

The morphology of a Messinian valley and its hinterland (Ventimiglia, NW Italy): a Miocene to Pliocene reconstruction

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Along the Ligurian coast (NW Italy), Alpine-folded and slightly metamorphosed rocks experienced fluvial to marine erosion prior to and during the base level fall associated with the Messinian salinity crisis. Following the subsequent sea-level rise at the onset of the Pliocene, valleys incised along the coastal margins during the Messinian salinity crisis were partly filled with Pliocene marine and continental deposits. One such valley-infill system is exposed near Ventimiglia (NW Italy). Using geological cross-sections and geomorphological analysis we have constrained its shape and dimensions, as well as the morphology of its hinterland. The Messinian valley was very open, ~10 km wide and probably 500 m deep. The basal unconformity between the Pliocene sediments and the underlying substratum is characterized by a smooth surface that has on either side of the palaeo-valley a dip between 2 and 10°. The basal unconformity in the southernmost part of the palaeo-valley roughly coincides with present-day sea level. The hinterland of the middle Pliocene sea was characterized by kilometres-wide valleys surrounded by mountains with a relief gentler than at present. The shapes and dimensions of the Messinian Ventimiglia valley and the relief during Pliocene times are different from those derived from comparable structures in SE France and NW Italy. We interpret this as being due to the exhumation history that the Ventimiglia region, different from the surrounding areas, experienced over the last few million years. Copyright © 2006 John Wiley & Sons, Ltd.

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1. INTRODUCTION

Localized outcrops of Pliocene marine to continental sediments are found along the coastal regions of the (Western) Mediterranean Sea, often elevated up to several hundred metres above sea level (e.g. Chumakov 1973; Clauzon 1973, 1978; Boni 1986; Cavazza and DeCelles 1993). These sediments make up the incomplete record of major tectonic, palaeo-oceanographic and climatic interactions that occurred during and following the late Miocene (the Messinian salinity crisis, Hsü *et al.* 1973) in the Mediterranean region. During the Messinian salinity crisis, the Mediterranean Sea was isolated from the Atlantic Ocean resulting in a dramatic drop in Mediterranean base level, locally up to 2 km (e.g. Ryan 1976; Clauzon 1982; Réhault *et al.* 1984). The drop in base level resulted in extensive erosion along the Mediterranean margins whereby, in regions near major rivers, the margins were eroded and (deep) fluvial valleys were incised (e.g. Chumakov 1973; Clauzon 1973, 1978, 1982). During the subsequent refilling of the Mediterranean at the onset of the Pliocene, these valleys were drowned and filled with marine to continental sediments, often arranged in large Gilbert-type delta settings (e.g. Clauzon and Rubino 1995; Clauzon *et al.* 1996; Cavazza and DeCelles 1998; Gnaccolini 1998; Breda 2002). Examples of these systems are found in the Provence

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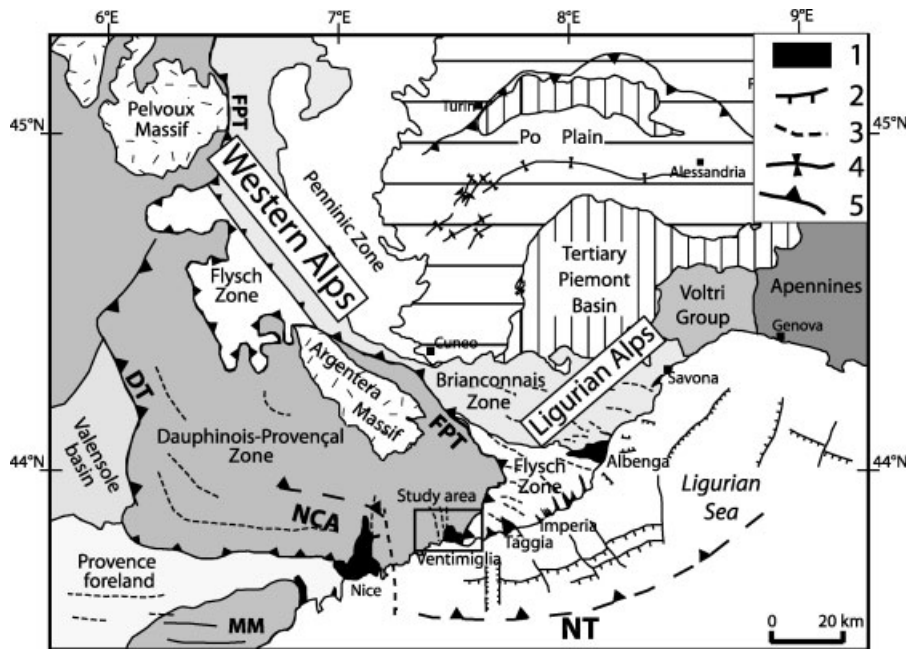


Figure 1. Tectonic map of the Ligurian Alps and adjacent areas showing the main structural units (map compiled and modified after Vanossi *et al.* 1994; Bigot-Cormier 2002). NCA, Nice Castellane Arc; MM, Maurès-Esterel Massif; NT, north-dipping thrust; FPT, Frontal Penninic thrust; DT, Digne thrust. 1, Pliocene sediments along the Ligurian coast; 2, normal faults; 3, meso-Alpine fold axis; 4, post-Alpine fold axis; 5, thrust (discontinuous where inferred). Box shows study area.

(South France, e.g. Clauzon 1973, 1978, 1979) and along the Nile (Chumakov 1973). In the specific cases of the Rhône (SW France) and the Nile rivers, the base of these Messinian valleys at the position of the present-day coastline is found >1300 m below present-day sea level (e.g. Chumakov 1973; Clauzon 1982). Based on these examples, it is generally assumed that the Messinian valleys are deep and extend for several (hundreds of) kilometres inland (Chumakov 1973; Clauzon 1982 and references therein).

In the Italian Ligurian Alps, large occurrences of Pliocene sedimentary rocks are found near Ventimiglia, Taggia, Imperia and Albenga (Figure 1; Boni *et al.* 1984, 1985; Clauzon *et al.* 1996; Gnaccolini 1998; Marini 2000, 2001; Breda 2002). With few exceptions (see Marini 1984; Boni *et al.* 1985), there is general agreement that the depocentres hosting the Pliocene rocks are the result of fluvial erosion caused by the Messinian sea level fall, that is they are Messinian (palaeo) valleys (e.g. Clauzon *et al.* 1996; Breda 2002).

Most of the work carried out in the last decades in the Italian Ligurian Alps has focused on the sedimentology and stratigraphy of the Pliocene deposits (Irr 1975; Boni *et al.* 1984, 1985; Clauzon and Rubino 1995; Clauzon *et al.* 1996; Gnaccolini 1998; Marini 2000, 2001; Breda 2002). Comparably less attention has been devoted to the analysis of the shape of Messinian valleys hosting those sediments and a V-shape has implicitly been assumed (Clauzon *et al.* 1996). The idea that Messinian valleys are V-shaped, deep and extending for several (tens of) kilometres inland is mainly based on observations carried out in the Var and Rhône valleys (e.g. Clauzon 1973, 1978, 1979, 1982). A similar shape can be proposed for the Messinian valley of Albenga despite the absence of seismic data (Clauzon *et al.* 1996). A general V-shape for all Messinian valleys also reflects the implicit idea that the palaeo-topography following the Messinian salinity crisis was comparable to that observed today, that is, it was characterized by fairly steep relief in both the on- and offshore domains.

Despite their first-order similarity, there are significant differences in the distribution of Pliocene sediments in the Provence and the Ventimiglia-Taggia region. Perhaps, the most characteristic aspect of the latter is that the base of the Pliocene sediments, which corresponds to the Messinian valley floor, has experienced substantial uplift and is

largely exposed and cut by (present day) rivers. This is not the case in the Provence and further to the east in the Albenga region of the Ligurian Alps. This demonstrates that westernmost Liguria has undergone a Messinian to Present evolution that is different from the adjacent sectors. Indeed, recent thermochronological studies in this segment of the Ligurian Alps have demonstrated that significant exhumation has taken place from the Messinian to Present (Foeken *et al.* 2003). In addition, offshore studies have shown that significant post-Pliocene uplift of the Ligurian margin has occurred (e.g. Chaumillon *et al.* 1994; Bigot-Cormier *et al.* 2004), giving further evidence that the late Miocene setting might have been different than at present.

There are further differences between the Provence and westernmost Liguria. In the latter area, Pliocene sediments are found only a few (<10 km) kilometres inland (Boni *et al.* 1984, 1985; Gnaccolini 1998; Marini 2000; Breda 2002) while the same sediments on the French side penetrate up to ~200 km inland (Perriaux 1957; Irr 1975; Clauzon 1978, 1982). Furthermore, detailed sedimentological analysis of the infill in the Ventimiglia Messinian valley (Gnaccolini 1998; Marini 2001; Breda 2002) shows that the steep fore-sets of the Pliocene delta downlap towards the present-day coast line where they grade to bottom- and toesets. This is an additional indication that the Ventimiglia palaeo-valley is less deep than generally assumed (see e.g. Clauzon and Rubino 1995).

In this study, we document the shape of the Messinian valley in the region of Ventimiglia, close to the French-Italian border. Expanding on available maps (Boni *et al.* 1984; Gnaccolini 1998; Marini 2001; Breda 2002), we mapped in detail the contact between Pliocene sediments and their deformed substratum. We present results showing that an alternative to the V-shaped morphology can be observed for Messinian valleys. Furthermore, we carried out palaeo-stress analysis constraining the stress regime under which the area was uplifted. Using morphological observations we attempt a reconstruction of the Pliocene hinterland morphology at the time of deposition of the Pliocene sediments in the Messinian valley.

2. GEOLOGICAL SETTING

The Ligurian Alps (Figure 1) are a WSW–ENE-trending mountain chain located at the southern continuation of the Western Alps. It developed in response to Europe/Africa continent collision that initiated in the Eocene (e.g. Debelmas 1989; Dewey *et al.* 1989; Laubscher *et al.* 1992; Vanossi *et al.* 1994). The Ligurian Alps had its peak-shortening stage during the Late Eocene–Early Oligocene (Lorenz 1984; Vanossi *et al.* 1984; Carrapa *et al.* 2003) and, from the late Oligocene, changes in the kinematics of continental fragments resulted in a switch from a contractional to an extensional regime in the western Mediterranean region, eventually leading to the opening of the Liguro-Provençal basin (late Oligocene to early Miocene, e.g. Moullade 1978; Réhault *et al.* 1984; Jolivet and Faccenna 2000; Speranza *et al.* 2002), and Tyrrhenian Sea (Late Miocene to Pliocene Kastens and Mascle 1990; Gueguen *et al.* 1998).

Recent low-temperature apatite (U-Th)/He and fission track studies have shown that vertical movements in the Ligurian Alps are not limited to the orogenic stage (Paleogene) but persisted during the Miocene to Present (Foeken *et al.* 2003; Bertotti *et al.* 2006). Although not resolved in detail yet, the late Miocene to Present exhumation of the Ligurian Alps is thought to be partially accommodated by movement along a north-dipping thrust (Foeken *et al.* 2003), emerging at the surface at the foot of the Ligurian margin (NT in Figure 1, after Bigot-Cormier *et al.* 2004). Displacement along the northern (deep) continuation of this thrust is thought to be partly responsible for the Pliocene exhumation of the Argentera Massif (Bigot-Cormier *et al.* 2004). According to these reconstructions, the thrust would have a E–W strike from the Gulf of Genoa to the longitude of Ventimiglia. Further to the west it would be replaced by a N–S transfer zone kinematically connecting it with the Castellane Arc west of Nice (Bigot-Cormier *et al.* 2004 and references therein).

During the late Miocene, the uplifting area was affected by the Messinian base level drop, which led to extensive erosion in the onshore Ligurian Alps (Foeken *et al.* 2003) and offshore Ligurian margin (e.g. Savoye and Piper 1991). Following the Pliocene sea-level rise and the subsequent deposition, the Pliocene sediments themselves were uplifted to their present-day position of several hundred metres above sea level. Deformation of the Pliocene

sediments along the Italian side was minor and associated with predominantly NW–SE and NE–SW-trending normal faults (Marini 1984; Boni *et al.* 1985; Marini 2000).

3. THE MESSINIAN VALLEY AND PLIOCENE INFILL OF VENTIMIGLIA

3.1. General features

The Pliocene outcrops of Ventimiglia are located close to the border between France and Italy and occupy an area spanning ~ 7 km in N–S direction and ~ 10 km in W–E direction (Figure 2, simplified from Marini 2001; Breda 2002). The >500 m-thick exposed sediments overlie a substratum of folded and slightly metamorphosed Eocene flysch. The Pliocene succession is roughly characterized by a repetition of coarse-grained conglomerates and marine shales (Boni *et al.* 1985; Gnaccolini 1998; Marini 2001), referred to as upper and lower conglomerates and upper and lower shales, respectively (Breda 2002). Biostratigraphic dating of the shale intervals yielded an early to middle Pliocene age (Boni *et al.* 1985; Breda 2002). The internal architecture of the Pliocene infill is characterized by a stack of Gilbert-type deltaic sequences (Clauzon *et al.* 1996; Gnaccolini 1998; Breda 2002) with up to $\sim 20^\circ$ steep fore-sets (the lower and upper conglomerates, Breda 2002) separated by the shale intervals (lower and upper shales, Breda 2002). The deltaic sequences that make up the Pliocene succession are controlled by two transgressive-regressive cycles, in which the lower and upper shales mark the transgressive stages (Figure 3, Breda

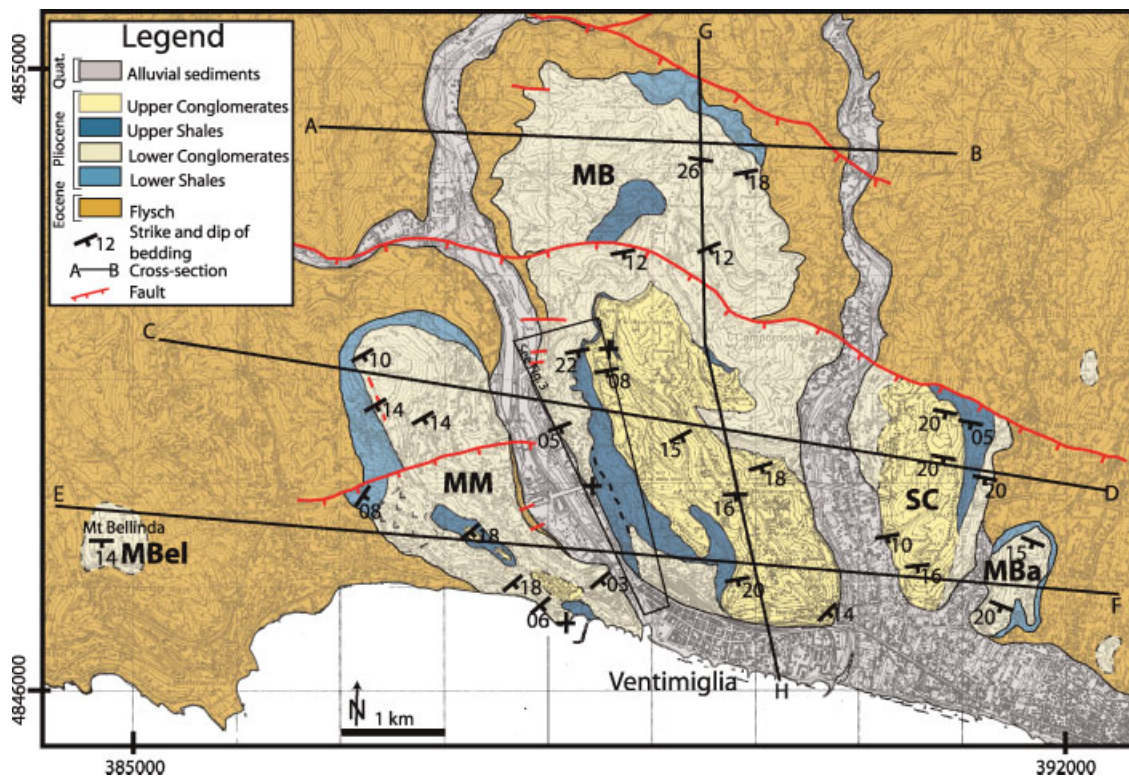


Figure 2. Geological map of the Ventimiglia Pliocene basin; simplified from Breda (2002) and Marini (2001), expanded with own field observations. MM, Mt Magliocca cluster; MB, Mt Baracone cluster; SC, Santa Croce cluster; MBa, Mt Bauso cluster; MBel, Mt Bellinda cluster, representing main clusters of Pliocene outcrops in the Ventimiglia area. The box along the southwestern side of the MB cluster is shown in Figure 3 (Topographic maps from Regione Liguria 1986a; Regione Liguria 1986b, with coordinates in UTM, Zone 32). 'This figure is available in colour online at www.interscience.wiley.com'

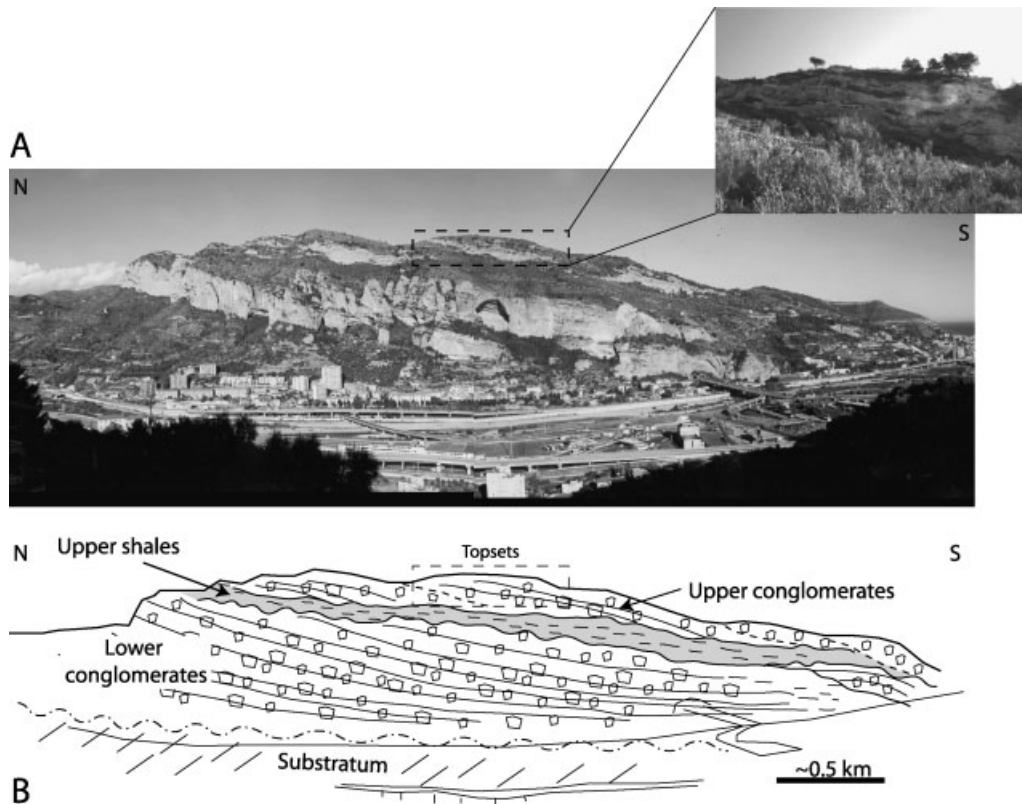


Figure 3. (A) Photo showing the southwestern side of the Mt. Baraccone unit. Inset photo shows top-sets observed in the Pliocene succession. (B) Interpretation of the different delta sequences with erosional surfaces (dashed lines). Interpretation after Breda (2002). Dashed-dotted line shows the interpreted Messinian erosion surface (i.e. the base of the Messinian valley).

2002). The lower shales have at present a $\sim 5\text{--}10^\circ$ S to SE dip interpreted as the original dip of the bottom-sets (Clauzon *et al.* 1996) or post-depositional tilting during uplift of the Pliocene sediments to their present location (Lorenz 1984).

As a consequence of post-depositional erosion, the initially continuous Pliocene sediments are now found in five clusters of outcrops, from west to east in the areas of Mt Bellinda (MBel), Mt Magliocca (MM), Mt Baraccone (MB), St Croce (SC) and Mt Bauso (MBa). Smaller outcrops of Pliocene conglomerates are also present north and east of the MBa (Figure 2).

3.2. Geological sections and the shape of the Messinian valley

To document the shape and nature of the Messinian valley in the Ventimiglia region, we present four geological cross-sections based on compilation of available maps and our own detailed mapping at 1:10 000 scale. Three sections are at a high angle to the axis of the Messinian valley, a fourth is parallel to it (Figure 4).

The Pliocene to Present uplift of the Ventimiglia area and the consequent river erosion has allowed the exposure of the large parts of the Pliocene sediments and the underlying Paleogene flysch. Consequently, the Messinian valley floor can be carefully mapped and a detailed 3D geometry of the Messinian valley can be reconstructed using outcrops, their position relative to each other and, at a larger scale, interpreting the map-view intersection of the palaeo-valley floor with the topography. The detail obtained is greater than in other neighbouring coeval features

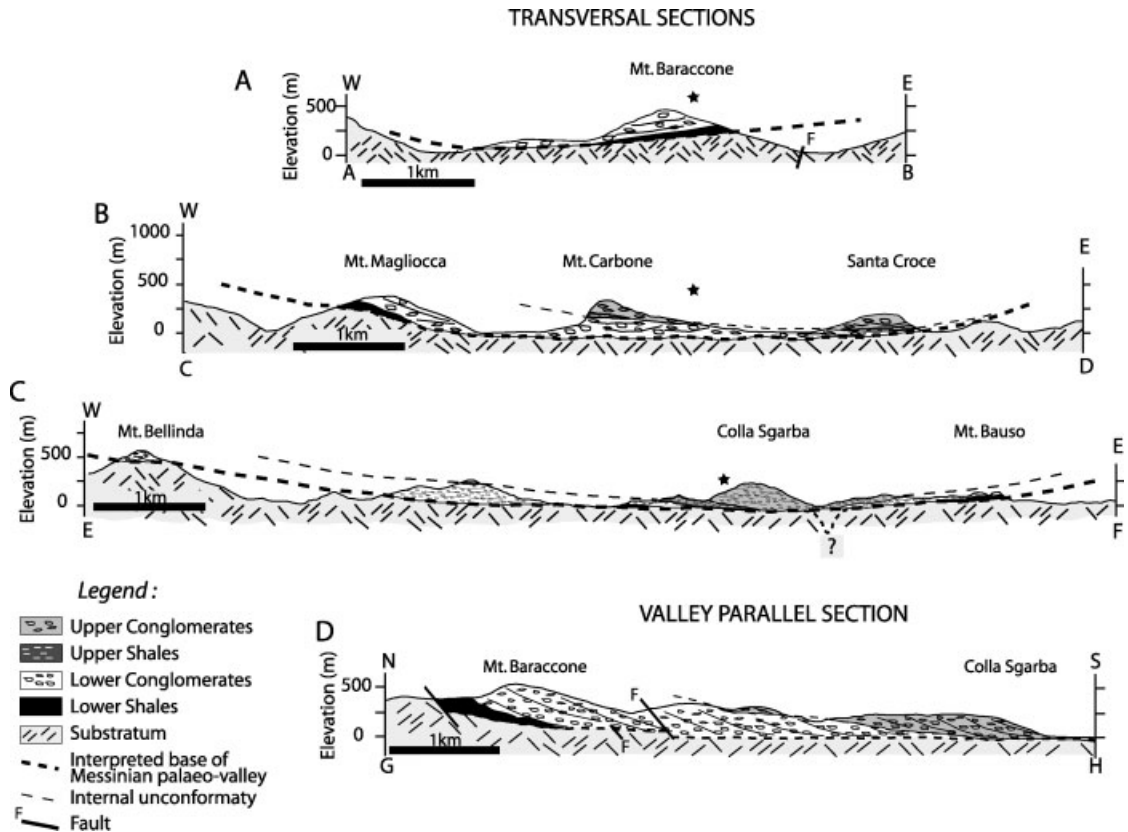


Figure 4. (A–C) West–east (transversal) cross-sections perpendicular to the valley’s main axis (see Figure 2 for locations). Black star in profiles marks crossing point with the N–S profile. (D) North–south cross-section parallel along the valley’s main axis. All cross-sections drawn to scale; no vertical exaggeration has been applied.

where uplift and erosion were not as profound and the floor of the Messinian valleys is still buried in the subsurface. Consequently, their shapes are poorly constrained. In most places in the Ventimiglia section, the error in the position of the base of the Pliocene sediments is limited, often within a 10–20 m uncertainty. Only in the southern central area is the uncertainty larger.

Transversal sections

The first cross-section through the northern part of the Pliocene sediments infilling the Messinian valley (Figures 2 and 4A) traverses the MB outcrops. Two Pliocene lithological units are found: lower shales and lower conglomerates (Breda 2002). The basal contact is exposed in several outcrops along small trails on the W and E sides of the MB (scale of the exposures is often a few metres). Basal contact outcrops on the western side are observed at elevations between 250 and 150 m, while on the eastern side of the MB, they are found at 450–350 m of elevation. The map-view trace of the basal contact along the northern side of the MB displays a west-dipping trace that gently crosses lower contours westwards. From these observations, we derive a $\sim 5^\circ$ westwards-dipping basal surface (Figure 4A).

The cross-section in Figure 4B reconstructs the Messinian valley underneath the central part of the Pliocene succession and traverses the MM, the MB and the SC clusters. Outcrops of the basal contact are mainly observed in the MM and SC. Few relevant exposures are found along the northern termination of the MM, but the contact position is well constrained and decreases in elevation from ~ 250 to 50 m over a horizontal distance of

approximately 1 km. Along the northwestern side of the MM, a few basal outcrops are found at approximately 300 m elevation; on the eastern side they roughly coincide with the present-day riverbed. The map-view trace of the contact along the northern termination of the MM displays a gradually eastward-dipping trace that gently crosses lower elevation contours at low angle. These observations suggest a $\sim 6^\circ$ eastward-dipping geometry of the basal contact underneath the MM. In the MB, the basal contact is not exposed. Indirect evidence on its shape and position is derived from the subhorizontal dip of the lower conglomeratic layers (Figures 2 and 3), interpreted by Breda (2002) as bottom-sets. In the SC, outcrops of the basal contact are found only along the eastern side, where they coincide with the present-day riverbed of the Vallecrosia river. Along the eastern sides of the MM and the SC the basal contacts are approximately at the same elevation (Figure 4B). The integration of the above observations documents a wide basal-contact geometry in this part of the basin with a dip of $\sim 5\text{--}10^\circ$ on either side. Taking into account the subhorizontal dip of the bottom-sets in the lower conglomerates of the MB, we assume that the Messinian valley floor is approximately subhorizontal and close to present-day sea level (Figure 4B).

The southernmost cross-section traverses all major Pliocene outcrops (Figure 4C). In the MBel cluster, the basal contact is not exposed but its position can be defined within a $\sim 10\text{--}20$ m uncertainty. Elevations of the basal contact are ~ 500 m along both the western and eastern sides, suggesting a fairly horizontal geometry along this part of the palaeo-valley. The map-view trace along the southern side of the MBel shows a similar trend. In the southern part of the MM, the basal contact is found at slightly higher elevations (~ 75 m) along the western side than along the eastern side (~ 25 m), where it is close to the present-day riverbed (Figure 2). The interpretation that the basal contact underneath the MM is close to present-day sea level is derived from the (sub)horizontal dip of the basal lower conglomerates in the southernmost, present-day coastline part of the MM. The above observations suggest that the basal contact underneath the MM consists of a $\sim 2\text{--}3^\circ$ eastward-dipping surface. The bottom of the palaeo-valley is not exposed in the MB and SC, but information on its position can be approximated using sedimentological observations. The presence of toe- and bottom-sets in the southern part of the MB (Breda 2002) indicates that the Messinian valley floor is immediately underneath the MB sediments. The basal contact is not exposed in correspondence with the SC. Further to the E, in the MBa, outcrops of the basal contact are predominantly found along the eastern and southern sides (both at ~ 50 m of elevation to sea level). In map view, the trace of the basal contact along the northern and southern sides of the MBa decreases in elevation westwards. We conclude that the basal geometry underneath the MBa consists of an $\sim 3\text{--}5^\circ$ west-dipping surface. Combining all observations along the southern section (Figure 4C), we derive an open and wide Messinian valley floor that, in the southern part of the studied area, is close to present-day sea level.

Valley-parallel section

A north–south cross-section illustrates the geometry of the Messinian valley along its main axis (Figure 4D). We have opted for a section traversing the MB because it has the best exposures and most complete stratigraphy (Breda 2002). In the northwestern part of the MB, basal-contact exposures are at an elevation of 400 m (the northernmost point of the MB). Towards the south, the position of the contact is visible along the east side of the MB, where exposures of the basal contact are found at ~ 100 m elevation (Figure 2). The map-view trace of the contact displays a gently southward-dipping shape. Although the basal contact is not continuously exposed, extrapolation of the elevations at which exposures are found suggests that the palaeo-valley basal contact has an initial $\sim 5\text{--}15^\circ$, southward dip along its northernmost 1–2 km (Figure 4D).

Continuing southwards, the position of the basal contact is constrained by exposures along the western side of the MB (Figure 3). Outcrops of the Messinian valley floor are at approximately the same elevation, indicating that towards the central part of the MB the basal contact becomes subhorizontal (Figures 3 and 4D). Similar observations are made along the eastern side of the MB, where outcrops are found at similar elevations. Locally, the basal contact has been affected by syn-depositional faulting, with displacement in the order of a few (tens of) metres (Figure 5). In the locality of Figure 5, the basal contact is a $2\text{--}3^\circ$ southward-dipping surface.

No outcrops of the Messinian valley floor are found in the southern part of the MB. Here, its geometry is inferred from sedimentological observations in the Pliocene conglomerates at or close to the basal contact (Figure 3). In the southern part of the MB, the steep ($\sim 20^\circ$ dipping) fore-sets of the lower conglomerates become shallower dipping



Figure 5. Syn-sedimentary faulted contact between the lower conglomerates (black solid lines) and the Eocene substratum (white solid lines). Faults (black dashed lines) dip 220/84 and 225/64 (azimuth/dip). White dashed line marks Messinian erosional surface.

and eventually subhorizontal (Figure 2). In addition, they are replaced by shales in the southernmost part of the MB (Breda 2002). These observations are interpreted to represent a downlap in the delta system, that is a change from fore- to toesets (Breda 2002) and would confirm that the sediments are deposited at or close to the base of the palaeo-valley (Figure 4D). Observations similar to those described for Figure 4D can also be made in the areas of MM and SC.

3.3. The overall shape of the Messinian valley

Combining the transverse and valley-parallel sections, we derive a 3D image of the Ventimiglia Messinian valley. Its most characteristic feature is its open and wide shape. In north–south direction, the base of the Messinian valley initially dips 5–15° to the S and then rapidly becomes approximately subhorizontal. The length of the flat part of the palaeo-valley floor is ~4 km and in the southern part corresponds roughly to the present-day sea level. In west–east direction, the flanks of the Messinian valley generally dip <5° becoming shallower towards the subhorizontal floor of the valley.

Considering the outcrops described in preceding sections and those found further to the W at Mount Bellinda (Figures 2 and 4C), we derive a minimum width of the Ventimiglia Messinian valley in west–east direction of 10 km. The post-Pliocene erosion of the palaeo-margins of the Messinian valley makes estimating the palaeo-relief ambiguous. The preserved difference between elevations of the margins and that of the centre of the Messinian valley floor is ~500 m.

3.4. Deformations prior to, during and following Pliocene sedimentation

Palaeo-stress measurements and outcrop-scale observations were carried out in the region to assess the deformation regime prior to, during and following Pliocene deposition. Palaeo-stress analysis was performed using the TENSOR package (TENSOR, Delvaux 1993; Delvaux *et al.* 1995). Due to the lack of fault planes with striations, not enough measurements could be performed in the Pliocene sediments and meaningful conclusions could be derived only from stations in the substratum (Figure 6 and Table 1).

Palaeo-stress analysis reveals NW–SE to W–E-directed tension in 6 of the 10 measured stations. Three stations yielded NE–SW-directed tension and one station showed NW–SE-directed compression. The NW–SE-directed tensional axes fit the regional pattern and associated structures as widely documented in the Ligurian region (e.g. Vanossi *et al.* 1984; Boni 1986). These features are related to Liguro-Provençal basin opening, which occurred during the late Oligocene to early Miocene (e.g. Moullade 1978; Réhault *et al.* 1984; Jolivet and Faccenna 2000; Speranza *et al.* 2002). We therefore interpret the NW–SE to W–E structures to be of late Oligocene to early Miocene age.

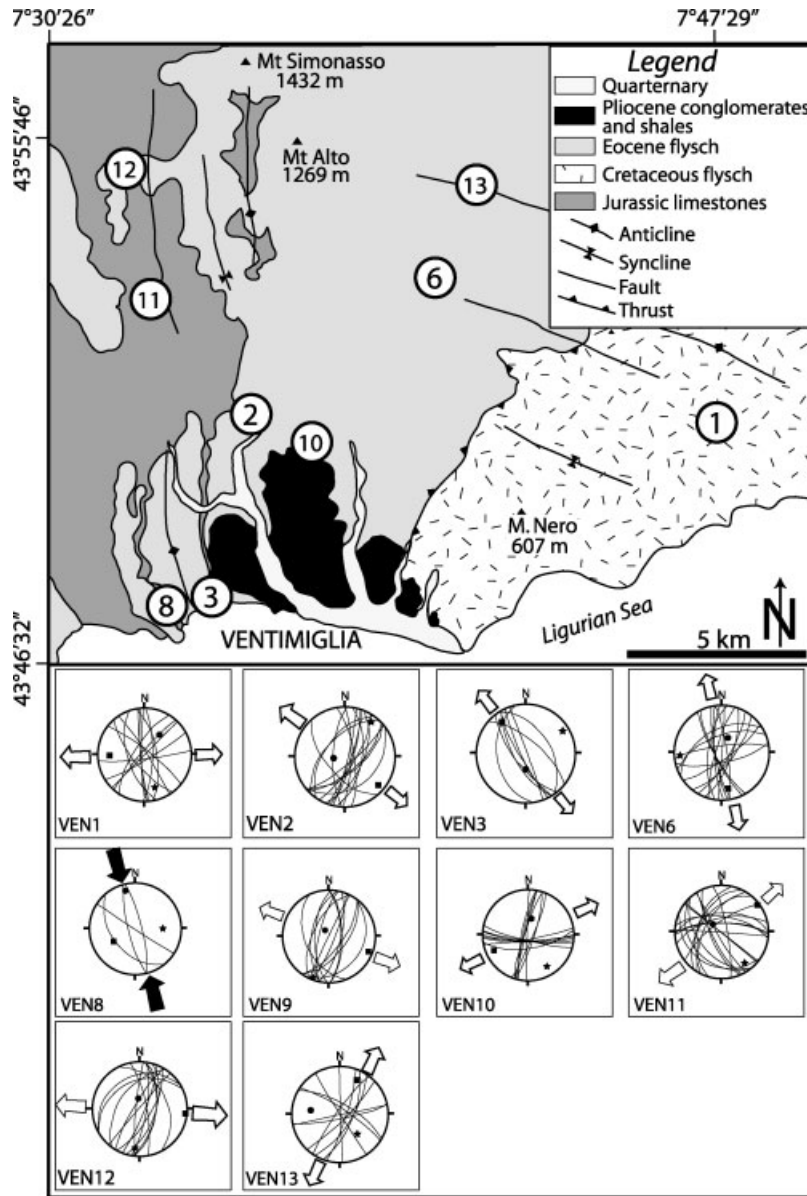


Figure 6. Map showing the location of palaeo-stress measurements in the surrounding substratum (1, VEN1, etc). Principal-stress axes are displayed in diagrams as: σ_1 , black circle; σ_2 , black star and σ_3 , black square (see Table 1 for details). Two main extensional directions are seen: NW-SE and NE-SW.

Deformation under a similar dynamic setting continued during the deposition of the Pliocene sediments as evidenced by NE-SW to ENE-WSW-trending syn-depositional faults that cut the basal unconformity and die out in the overlying Pliocene sediments (e.g. at the base of the MB and MM, see Figures 2 and 5). In the MM a southeast-dipping normal fault displaces lower shales and conglomerates. However, this fault does not seem to affect the upper conglomerates. Displacements are in the order of few (tens of) metres. Two SW-dipping normal faults form the northern boundaries of the Pliocene sediments at MB and SC (Figure 2) and are considered to be of post-Pliocene age. The interpreted deformation structures in the Pliocene succession fit within the stress patterns derived

Table 1. Palaeo-stress tensors for the Ventimiglia area

Site	N	E	Description	n	σ_1	σ_2	σ_3	R	α	Q	Tensor type
Ven1	399375	4855387	Cretaceous flysch	15	035/45	161/31	271/29	0.83	54.9	C	Oblique extensive
Ven2	386771	4854677	Cretaceous flysch	18	268/75	036/11	129/14	0.7	17.3	B	Pure extensive
Ven3	385225	4850475	Cretaceous siltstones	9	182/64	058/15	322/21	0.67	0.0	A	Pure extensive
Ven6	391640	4859775	Cretaceous flysch	18	024/62	266/14	170/24	0.71	71.3	C	Pure extensive
Ven8	383125	4849387	Cretaceous limestones	6	346/18	091/39	237/45	0.5	57.2	D	Oblique compressive
Ven9	388525	4858364	Cretaceous limestones	13	326/76	203/08	111/12	0.64	16.0	B	Pure extensive
Ven10	388475	4854937	Cretaceous flysch	15	013/58	148/24	247/20	0.8	33.9	C	Strike-slip extensive
Ven11	383950	4858750	Jurassic limestones	22	315/69	143/21	052/03	0.56	58.1	C	Pure extensive
Ven12	381837	4862850	Jurassic limestones	16	358/70	185/20	094/02	0.4	63.2	C	Pure extensive
Ven13	391950	4861937	Cretaceous flysch	13	278/35	140/47	024/22	0.5	39.6	C	Oblique extensive

n is the number of geological structures used to calculate the reduced palaeo-stress tensor; σ_1 , σ_2 and σ_3 are the principal stress directions. R , stress ellipsoid shape ratio. α describes the mean deviation between theoretical and observed fault movement and is a measure of the accuracy of the calculated tensors. Q is the quality of the calculated tensor, taking into account n and α .

A, good; B, medium; C, poor and D, not reliable.

Stress tensors calculated with TENSOR (Delvaux 1993). Coordinates in UTM, Zone 32.

from earthquake focal mechanisms indicating NW–SE extension in the Ligurian basin (Bethoux 1992; Eva and Solarino 1998; Eva *et al.* 2001) and NW–SE compression in the Western Alps (Calais *et al.* 2002).

4. PLIOCENE HINTERLAND MORPHOLOGY

At the onset of the Pliocene, the rising Mediterranean sea level invaded the wide and gentle Messinian valley described above and resulted in the deposition of coeval sediments. The apparent difference between the shape of the Messinian valley and the present-day steeper and well-incised valleys suggests that the topography of the hinterland of the gulf in which Pliocene sediments were being deposited was different from the one observed today. In this section we present a reconstruction of the hinterland morphology and we address the question: was the Ventimiglia gulf surrounded by steep mountains or was there a gentler coastal region?

Our reconstruction hinges on the geometry of Middle Pliocene sediments and is, strictly speaking, applicable to the same time period. We assume, however, that the morphology was created either immediately prior to or during the base-level drop of the Messinian, and remained relatively constant throughout the entire period of Pliocene deposition.

4.1. The northern margin of the Taggia Messinian valley: an analogue

At Present, the northern termination of the Ventimiglia Pliocene deposits is only partly preserved due to post-Pliocene erosion and fault displacement. A well-preserved margin at the northern end of a cluster of Pliocene outcrops is, however, found near the town of Taggia, some 20 km east of the Ventimiglia valley (Figure 1). The Taggia palaeo-valley is slightly smaller than the Ventimiglia one, but its sedimentary fill and evolution are very similar (Marini 2000) and therefore represents an excellent analogue. The northern termination of the Taggia Pliocene basin is imaged in Figure 7. Here, conglomerates are organized in top-sets, characterized by channelized fluvial distributary facies (Marini 2000). These facies are indicative of the position of the Pliocene rivers feeding the Taggia delta and, given their proximity to the marine delta, of the position of the Pliocene sea level. Towards the north, the top-sets overlap on an approximately 20° south-dipping surface that forms the boundary between the substratum and the Pliocene sediments. This south-dipping surface is interpreted as a palaeo-slope upon which the Pliocene delta prograded. Just north of the palaeo-margin, suites of morphological terraces are found along the hill slopes at an elevation equal to the level of the top-sets (near the locality of the Lampedusa Sanctuary, Figure 7).

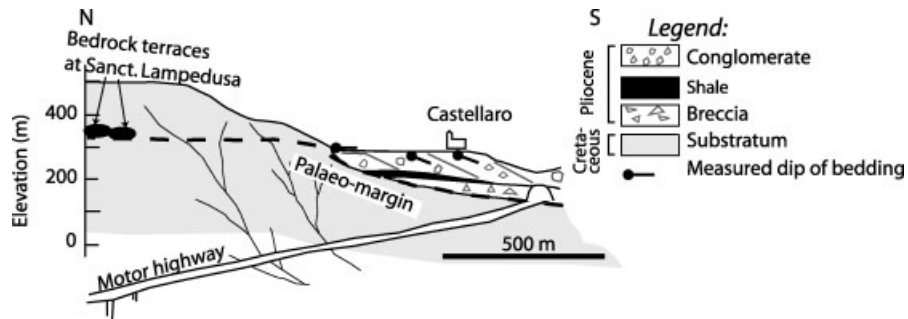


Figure 7. Geological section for the northern termination of the Taggia Pliocene basin near the town of Castellaro. Data on the Pliocene succession were redrawn from a N–S section in Marini (2000) together with our own field observations. Note the flat-lying surface to the north of Castellaro along which the bedrock terraces are observed. Pliocene sediments are onlapping on this surface, which is interpreted to represent the palaeo-margin along which the Pliocene delta prograded (Marini 2000). No vertical exaggeration has been applied to the section.

We interpret these bedrock terraces to reflect the palaeo-position of the Pliocene rivers feeding the delta and thus the Pliocene base level in the Taggia area. We conclude, therefore, that the Taggia marine gulf was bounded to the north by a flat plain entering the present-day valley for a length of 2 km. It was then eroded and disrupted during post-Pliocene uplift and erosion.

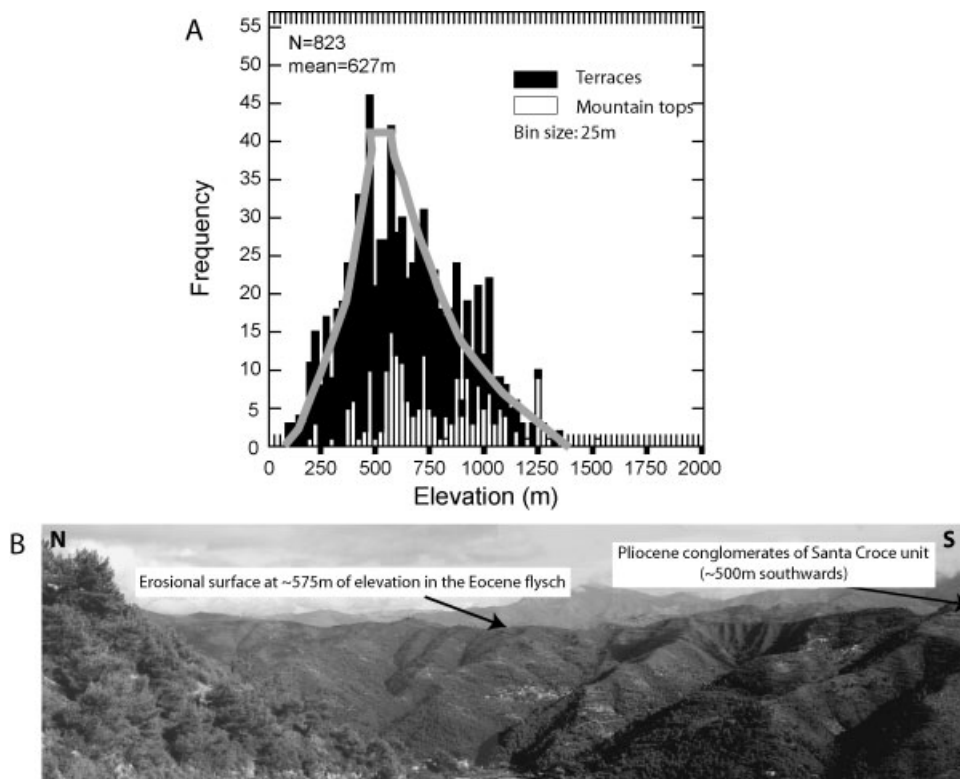


Figure 8. (A) Frequency diagram showing 823 measured terraces and mountain tops in the Ventimiglia hinterland (see text for discussion on how terraces were identified on map). First-order peak corresponds to 500–600 m elevation interval; smoothed line is fitted by eye. Several second-order peaks are also observed, for example at 450 and 550–600 m. (B) Example of erosional surface in the Eocene flysch, just north of the Santa Croce unit that is interpreted as reflecting the position of Pliocene sea level.

4.2. The hinterland of the Ventimiglia Messinian valley

Detailed sedimentological analysis of the upper conglomerates in the MB of the Ventimiglia palaeo-valley has documented a top- to fore-set transition (Figure 3, Breda 2002). The top-sets show channellized fluvial distributary facies (Breda 2002) typical of river-dominated deltas. At Present, the top- to fore-set transition is at roughly 420 m above sea level and lies stratigraphically immediately above a shale interval that has been biostratigraphically dated as late Early Pliocene (biozone MPI 4a, Breda 2002).

To search for morphological features indicative of the Pliocene shape of the Ventimiglia gulf hinterland (Marini 2000), we use a Digital Elevation Model (DEM, with a 70 m horizontal and vertical resolution). Surfaces of equal elevation were determined by analysing the topography in a 10 m (vertical) interval. To increase the resolution of our observations we have handpicked map-scale terraces and mountain tops from 1:25 000 topographic maps (25 m contour interval, Istituto Geografico Militare 1960). We define map-scale terraces as undulations of contours along mountain slopes that show clear, flat surfaces. Dimensions of the considered surfaces are in the order of 25–50 m. We assume that post-Pliocene erosion of these terraces has been minimal.

The most important result of our analysis is the presence of a first-order, overall peak between 500 and 600 m, which is present in the terraces and, less clearly, in the mountain tops (Figure 8A). The maximum of this peak roughly corresponds to the (present day) elevation of the upper Early Pliocene deltaic top-sets in the MB. Because the deltaic top-sets indicate the position of the base level during the late Early Pliocene, we interpret mapped morphological surfaces as remnants of the Pliocene valley close to base level. In map view, these features are located over a wide region and document the existence of a wider plain situated around the late Early Pliocene base level (Figure 8B). The slight offset between the maximum elevations at which the late Early Pliocene top-sets are found at present day (~420 m), and the first-order peak between 500 and 600 m, can be attributed to post-Pliocene fault displacement or might reflect a gentle slope in the (palaeo) plain.

To derive a 3D impression of the Mio-Pliocene topography, we have connected all points presently lying between 500 and 600 m above sea level and eliminated the morphology beneath. A smoothed reconstruction over this interval of the late Early Pliocene hinterland morphology is imaged in Figure 9. It shows that during deposition of

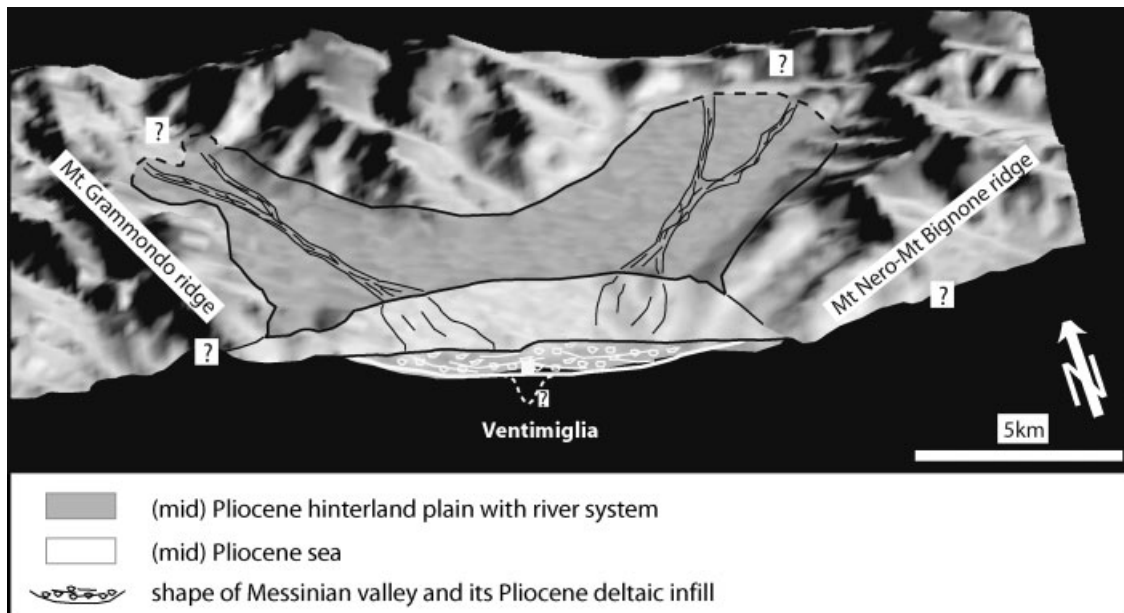


Figure 9. Reconstruction showing the Pliocene hinterland morphology. Pliocene morphology had a broad coastal plain bordering the Ventimiglia Messinian valley to the north. Two high ridges bound the Ventimiglia valley to the west and east.

the upper conglomerates, the Pliocene Ventimiglia gulf was bounded to the north by a broad, approximately 10–15 km (west–east) by 5 km (north–south) coastal plain immediately north of the present-day outcrops of the Pliocene sediments. Towards the north, the coastal plain diverges in two branches probably reflecting the major tributary systems of the Pliocene delta. The coastal plain was flanked to the east by the ridge of Mt. Grammondo and to the west by the ridge of Mt Bignone-Mt Nero, with heights up to 500–750 m. The morphology of the Ventimiglia region derived here for the Early Pliocene differs is much smoother and more subdued than the present-day morphology. Palynological data suggest subtropical to warm conditions during the Messinian and warm temperate to temperate conditions during the Early Pliocene for north-central Italy (Bertini 1994). The Messinian subtropical climate conditions probably contributed to the smooth and subdued relief that we have obtained for this period.

5. DISCUSSION

5.1. Messinian valley geometry

Based on detailed field mapping, we reconstructed the geometry of a Messinian palaeo-valley near Ventimiglia and derived a shape that is open and wide and has a relatively smooth basal unconformity between the Pliocene sediments and the underlying Eocene substratum. Geomorphological reconstruction shows that the Ventimiglia gulf was bordered to the north by a wide erosional plain.

Although the (Pliocene) sedimentological evolution of the Ventimiglia palaeo-valley has received wide attention, its actual shape and geometry have never been discussed in detail prior to our work. A few rudimentary outlines on its morphology have been presented by Clauzon *et al.* (1996), who inferred the shape and geometry mainly based on interpretations made in other Messinian valleys with V-shaped morphologies (e.g. the Var, Rhône and Nile Messinian valleys, Chumakov 1973; Clauzon 1973, 1978, 1982). Our reconstruction of the Ventimiglia palaeo-valley differs from those interpretations, but is, however, for the most part, well constrained. An open and gentle shape is present in the entire northern part and in most of the southern part. We have no direct information on the shape of the palaeo valley along the coastal, central 1–2 km of the section (Figure 4C, at the position of the town of Ventimiglia) in the MB and therefore cannot exclude the possibility of a small V-shaped incision in this part of the palaeo-valley. However, if such a morphology is present, it would be a smaller, secondary feature within the larger open valley (see for a comparison the Nile Messinian valley, Chumakov 1973).

In our interpretation, the elevation of the basal unconformity between the Pliocene sediments and the Eocene substratum of the Ventimiglia valley along the present-day coast corresponds roughly with present-day sea level. This interpretation is different from Clauzon *et al.* (1996), who argued for a minimum depth for the Ventimiglia valley floor of ~1000 m. Their estimate is based on Messinian unconformities identified on seismic sections in Chaumillon *et al.* (1994). However, these available seismic lines provide little constraint on the immediate offshore shape of the palaeo-valley as they start several kilometres off the coast and are located to the west and east of the axis of the Ventimiglia palaeo-valley. In addition, the closest seismic line parallel to the Ventimiglia coast (Finetti and Morelli 1973) runs several kilometres offshore. Consequently, the available seismic sections (in Finetti and Morelli 1973; Chaumillon *et al.* 1994) do not allow a detailed reconstruction of the offshore Ventimiglia segment, unlike, for example what has been demonstrated in the Rhône Messinian valley (Clauzon 1973, 1982).

We have estimated the depth of the Messinian valley at ~500 m (Figure 4). We consider this value as well constrained along sections through the central outcrops of the Pliocene sediments. Information on the depth of the palaeo-valley in the coastal section (Figure 4C) is limited; however, from localities where the basal contact is observed along the coast, we argue that the palaeo-valley reaches a depth of 500 m in the coastal part too.

5.2. Post-Messinian uplift and morphology of the Ventimiglia region

We explain the peculiar shape of the Ventimiglia Messinian valley compared to other Messinian valleys along the Provençal coast as a consequence of the late Neogene palaeo-geographic and tectonic setting in the Ventimiglia

Ligurian region. We infer that the open and wide shape of the Ventimiglia palaeo-valley results from a slope of the margin between the onshore Ligurian Alps and the offshore Ligurian basin that was gentler than what is observed today. At present day, the morphology of the offshore margin in this area is characterized by a $\sim 14^\circ$ dipping slope (Bigot-Cormier *et al.* 2004). Reconstructing the morphology of the margin to pre-Pliocene times suggests a $\sim 5^\circ$ dipping margin (Bigot-Cormier *et al.* 2004), which is much lower than at present.

We attribute the shallower slope of the Ventimiglia Ligurian margin at pre-Pliocene times to a combination of post-Pliocene uplift in the onshore area and subsidence in the offshore Ligurian basin. Onshore, the post-Pliocene uplift of 500 m of the Ventimiglia region took place during Late Miocene to Present exhumation occurring in the western Ligurian Alps (Foeken *et al.* 2003). The upward movement is possibly accommodated along a north-dipping thrust present at the foot of the Ligurian margin (NT in Figure 1, after Bigot-Cormier *et al.* 2004). Isostatic uplift of the margins in response to the desiccation of the Mediterranean basin during the Messinian salinity crisis (Norman and Chase 1986; DeCelles and Cavazza 1995) coincided with this. In the offshore Ligurian basin, seismic analysis of sections perpendicular to the Ligurian margin have shown that significant post-Pliocene subsidence has taken place in the Ventimiglia area (more than 1500 m, Réhault *et al.* 1985; Savoye and Piper 1991; Chaumillon *et al.* 1994; Bigot-Cormier *et al.* 2004). Although Bigot-Cormier *et al.* (2004) attributed the post-Pliocene displacement to uplift of the margin, part of the observed displacement could be related to post-Messinian subsidence of the Ligurian basin floor (Réhault *et al.* 1985; Savoye and Piper 1991).

6. CONCLUSIONS

Based on reconstructions of four cross-sections through Pliocene sediments, we constrain the morphology of the Ventimiglia Messinian valley (NW Italy). We derive a geometry for the Messinian valley that is several (~ 10) kilometres wide and has an open shape. We observe that the basal unconformity between the Pliocene sediments and the underlying Eocene substratum is characterized by a smooth surface, with dips towards the valley axis generally in the order of 5° . In the flat central part of the valley, the basal unconformity roughly coincides with present-day sea level. Our results show that the Ventimiglia Messinian valley is not as deep and narrow as previously thought. The different geometry between the Ventimiglia Messinian valley and other more V-shaped valleys documented along the Provençal margins can be explained as the result of the pre-Pliocene palaeo-tectonic setting of the Ligurian onshore and offshore tectonic setting. In pre-Pliocene times a less steep gradient existed along the Ventimiglia Ligurian margin, which resulted in less fluvial down-cutting along the margin. A reconstruction of the late Early Pliocene hinterland morphology shows that it was characterized by a broad coastal plain, immediate north of the present-day outcrops of the Pliocene sediments. This study underlines the importance of post-orogenic vertical movements in shaping the Messinian to recent geomorphology of the Mediterranean coast.

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