
Istituto di Geologia Ambientale e Geoingegneria (IGAG) - CNR, Roma, Italy

Received 28 January 2003; revised 8 May 2003; accepted 21 May 2003; published 15 July 2003.

[1] The foreland regional monocline related to the northern Apennines subduction can be followed from the Po Basin to the Friuli region, Italy, at least 240 km north-eastward. In seismic reflection profiles of the Po Basin and of the northern Adriatic Sea, the dip of the regional monocline gradually decreases from about 22° to close to 0°. Pleistocene sediments onlap and pinchout to the northeast. Venice is located on a segment of the active monocline dipping about 1.8° to the southwest. In sediments around the Venice area, the 1.43 Ma limit is in the 960–1500 m depth range, indicating a long term subsidence rate of about 0.7–1.0 mm/yr. Therefore a significant part of the natural component of the town subsidence is related to the north-eastward retreat of the Adriatic subduction. The subduction related downflexure affects the whole of the Po Plain basin and part of the Southern Alps, where it opposes to the general uplift related to orogenesis. *INDEX TERMS:* 3040 Marine Geology and Geophysics: Plate tectonics (8150, 8155, 8157, 8158); 8105 Tectonophysics: Continental margins and sedimentary basins (1212); 8110 Tectonophysics: Continental tectonics—general (0905); 8150 Tectonophysics: Plate boundary—general (3040). **Citation:** Carminati, E., C. Doglioni, and D. Scrocca, Apennines subduction-related subsidence of Venice (Italy), *Geophys. Res. Lett.*, *30*(13), 1717, doi:10.1029/2003GL017001, 2003.

1. Introduction

[2] The longstanding problem of the drowning of the renaissance city of Venice is still unsolved. Engineering solutions have not been settled and the origin of the subsidence is still debated. Fluids extraction from the subsurface has been so far considered the main cause of the lowering, but the thick alluvial-shallow water Quaternary sediments of the area suggest a much earlier history for the subsidence which occurs ubiquitously in the Po Basin and in the northern Adriatic Sea. Because Venice is at sea level, this phenomenon is particularly grave.

[3] Venice is located at the north-eastern border of the Po plain (Figure 1), which is the foreland basin of two fold-and-thrust belts: the N-NE vergent northern Apennines and the S vergent Southern Alps [*Doglioni*, 1993].

[4] Venice is affected by subsidence, like other adjacent historical towns (e.g., Ravenna), which through the centuries resulted in an increase of sea flood frequency and amplitude. The assessment of subsidence rates, of its origin (natural and anthropogenic) and variations through time is a hot and crucial issue when evaluating the adequacy of countermeasures planned by scientists and politicians [*Carbognin et al.*, 2000; *Pirazzoli*, 2002; *Bras et al.*, 2002]. The issue of subsidence rates has been addressed using different data sets such as stratigraphic data from commercial boreholes [*Carminati and Di Donato*, 1999], ^{14}C ages of recent sediments [*Fontes and Bortolami*, 1973; *Bortolami et al.*, 1977], topography levelling surveys [*Arca and Beretta*, 1985; *Bergamasco et al.*, 1993], tide gauge measurements [*Carbognin and Taroni*, 1996], archaeological and historical data [*Flemming*, 1992; *Pirazzoli*, 1996], SAR Interferometry [*Tosi et al.*, 2002]. From these studies it emerges that the natural component of subsidence can be split into: i) a long term component controlled by tectonics and geodynamics, active on time spans of about 10^6 yr; ii) a short term component, likely controlled by climatic changes (glaciation cycles), acting on periods of 10^3–10^4 yr [*Pirazzoli*, 1996; *Carminati and Di Donato*, 1999].

[5] Although it is well established that the long term natural component is in the order of 1 mm/yr in the area of Venice [*Doglioni*, 1993], little is known about its causes. In this paper we show that long term natural subsidence in the Venice area and in the Po plain is mostly controlled by subduction associated with the Apennines.

2. Seismic and Borehole Data

[6] Since the early paper by *Pieri and Groppi* [1981] it was possible to recognize the gradual steepening of the basement from Friuli in northeast Italy, toward the south-west at the Apennines front (see their section 11). All around the Apennines foredeep, the regional monocline gradually becomes steeper underneath the belt with angles variable from 2° to 20° [*Mariotti and Doglioni*, 2000]. It has been shown that subsidence in the foredeep of the Apennines cannot be explained by the load of the advancing Apenninic wedge [*Royden and Karner*, 1984] but it must mostly reside in the dynamics of the subducting Apenninic slab (either slab pull, e.g., *Royden et al.* [1987], or 'eastward mantle push', *Doglioni* [1993]).

[7] A new seismic reflection profile, section M18, acquired within the framework of the CROP Project (the italian deep crust exploration project), allows to see with larger detail the foreland monocline and to measure the basement dip in the northern Adriatic, just offshore Venice (Figure 2). On the TWT seismic section, we show the Pliocene-Pleistocene boundary, interpreted considering the available industrial wells; moreover, the trend of the regional monocline can be clearly recognized. The section is not quite perpendicular to the Apennines front (Figure 1) and for this reason, after

0094-8276/03/2003GL017001$05.00

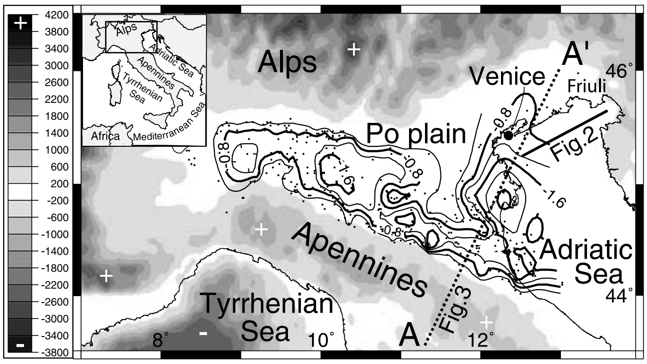

Figure 1. Isolines of Pleistocene-Present subsidence rate (mm/yr) in the Po plain and Venetian-Friuli area to the northeast, based on industrial wells (indicated by dots), modified after *Carminati and Di Donato* [1999]. The mapping was done using GMT software by *Wessel and Smith* [1995]. Note how the subsidence increases approaching the Apennines front, buried underneath the Po Plain sediments. Topography (in meters) is also shown in gray shades.

depth conversion, it gives a slightly lower apparent dip of the regional monocline (1.5°), which corresponds to a real 1.8° dip south-westward of the basement and the sedimentary cover including the Pliocene. For the depth conversion, velocities of 2000 m/s for Pleistocene and of 2600 m/s for Pliocene sediments were adopted. The Pleistocene alluvial-shallow marine sediments are almost horizontal, and they thin slightly north-eastward, showing progressive north-eastward migrating onlap and pinchout on the underlying sediments, as evident in Figure 2.

[8] In the Venice area, industrial wells found the base of the Pleistocene sediments between 960–1500 m. The

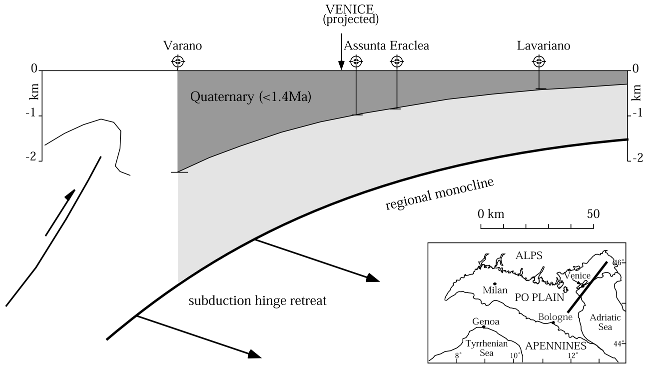

Figure 3. Seismic and borehole data constrain the geometry and southwestward thickening of the Pleistocene sediments in the Po Basin, northern Adriatic Sea and Friuli plain.

spacing for the Pleistocene sediments is clearly accommodated by the down-flexure towards the south of the Adriatic plate (Figure 3). The Pleistocene-Pliocene boundary is quite undulated. However, moving toward the Friuli plain or the north easternmost Adriatic Sea, the upper Pleistocene sediments gradually thin (due to a lowering of subsidence rates, Figure 1), and lie directly on Miocene sediments [*Merlini et al.*, 2002]. Lower Pleistocene reflectors (Figure 2) parallel the Pliocene-Pleistocene boundary, being tilted to the south-west, whereas Upper Pleistocene reflectors are less inclined. The foreland regional monocline is then a growing Pleistocene structure (Figure 4). This observation is in good agreement with forward modeling results [*Zoetemeijer et al.*, 1993]. The Upper Pleistocene sediments in the seismic profile of Figure 2 exhibit progradational pattern related mainly to the deltas of the Adige, Brenta and Piave rivers.

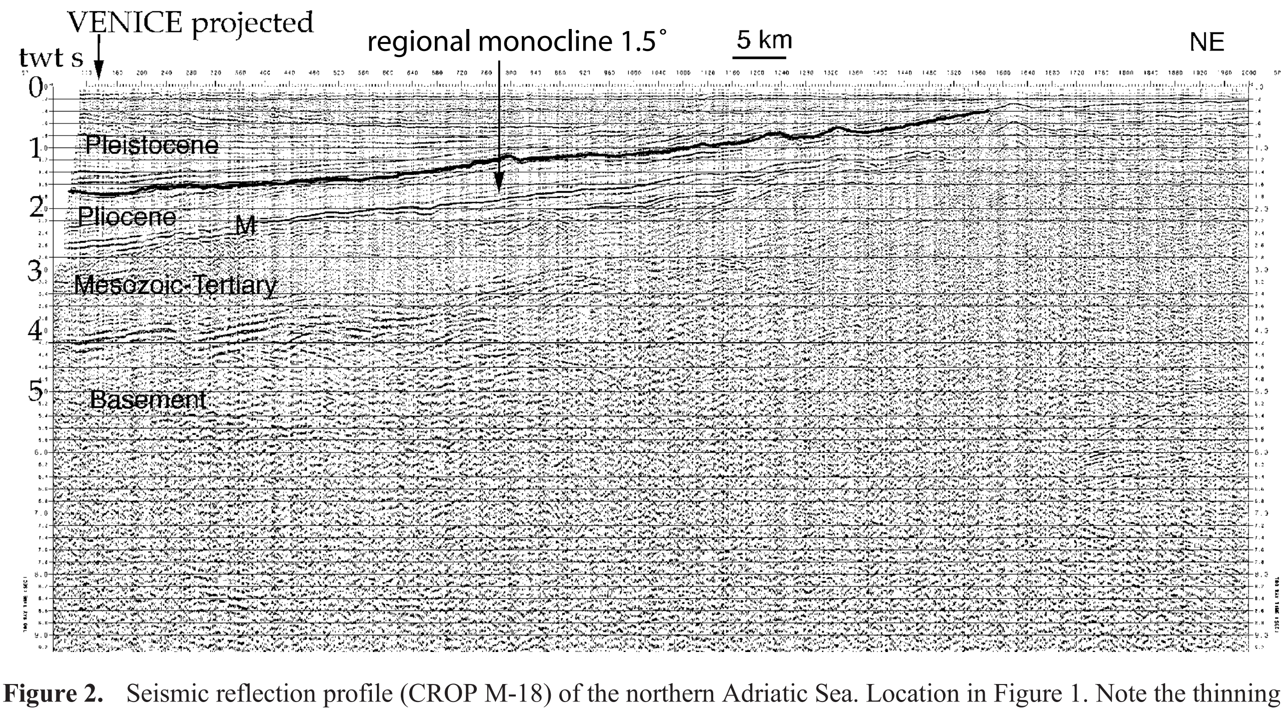

Figure 2. Seismic reflection profile (CROP M-18) of the northern Adriatic Sea. Location in Figure 1. Note the thinning of the Pleistocene sediments moving north-eastward, indicating coeval differential subsidence in the underlying rocks. The Pleistocene-Pliocene boundary is marked. M, Messinian unconformity. Vertical scale in seconds, two way time.

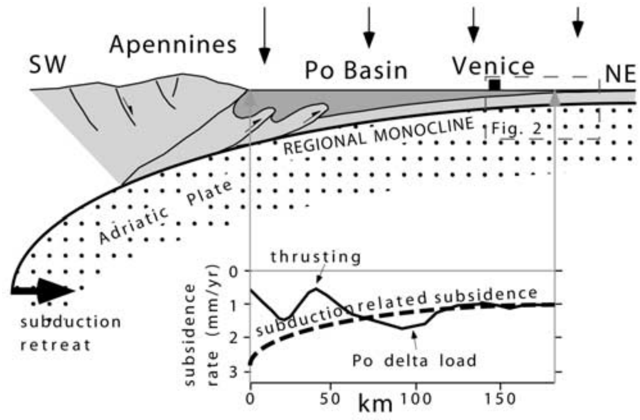

Figure 4. Schematic profile across the Apennines, Po Basin and Venetian area, showing the curvature of the Adriatic plate in the foreland of the Apennines, associated to the slab retreat. Venice subsidence appears as a detail of the larger geodynamic system. Profile location is shown in Figure 1. Subsidence rates, taken from Figure 1, along the profile trace are also shown (solid line in the graph). Notice that the regular subsidence trend due to subduction retreat is perturbed by thrust tectonics.

At the edge of the section, to the southwest the Po river and to the northeast the Tagliamento river also contributed to the filling of the foredeep basin. Clinoforms in the Pleistocene sediments could suggest a filling of a pre-existing basin, claiming for lower or absent subsidence rates during that time frame. However, recent and asymmetric (faster to the southwest) subsidence is testified by stratigraphic and geodesy measurements in the whole Po Basin, which is in places below sea-level [*Carminati and Martinelli*, 2002]. Moreover, subsidence occurred during the Late Pleistocene well outside the effects of the rivers deltas (e.g., the well Lavariano in the Friuli plain). It is noteworthy that mean Pleistocene subsidence rates in the Po Basin have similar velocity of other parts of the Apennines foredeep (e.g., the Pescara Basin to the south along the Adriatic coast [*Colantoni et al.*, 1989]) where large deltas do not occur.

[9] These observations are in agreement with Pleistocene to Present subsidence velocities calculated from deep wells and seismic lines following a sediment decompaction procedure (Figure 1). Quaternary sedimentation rates in the Po plain can be reasonably assumed to be equal to subsidence rates, since the entire sequence was deposited in shallow marine to continental environments. The obtained subsidence rates range between 0 and −2.5 mm/yr, with the largest rates (greater than −1 mm/yr) occurring in the southern part of the Po Plain and in the Po Delta. As discussed by *Carminati and Di Donato* [1999], backstripping analysis suggests that tectonics accounts for about 50% of the long term natural subsidence, whereas compaction and sediment load account for about 30 and 20%, respectively.

[10] In the uppermost part of the Pleistocene, prograding clinoforms can be observed suggesting that second order processes of basin filling cannot be neglected. The calculated velocities are thus to be considered an upper bound. The Pleistocene is notoriously marked by lower sea level relative to the Pliocene [*Haq et al.*, 1987]; this produced larger clastic influx from the Alps and Apennines and a higher sedimentation rate.

[11] Due to the increased ratio between sediment supply and subsidence, the tilting rate in the Upper Pleistocene sediments decreases, making more difficult to appreciate dip variations of the reflectors in a regional seismic line. Moreover, the seismic section of Figure 2 cuts clinoforms obliquely. Therefore they do not indicate their maximum dip and do not provide information on how they might have been tilted by the regional subsidence. However, their very low dip in the southwestern part of the vertically exaggerated section is suggesting post progradation tilting, i.e., steepening of the regional monocline up to at least 0.2 secs.

[12] A subsidence rate graph, along the section trace shown in Figure 1 is displayed in Figure 4. The graph shows in the north-eastern part a slow increase of subsidence rates, followed in the Po delta area by a rapid increase. More to the south-west, approaching the Apennines front and the southern border of the Po Plain, subsidence rates decrease and show an undulated pattern. Two curves can be inferred: one, constructed taking the basement as a possible subsiding repere, is associated to the steady state slab retreat (subduction related subsidence in Figure 4, dashed line); the second accounts for the subsidence at the surface above the accretionary prism, where the folds uplift partly compensate the basement subsidence; moreover it includes the subsidence due to the deltas load and the compaction of the sediments (Figure 4).

3. Discussion and Conclusions

[13] The effects of the curvature of the Apennines subduction occur more than 200 km northeast from the buried front of the Apennines, which in some parts is 40 km north of the morphological front of the Apennines.

[14] In a cross sectional view, the Apennine belt shows a width ranging from 70 to 200 km, a low topographic relief (average about 400–600 m), and an area smaller than that of its foredeep. The effects on bending of the Adriatic lithosphere are larger than the belt itself (Figure 4). As shown in Figure 5, the curvature of the foreland is also

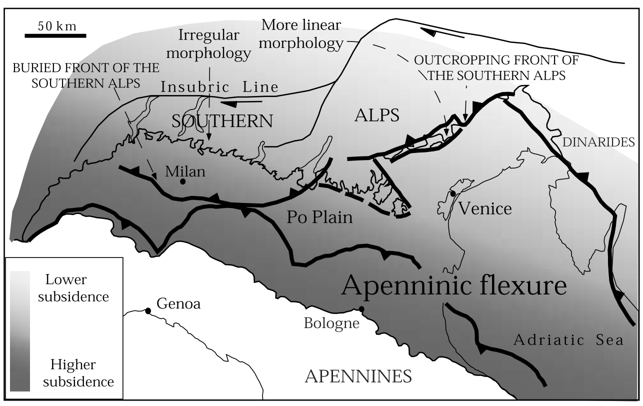

Figure 5. Subsidence related to the flexure induced by the Apennines subduction decreases from south to north. It affects all of the Po Plain basin and part of the Alps and of the Dinarides, where it contrast the general uplift trend related to orogenesis.

likely to affect the Alps, particularly to the northwest of the Po Basin, providing a subsidence contrasting their general uplift [*Doglioni*, 1993]. This is confirmed by the observation that the front of the central and western Southern Alps is buried underneath the Po Plain sediments. At a greater distance from the Apennines subduction hinge, subduction related downflexure decreases and the front of the eastern Southern Alps crops out (Figure 5).

[15] The Dinarides in the eastern side of the Adriatic are also affected by the curvature of the Apennines subduction. This is evident again by the eastward thinning of the Pliocene-Pleistocene sediments of the Apennines foredeep, and their unconformable contact with the frontal eroded anticlines of the Dinarides orogen [*Bigi et al.*, 1990].

[16] The subsidence rate due to the subduction increases approaching the Apennines (Figure 3). In the northern part (Venice region), where thrust tectonics related to Alps and Apennines is absent, subsidence is monotonous and the tectonic component is almost entirely controlled by the retreat of the Adriatic plate subducting underneath the Apennines, as indicated by the accommodation space generated by the subsiding foreland regional monocline (seismic section CROP M-18; Figure 2). The subsidence rate, computed on the thickness of Pleistocene sediments crossed by industrial wells, is in the order of 0.7–1.0 mm/yr. Comparable subsidence rates occur along foredeeps associated to west-directed subduction zones [*Doglioni*, 1993]. In the internal part of the Po Basin, active Apenninic thrusts rather decrease the subduction-related subsidence. Therefore the basement is subsiding, but the overlying cover is subsiding less due to the contrasting effects of the active frontal anticlines of the Apennines accretionary wedge. More to the south, at the morphological front of the Apennines, the uplift is finally predominant.

[17] **Acknowledgments.** G. Mariotti, A.W. Bally and R. Frassetto are thanked for fruitful discussions through time. R. Fantoni and S. Merlini are kindly acknowledged for borehole data. The CROP steering committee permitted publication of M-18 seismic profile. D. Frizon de Lamotte and an anonymous reviewer are thanked for constructive criticism. Research supported by ASI and Cofin 2001.

References

Arca, S., and G. P. Beretta, Prima sintesi geodetico-geologica sui movimenti verticali del suolo nell'Italia Settentrionale (1897–1957), *Boll. Geod. Sc. Aff.*, *44*, 125–156, 1985.

Bergamasco, A., P. Teatini, and L. Carbognin, Confronto critico tra kriging e analisi oggettiva, *Il Nuovo Cimento*, *16*, 289–302, 1993.

Bigi, G., D. Cosentino, M. Parotto, R. Sartori, and P. Scandone, Structural model of Italy, Scale 1:500.000, C.N.R. Progetto Finalizzato Geodinamica, Firenze, Italy, 1990.

Bortolami, G. C., J. C. Fontes, V. Markgraf, and J. F. Saliege, Land, sea and climate in the northern Adriatic region during late Pleistocene and Holocene, *Pal. Pal. Pal.*, *21*,139–156, 1977.

Bras, R. L., D. R. F. Harleman, A. Rinaldo, and P. Rizzoli, Obsolete? No. Necessary? Yes. The gates will save Venice, *EOS*, *83*, 217–224, 2002.

Carbognin, L., and G. Taroni, Eustatismo a Venezia e Trieste nell'ultimo secolo, *Atti Istituto Veneto di Scienze e Lettere ed Arti*, *CLIV*, 281–298, 1996.

Carbognin, L., G. Gambolati, and A. I. Johnson (Eds.), Proceedings of the Sixth International Symposium on Land Subsidence, Ravenna 24–29 September, vol. I and II, 2000.

Carminati, E., and G. Di Donato, Separating natural and anthropogenic vertical movements in fast subsiding areas: The Po plain (N. Italy) case, *Geophys. Res. Lett.*, *26*, 2291–2294, 1999.

Carminati, E., and G. Martinelli, Subsidence rates in the Po Plain, northern Italy: The relative impact of natural and anthropogenic causation, *Eng. Geol.*, *66*, 241–255, 2002.

Colantoni, P., A. Asioli, A. M. Borsetti, L. Capotondi, and C. Vergnaud-Grazzini, Subsidenza tardo-pleistocenica ed olocenica nel medio Adriatico evidenziata dalla geofisica e da ricostruzioni paleoambientali, *Mem. Soc. Geol. It.*, *42*, 209–220, 1989.

Doglioni, C., Some remarks on the origin of foredeeps, *Tectonophysics*, *228*, 1–20, 1993.

Flemming, N. C., Predictions of relative coastal sea-level change in the Mediterranean based on archaeological, historical and tide-gauge data, in *Climatic change in the Mediterranean*, edited by L. Jeftic, et al., Edward Arnold, London, 247–281, 1992.

Fontes, J. C., and G. Bortolami, Subsidence of the Venice area during the past 40,000 yr, *Nature*, *244*, 339–341, 1973.

Haq, B. U., J. Hardenbol, and P. R. Vail, Chronology of fluctuating sea levels since the Triassic, *Science*, *235*, 1156–1167, 1987.

Mariotti, G., and C. Doglioni, The dip of the foreland monocline in the Alps and Apennines, *Earth Planet. Sci. Lett.*, *181*, 191–202, 2000.

Merlini, S., C. Doglioni, R. Fantoni, and M. Ponton, Analisi strutturale lungo un profilo geologico tra la linea Fella-Sava e l'avampaese adriatico (Friuli Venezia Giulia-Italia), *Mem. Soc. Geol. It.*, *57*, 293–300, 2002.

Pieri, M., and G. Groppi, Subsurface geological structure of the Po plain, Italy, *CNR, Prog. Final. Geod.*, 414, 13 pp., 1981.

Pirazzoli, P. A., Sea level changes, *The last 20,000 years*, John Wiley & Sons, Chichester, 211 pp., 1996.

Pirazzoli, P. A., Did the Italian government approve an obsolete project to save Venice?, *EOS*, *83*, 217–223, 2002.

Royden, L. H., and G. D. Karner, Flexure of the lithosphere beneath Apennine and Carpathian foredeep basins: Evidence for an insufficient topography load, *Am. Ass. Petrol. Geol. Bull.*, *68*, 704–712, 1984.

Royden, L., E. Patacca, and P. Scandone, Segmentation and configuration of subducted lithosphere in Italy: An important control on thrust-belt and foredeep-basin evolution, *Geology*, *15*, 714–717, 1987.

Tosi, L., L. Carbognin, P. Teatini, T. Strozzi, and U. Wegmuller, Evidence of the present relative land stability of Venice, Italy, from land, sea, and space observations, *Geophys. Res. Lett.*, *29*, 2002.

Wessel, P., and W. H. F. Smith, New version of the generic mapping tools released, *EOS*, *76*, 329, 1995.

Zoetemeijer, R., S. Cloetingh, W. Sassi, and F. Roure, Modelling of piggy-back-basin stratigraphy; record of tectonic evolution, *Tectonophysics*, *226*, 253–269, 1993.

E. Carminati and C. Doglioni, Dept. of Earth Sciences, University La Sapienza, P.le A. Moro 5, 00185, Roma, Italy. (eugenio.carminati@uniroma1.it)

D. Scrocca IGAG,-CNR P.le A. Moro 5, 00185, Roma, Italy.