Int J Earth Sci (Geol Rundsch) (2006) 95: 665–683
DOI 10.1007/s00531-005-0056-4

ORIGINAL PAPER

Stefano Carruba · Raffaele Casnedi · Cesare R. Perotti
Milly Tornaghi · Giorgio Bolis

# Tectonic and sedimentary evolution of the Lower Pliocene Periadriatic foredeep in Central Italy

Received: 11 April 2005 / Accepted: 22 October 2005 / Published online: 23 December 2005


**Abstract** The Periadriatic foredeep (Italy) was generated by Neogene downbending of the Adria Plate under the Apennine Chain. The basin is filled with Plio-Pleistocene siliciclastic turbidites. Its substratum consists of the carbonate succession of the southwestern Adria Plate margin. The influence of the basin's morphology on sedimentation and subsequent tectonic evolution is investigated in the Abruzzo sector of the foredeep (Cellino Basin). The substratum is composed of Messinian evaporites that dip towards the Apennines (W). A NNW component along the depocentral axis is divided into four blocks with different depths. The substratum was also affected by a Messinian extensional fault system, not involving the overlying Pliocene sequence. This morphology controlled the distribution of the turbidites in the lower part of the Cellino Basin. The Plio-Pleistocene compressional deformation of the foredeep produced an inner complex structure (Internal Structure), involving the foredeep substratum and an outer imbricate thrust system (Coastal Structure), detached over the faulted Messinian evaporites. This thrust system is parallel to the extensional faults, suggesting a strong influence of the substratum morphology on the development of the compressional structures. The overall structural setting was validated with a balanced cross-section. Out-of-sequence thrusting and non-coeval deformation within each thrust sheet characterize the local tectonic history.

**Keywords** Periadriatic foredeep · Tectonic evolution · Balanced cross-section · Pliocene tectonics · Basin morphology

S. Carruba · R. Casnedi · C. R. Perotti (✉)
Dipartimento di Scienze della Terra, Università di Pavia,
via Ferrata 1, 27100 Pavia, Italy
E-mail: cperotti@unipv.it
Tel.: +39-382-985849
Fax: +39-382-985890

M. Tornaghi · G. Bolis
Edison S.p.A., Foro Bonaparte 31, 20121 Milano, Italy

## Introduction

The Periadriatic Foredeep is the largest Foreland Basin System (sensu DeCelles and Giles 1996) in Italy and borders eastward the Apennine Chain (Fig. 1a). It developed from the Oligocene to the Neogene during the westward underthrusting of the continental Adria Plate. Under thrusting gave rise to the Apennine Chain, an arc-shaped fold-and-thrust belt running throughout the Italian Peninsula (Kligfield 1979; Boccaletti et al. 1980; Bally et al. 1986; Ricci Lucchi 1986; Royden 1988; Patacca and Scandone 1989; Doglioni 1991).

The Periadriatic Foredeep is filled by Late Oligocene to Quaternary clastic sediments and is composed of several sedimentary sequences deposited at different times in different sectors of the basin (migrating basins, Ricci Lucchi 1986; Casnedi 1991).

The retreating foreland ramp hinge led to the foredeep depocentres to shift towards the east (foreland). This process occurred in earlier times in the northern sector of the Apennines, where the oldest deposits are found (Macigno Formation, Upper Oligocene), and migrated progressively towards the southern part of chain. At present, in the Taranto Gulf (southern Italy, Fig. 1a) subduction is still active.

Since foredeep basins form in front of an actively migrating thrust front, their sedimentary fill is progressively deformed and incorporated into the fold-and-thrust-belt; the older foredeep successions therefore crop out in the Apennine belt. The Periadriatic Foredeep sediments not yet included in the orogenic wedge are mostly Plio-Pleistocene in age, extending from the Po Plain in the north to the Taranto Gulf in the south (Fig. 1a) and fill asymmetric, westward thickening troughs that contain up to 8 km of Pliocene-Quaternary deposits (Bigi et al. 1983; Ricci Lucchi 1986; Ori et al. 1993).

The foredeep substratum consists of the increasingly younger carbonate and marly sediments of the west-

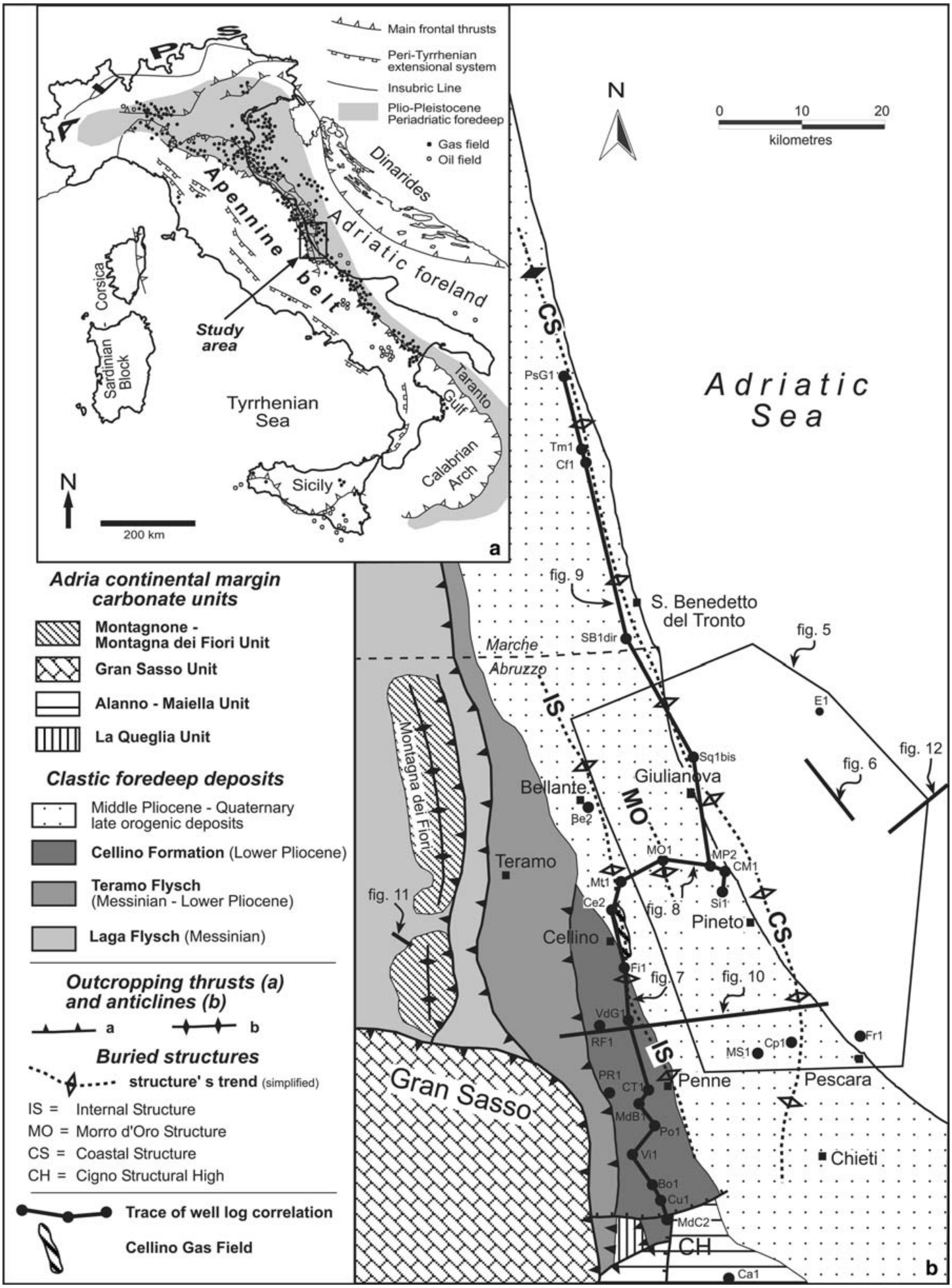


**Fig. 1** **a** Location of the study area in the Italian peninsula. The majority of the gas fields in Italy were found in the sand reservoirs of the more recent (Plio-Pleistocene) Periadriatic foredeep. **b** Simplified geologic map of the study area showing the foredeep deposits, the main structural units, the well log correlation profiles (Figs. 7, 8, 9) and the structural section of Fig. 10. Wells symbols: *Be2* Bellante 2, *Bo1* Bonanno 1, *Ca1* Caramanico 1, *Ce2* Cellino 2, *CM1* Campomare 1, *Cp1* Cappelle 1, *CT1* Colle Tavo 1, *Cu1* Cugnoli 1, *E1* Emilio 1, *Fi1* Fino 1, *Fr1* Fratello 1, *MdB1* Montebello di Bertona 1, *MdC2* Madonna della Croce 2, *MP2* Montepagano 2, *MO1* Morro d'Oro 1, *MS1* Montesilvano 1, *Mt1* Montarone 1, *Po1* Poggioragone 1, *PR1* Pietra Rossa 1, *RF1* Roccafinadamo 1, *Si1* Silvi 1, *SB1dir* San Benedetto 1 dir, *Sq1bis* Squalo 1bis, *VdG1* Villadegna 1, *Vi1* Vicoli 1

dipping Adria foreland ramp, on which progressive foreland-directed onlap of foredeep sediments occurred.

The Apennine Pliocene compressional tectonics led to the development of buried imbricate fold-and-thrust systems affecting the foredeep deposits and the foreland substratum. Deformation progressively becomes less intense towards the foreland (east). Simultaneous sedimentation accumulated clastic deposits over the frontal part of the orogenic wedge (wedge-top basins) and over the growing foredeep thrust sheets (piggy-back basins, Ori and Friend 1984), as well as in the still undeformed foredeep depozone. Therefore, there is an intrinsic continuity between the mountain chain and the foreland fold-and-thrust belt, which is actually the most peripheral extension of the Apennine belt.

In this paper we focus on the Pliocene structural and sedimentary evolution and the basin substratum morphology of the Abruzzo sector (central Italy) of the Periadriatic Foredeep, where the Cellino basin encloses an important Italian gas field, the Cellino field. Recently released and partly published subsurface data (about 750 km of seismic reflection profiles, as well as wireline electrical logs and lithologic data from 53 wells) have been interpreted and correlated. This interpretation was integrated with field analyses and validated by structural balancing to define the tectonic features of the foredeep basin involved in the latest stages of the Apennine orogeny.

## Geological setting

The study area is located in the transition zone between the northern Apennine chain and the Adriatic foreland in the Abruzzo region of Central Italy (Fig. 1b). In this sector, several stacked, folded and overthrust tectonic units formed during the deformation of the SW Adriatic continental margin and overlying foredeep deposits are present (Fig. 1b). The foredeep deposits, increasingly younger and structurally lower from west to east, are the following: the Laga Flysch (lower–middle Messinian), the Teramo Flysch (upper Messinian–Lower Pliocene), the Cellino Formation (Lower Pliocene) and the Middle Pliocene-Pleistocene late orogenic unconformable deposits. These turbiditic successions derive from the filling of foredeep basins progressively migrating eastwards. While the Laga and Teramo Flysch deposits are well exposed in the Gran Sasso foothills, the Cellino Formation is mostly buried and crops out in a narrow belt a few kilometers west of the Cellino gas field. As shown by the wells, the Cellino Formation extends under the younger (Middle Pliocene–lower Pleistocene)

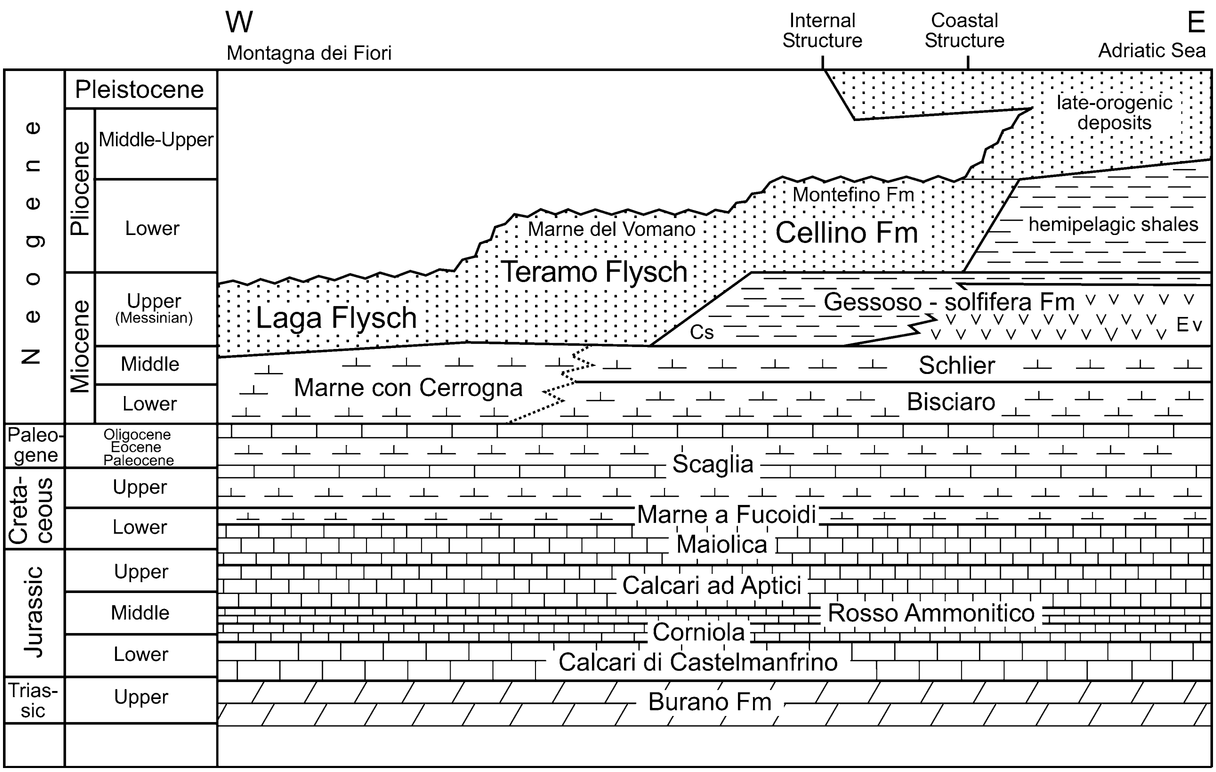


**Fig. 2** Schematic stratigraphic succession of the foreland basin system in Central Italy, showing the eastward-migrating foredeep basins from the Messinian Laga Flysch to the late-orogenic deposits. Turbiditic foredeep sediments were deposited onto the foreland ramp marls (Marne con Cerrogna) and shales (Colombacci shales, Cs) to the west and onto the Messinian evaporites (Ev) to the east. The Lower Pliocene succession in the Abruzzo region (Cellino Formation) is overlain by more recent (late orogenic) foredeep sediments. The foredeep substratum consists of the Meso-Cenozoic carbonate Umbria-Marche succession.

unconformable clastic deposits in the Abruzzo onshore. Seismic interpretation shows that the eastern border of the Cellino Basin in the early Pliocene was represented by the dipping Adria foreland ramp; the onlap of the Cellino turbidites are preserved in the current Adriatic offshore (Bolis et al. 2003; Carruba et al., in press).

The foredeep overlies the Adriatic crust, and its substratum was explored by the Villadegna 1 well

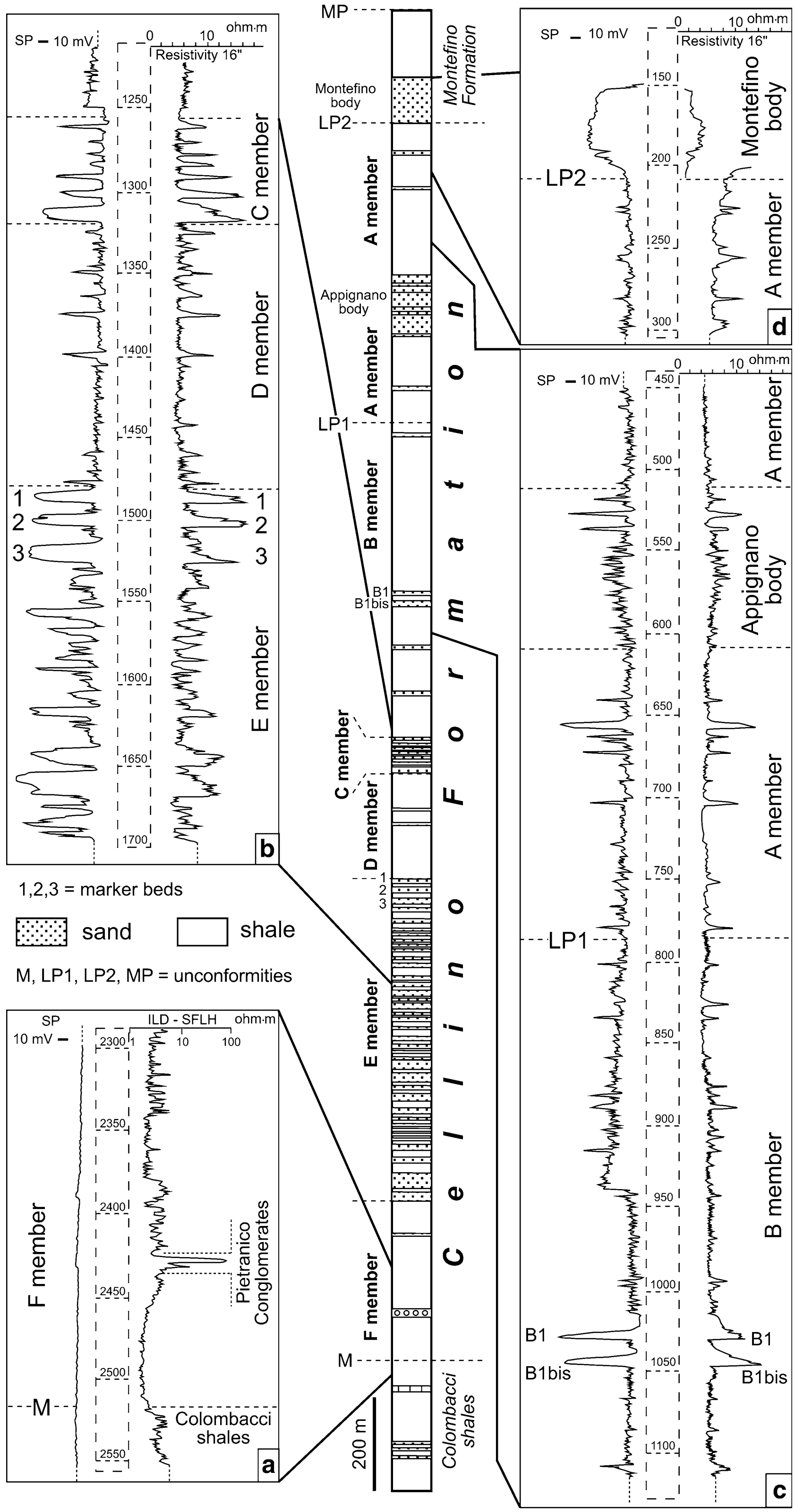


**Fig. 3** Stratigraphic column of the Lower Pliocene succession in the Abruzzo sector of the Periadriatic foredeep. Each member of the Cellino Formation has a characteristic log facies, which allows their correlation in the subsurface. The most distinctive patterns are shown by the Pietranico conglomerates (strong resistivity peak; **a**), the E member (strong deflections in the electrical curves due to thick sandstones with interbedded shales; **b**), the C member (“Christmas tree” pattern of seven sand units; **c**), and the sand-rich Appignano Body interbedded in the A member (numerous and closely spaced deflections; **d**). The conglomerates, the three uppermost sand layers (1, 2, 3) of the E member and the C member are also the best marker levels in the area, showing the greatest lateral continuity. Local marker beds are turbiditic megabeds in the B (B1 and B1bis) and A members

(Fig. 1b), as deep as 6,907 m, crosscutting the Jurassic-Tertiary Umbria-Marche sedimentary succession and reaching the Upper Triassic Burano Formation. Figure 2 shows the stratigraphic succession of the study area.

## Lower Pliocene stratigraphy

The Lower Pliocene Cellino Formation (Casnedi 1983) consists of a siliciclastic turbidite succession, about 2,500 m thick, that can be divided into six members, named A to F from top to bottom (Fig. 3). Field observations (Crescenti et al. 1980; Casnedi 1983; Vezzani et al. 1993, 1998) reveal a correlatable succession that crops out few kilometers west of the Villadegna 1 and Fino 1 wells. Each member of the Formation has a characteristic log pattern (Fig. 3). The integration of the electrical log facies with surface litho- and biofacies analysis (Fig. 4) characterizes the Cellino turbidite system.

The upper Messinian substratum (Argille a Colombacci Formation) consists of shales with interbedded limestones and cemented sandstones. Hemipelagic shales (90 m) with an interbedded conglomerate bed, well exposed in the southern part of the basin (Pietranico Conglomerates), represent the base of the Cellino Formation (F member, Fig. 3a). The conglomerates are found in most wells, showing a wide extent in Abruzzo and probably extending northward for more than 100 km (Monte Urano well, Marche region). The upper part of the F member (130 m) contains several thin sandstone layers embedded in hemipelagic shales. The sandstones gradually increase and thicken upwards to the sand-rich E member (750 m total thickness) composed of prevailing thick sandstones with interbedded shales (Fig. 3b). Facies analysis (Carruba et al. 2004) shows that most of these very thick (up to 10 m) sandy beds are characterized by a decrease in grain size and the presence, above a massive basal division, of abundant water-escape features and climbing ripples, followed by thick (up to 10 m), massive mudstone caps. Bioturbation is absent. Basal flute structures indicate flows of northern provenance. The sedimentological features of these megabeds suggest that they may derive from large-volume turbidity currents trapped by the confinement of the basin. The three uppermost sand beds of the E member (1, 2, 3 in Fig. 3b) represent the best marker beds in the area, showing a distinctive log facies and great lateral continuity.

In the overlying D member (160 m), thin minor sands in a shaly succession (thin-bedded turbidites) are present. The seven sand beds of the C member (70 m, Fig. 3b) are good markers in the basin, displaying a very

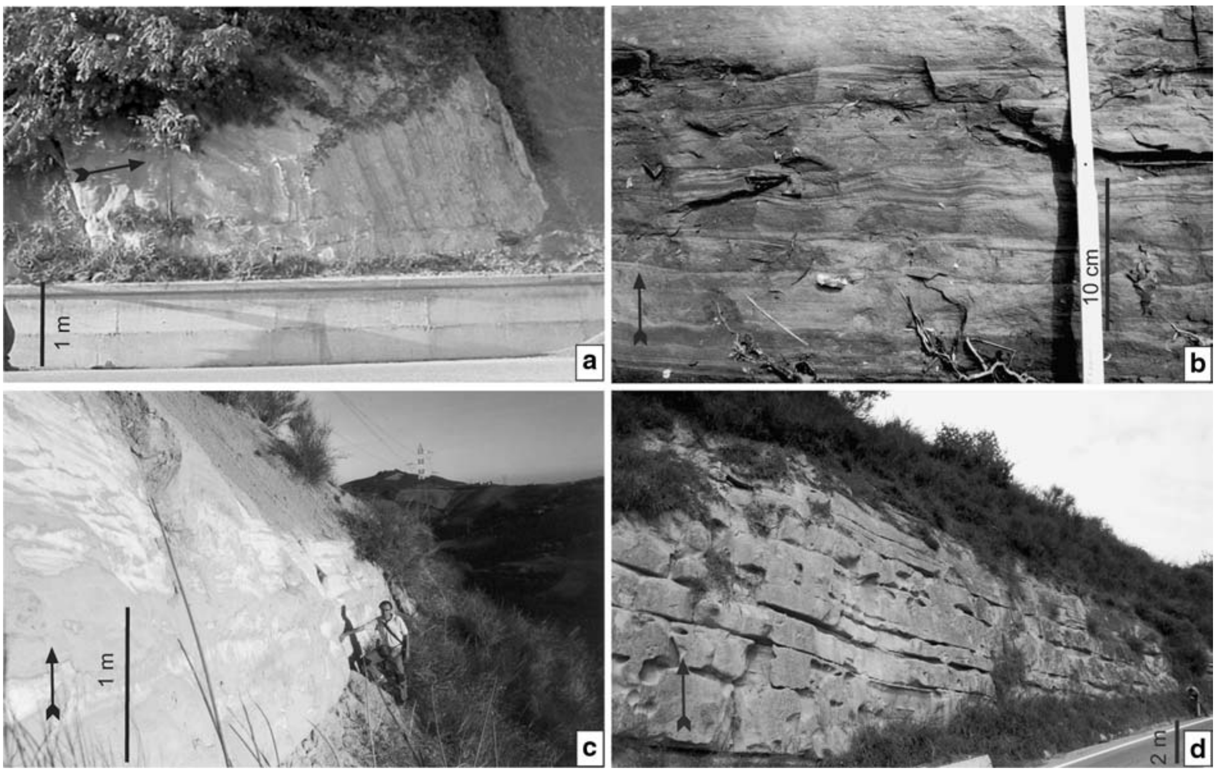


**Fig. 4** **a** Thick turbidite bed of the E member (Bisenti-Montefino road) consisting of a sand level (about 6 m) with a massive basal division and climbing ripples in the upper part, followed by a thick (about 3 m) mud cap. **b** Climbing ripples in the fine-grained portion of a turbidite bed in the E member (Barricello river near Roccafinadamo). **c** Turbiditic megabed interbedded in the A member (S. Giorgio village near Villadegna 1 well). **d** Amalgamated sandstone beds of channel-lobe transition environment of the Montefino Body (road to Montefino). M, LP1, LP2: sequence boundaries

distinctive log pattern, with a wide lateral correlation in the subsurface. The beds record an upward reduction in grain size and an associated increase of the shale fraction (“Christmas tree” pattern). The C member represents an overall thinning- and fining upward megasequence.

The B and A members (Fig. 3c) are characterized mainly by shales, with scattered thin sand beds. However, some turbiditic megabeds are found in the B (B1 and B1bis in Fig. 3c) and A members (Fig. 4). They constitute local marker beds correlatable for several kilometers but do not have a basin-wide extent, owing to the coeval migration of the depocenter. The sand-rich Appignano Body (60–100 m) intercalated in the A member (Fig. 3b) is a low-efficiency, southward prograding confined turbiditic fan.

A reduction in the shale fraction and the development of a thick (up to 200 m) sand body occurs at the top of the A member, called the Montefino Body (Fig. 3d), overlain by 100–200 m of shales (Montefino Formation). The boundary with the underlying Cellino Formation is transitional and marked by the appearance of thin-bedded turbidites arranged in a coarsening- and thickening-upward sequence (10 m). The lithofacies of the Montefino Body show erosive-channelled sandstone beds, mostly amalgamated, deposited in a channel-lobe transition environment. The Montefino Body evolves upward into shales of a basin-plain setting.

The Lower Pliocene of the Abruzzo foredeep is divided (Ori et al. 1993) into three main depositional sequences, limited by the M (top Messinian), LP1, LP2 (intra Lower Pliocene) and MP (base Middle Pliocene) unconformities, respectively. The LP1 unconformity marks the onset of the deformation phases, which affected this sector of the Periadriatic foredeep until the early Quaternary.

### Structure

The most significant tectonic structures affecting this part of the foredeep are from west to east (Fig. 1): the Montagna dei Fiori, Internal, Morro d’Oro and Coastal Structures. In the hanging wall of the Montagna dei Fiori Structure the carbonate substratum crops out, while the Internal, Morro d’Oro and Coastal Structures are buried and affect the Cellino Formation and younger deposits. All these structures have a NNW-SSE trend and comprise foreland-vergent thrust systems and related anticlines with a complex geometry and tectonic evolution (Bally et al. 1986; Calamita et al. 1991; Bigi et al. 1995; Artoni and Casero 1997; Bolis et al. 2003). Thrust surfaces developed during the Pliocene and separate the Laga, Teramo and Cellino formations. The carbonate Gran Sasso Unit was emplaced out-of-sequence onto the Laga and Teramo Flysch in the Middle Pliocene (Ghisetti and Vezzani 1991). Weaker and simpler compressional structures (foreland folds) are present in the offshore as well (Bally et al. 1986; Ori et al. 1986).

The Internal Structure is located in the subsurface along the Bellante-Cellino-Penne trend in a NNW-SSE direction (Fig. 1b). It consists of a complex system of stacked thrust sheets whose detailed geometry changes from N to S. Seismic images and deep wells (Villadegna 1, Caramanico 1) reveal that this structure involves the entire carbonate-clastic succession (Bally et al. 1986). The Cellino Anticline, holding the Cellino gas field, is linked to this structure.

The Morro d’Oro Structure is an intermediate fault-related anticline of limited continuity. This structure developed early in the Pliocene and was subsequently inactive and involved in the piggy-back basin derived from the growth of the Coastal Structure.

The Coastal Structure is an imbricate thrust system with a NNW-SSE trend, extending along the present Adriatic coastline from central Marche to Pescara (Fig. 1b). It borders a Plio-Pleistocene basin to the west (Notaresco Basin), carried piggyback by the imbricate system. The Coastal Structure consists of a set of east-verging thrust-related anticlines, detached over the Messinian substratum. The number and the geometry of the thrust sheets are strongly variable along strike: different structural arrangements are visible in seismic profiles separated only a few kilometers apart. The Coastal Structure started to grow in the Middle Pliocene, developing into a complex sequence of deformation, which includes out-of-sequence thrusting, reactivation and folding (Bolis et al. 2003). The out-of-sequence kinematics of thrusting in the Coastal Structure may have been induced by the considerable syntectonic sedimentation at the front of the growing structure.

The Messinian substratum of the foredeep, represented by the upper Messinian Argille a Colombacci to the west and by the evaporites (gypsum) of the Gessoso-Solfifera Formation in the eastern area (Fig. 2), is affected by a conjugate system of normal faults that form a set of horst and grabens with a N170°–175° trend. The close relationship between the Coastal Structure and the underlying normal fault system and the role of the substratum steps in triggering and localizing the overlying compressional deformation were pointed out and modeled using sandbox analogues by Bolis et al. (2003).

## The Cellino Basin

The Messinian sediments (Argille a Colombacci to the west and the evaporites of the Gessoso-Solfifera Formation in the east) represent the foredeep substratum of the study area. Since the substratum has been affected only by subsidence and possible tilting, without deformations, that significantly changed the basic features of its morphology, the Messinian structure is similar to the structure and paleo-morphology of the Pliocene, when the Cellino Formation progressively filled the foredeep.

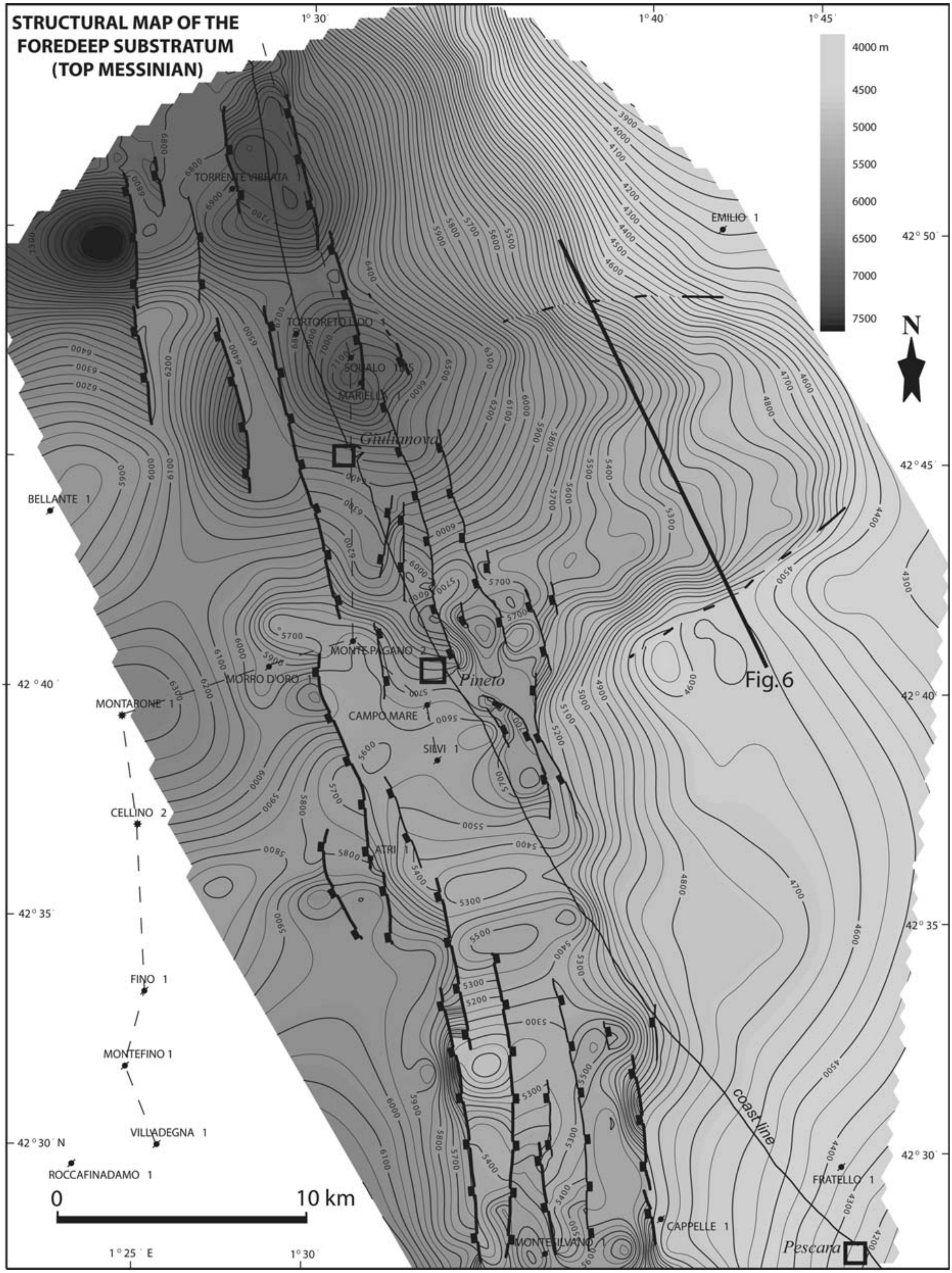


**Fig. 5** Structural map (contour depth in meters) of the foredeep substratum in the external Abruzzo foredeep (top Gessoso-Solfifera Formation, near top Messinian). The substratum is affected by a system of conjugate normal faults running below and parallel to the Coastal Structure. On the whole, the substratum dips under the Apennine chain (westward). It also rises towards the south and is segmented into areas of different gradient and depth separated by transversal lineaments (offshore). *Dashed lines* are the traces of the well-log correlation transects (Figs. 7, 8, 9)

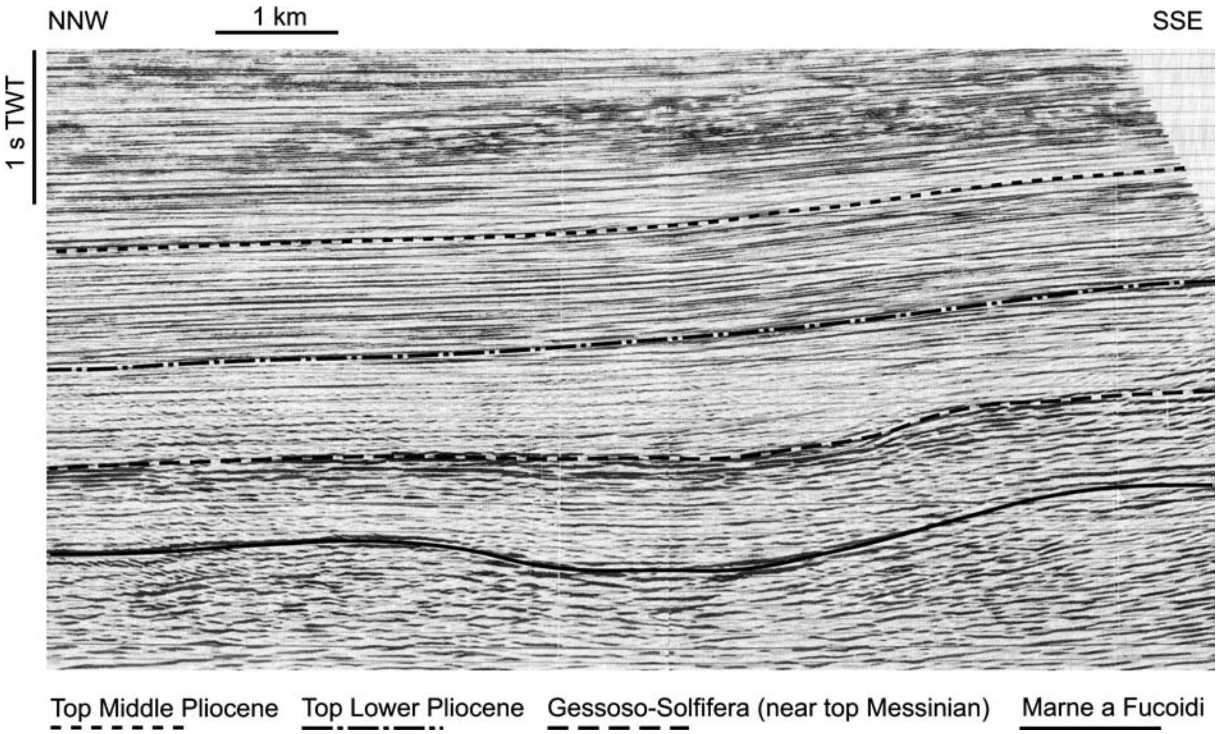


**Fig. 6** Seismic image of the transverse structures affecting the foredeep substratum in the offshore Abruzzo. The pre-Messinian carbonate succession is deformed by WSW–ENE trending folds. Location in Figs. 1 and 5

On seismic images, the Messinian horizon is characterized by two distinctively high-amplitude reflectors, marking the M unconformity. The Messinian reflectors can be traced westward from the offshore (Emilio 1 and Fratello 1 wells) through the Coastal Structure in a number of seismic profiles. By correlating this horizon we created a time structural map of the foredeep substratum morphology in this region. The map was subsequently converted to a depth ($V_0$-$k$ method, Marsden 1992) using a velocity at the surface ($V_0$) of 1,900 m/s with a depth increment of $k=0.45$, deduced from the offshore and onshore (Coastal Structure) well data.

The foredeep substratum (Fig. 5) has a depth between 4,000 and 7,000 m and is affected by a conjugate system of normal faults forming a set of horst and grabens with a N170°–175° trend. The throw of each fault is around some hundreds of meters, up to a maximum of approx. 1,500 m. The normal faults are arranged in a typical en èchelon pattern. Within the transfer zones, the deformation is probably accommodated by faulting and fracturing below seismic resolution. The foredeep substratum progressively rises along a N-S direction from its maximum depth (7,600 m) in the northern sector (Giulianova) to the south (Pescara), where it is about approx. 4,200 m deep. This longitudinal plunge is superimposed on the general dip towards the Apennine Chain towards W–WSW. In the offshore, the substratum is clearly segmented into areas of different inclination and depth, with a dip of about 3° in the southern sector and 12° in the northern one. These blocks are separated by transverse structures (Figs. 5 and 6) with an approximate ENE–WSW trend (dashed lines in Fig. 5), acting during the Messinian-(basal Pliocene?).

The extensional tectonics can be ascribed to the flexural extension (Bradley and Kidd 1991) of the upper part of the downbending Adriatic lithosphere under the Apennines during the Messinian (Scisciani et al. 2001; Bolis et al. 2003); the transverse structures could be connected to a differential downbending of adjacent sectors of the Adria Plate, possibly caused by lateral geometric and rheological variations of the plate.

The complex substratum geometry played an important role in the deposition and distribution of the sediments. The extensional and transversal fault system formed local tectonically controlled depocenters and acted as the confinement of the basin for trapping the large-volume turbidity currents of the lower part of the Cellino Formation. To inspect the sedimentary features of the Lower Pliocene foredeep deposits, we correlated well logs along three transects through the Cellino Basin. The location of these transects (Fig. 1b) reflects the irregular distribution of the wells over the area, targeting structural highs of the Internal, Morro d'Oro and Coastal structures.

The southern transect (Cellino Transect, Fig. 7) extends along the Internal Structure (basin depocenter) from the Cellino field to the Cigno structural high. Bed-to-bed correlation of the sand bodies of the E and C members is excellent (see also Casnedi et al. 1978; Carruba et al. 2004), suggesting continuity of sand bodies in a down-current direction for more than 40 km. Moreover, since most of the wells in this transect reached the foredeep substratum, we can gain a picture of the basin morphology along the depocenter axis of the Cellino Basin. From the Poggioragone 1 well southward, the substratum begins to rise, causing the progressive onlap of the F member and lowermost sand bodies of the E member against the Cigno High, representing the southern basin margin. Therefore, the base of the Cellino Formation can be considered as a correlative conformity in the basin center, becoming an unconformity (M) at the basin margins. The three uppermost sand layers of the E member (1, 2, 3 in Fig. 7) overlap the Cigno High, outcropping near the Madonna della Croce 1 well.

The Colle Tavo 1 tested a local high where the basal conglomerates were not deposited and the F member shales overlie a partially eroded substratum (the uppermost Miocene succession is lacking). This substratum feature, currently involved in the Internal Structure, was interpreted to be a structural high bounded by normal faults (section 11 of Vezzani et al. 1993).

The well log correlation shows the large extension of the E, D and C members. The tabular infill and basin-wide geometry of the turbidite megabeds match with their peculiar sedimentological features, indicating large-volume, confined turbidites. In the earlier Lower Pliocene, the turbidity currents flowed onto a substratum dissected by the earlier (Messinian) extensional events. Intrabasinal tectonic activity was practically absent except for the southernmost basin margin (uplift of the Cigno High; Casnedi and Mosna 1992). In contrast, the sedimentary bodies within the overlying B and A members are characterized by facies and thickness variations and a smaller longitudinal extent compared to the underlying units, reflecting syn-sedimentary movements.

A marked unconformity (LP1) is revealed by the wells at the base of the A member, some tens of meters below the Appignano Body. This unconformity can be

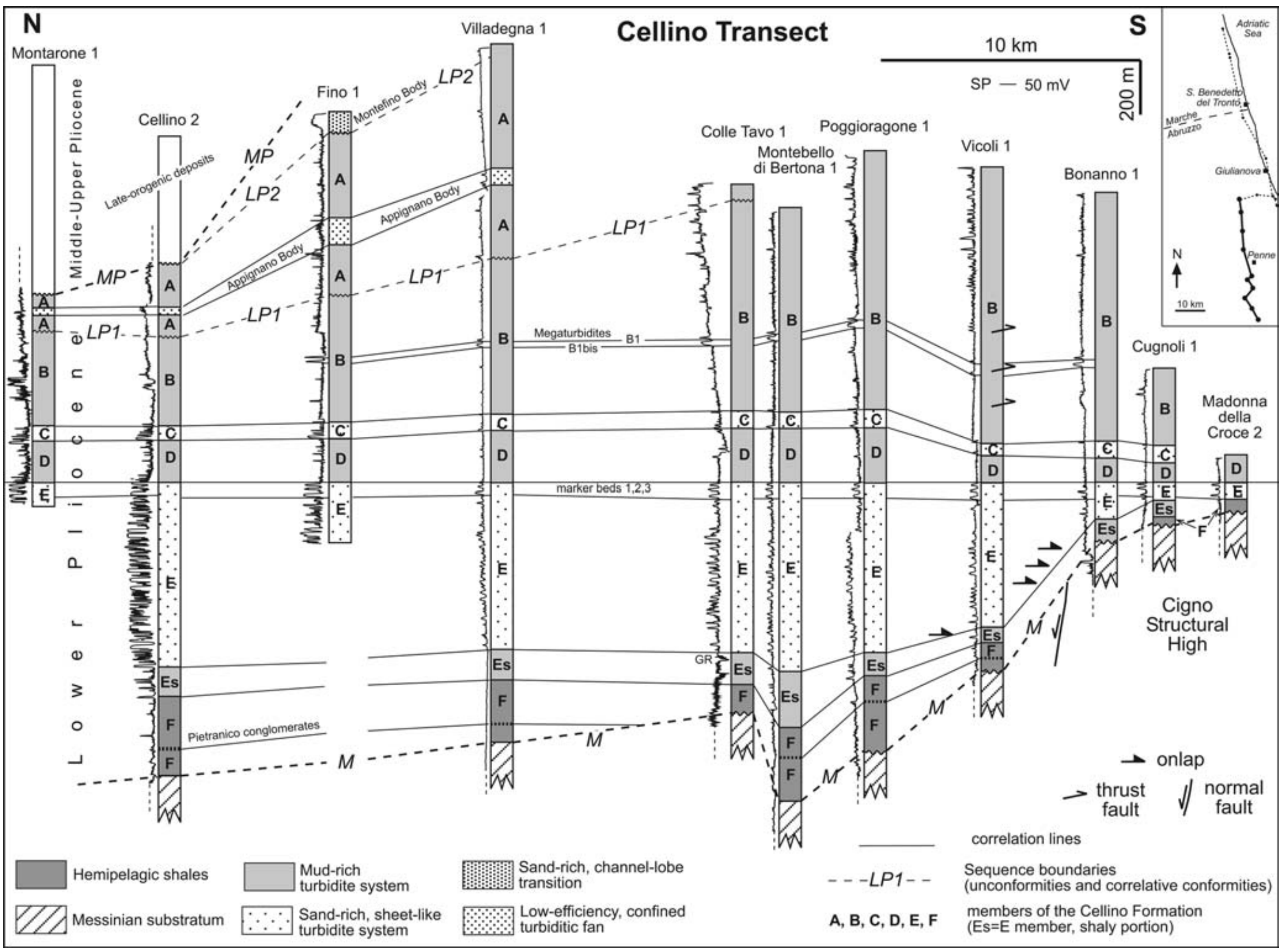


**Fig. 7** Well-log correlation of the Cellino Formation along the Internal Structure from the southern margin of the basin (Cigno High below the Madonna della Croce 2 well) to the Cellino gas field (Cellino 2 and Montarone 1 wells). The Colle Tavo 1 well drilled a local structural high (Pietranico conglomerates missing and Messinian substratum partially eroded)

correlated with an unconformity visible in the seismic profiles (Carruba et al. 2004).

The Appignano and Montefino bodies have a limited lateral and longitudinal extent, and are present only along the parts of the Internal Structure.

The Morro d'Oro transect (Fig. 8) links the longitudinal Cellino and Coastal transects crossing the Morro d'Oro Structure, allowing a correlation of the upper beds of the E member and of the seven beds of the C member between the Internal and Coastal Structure.

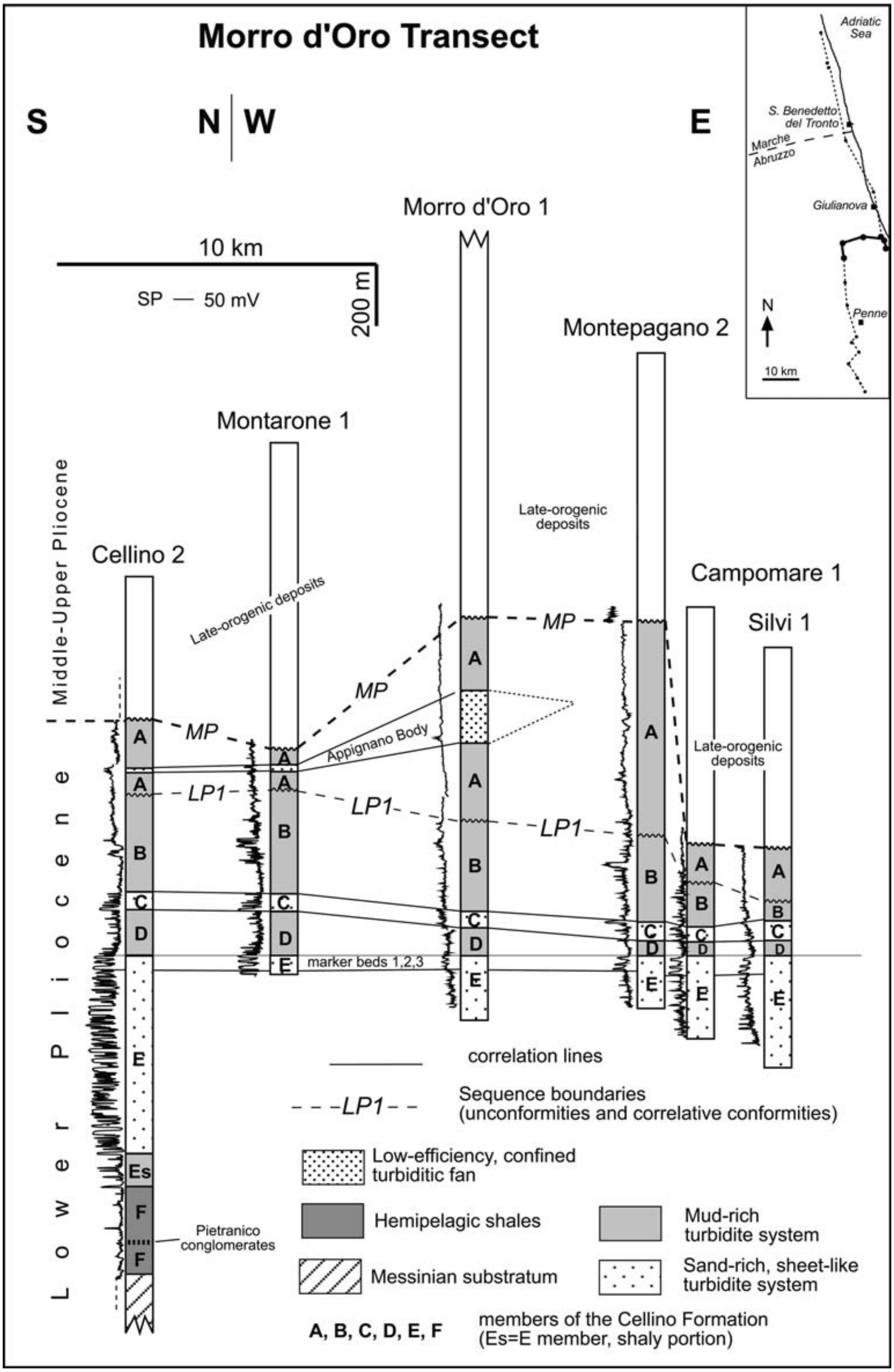


**Fig. 8** Well-log correlation of the Cellino Formation across the Morro d'Oro Structure, linking the Cellino and the Coastal transects

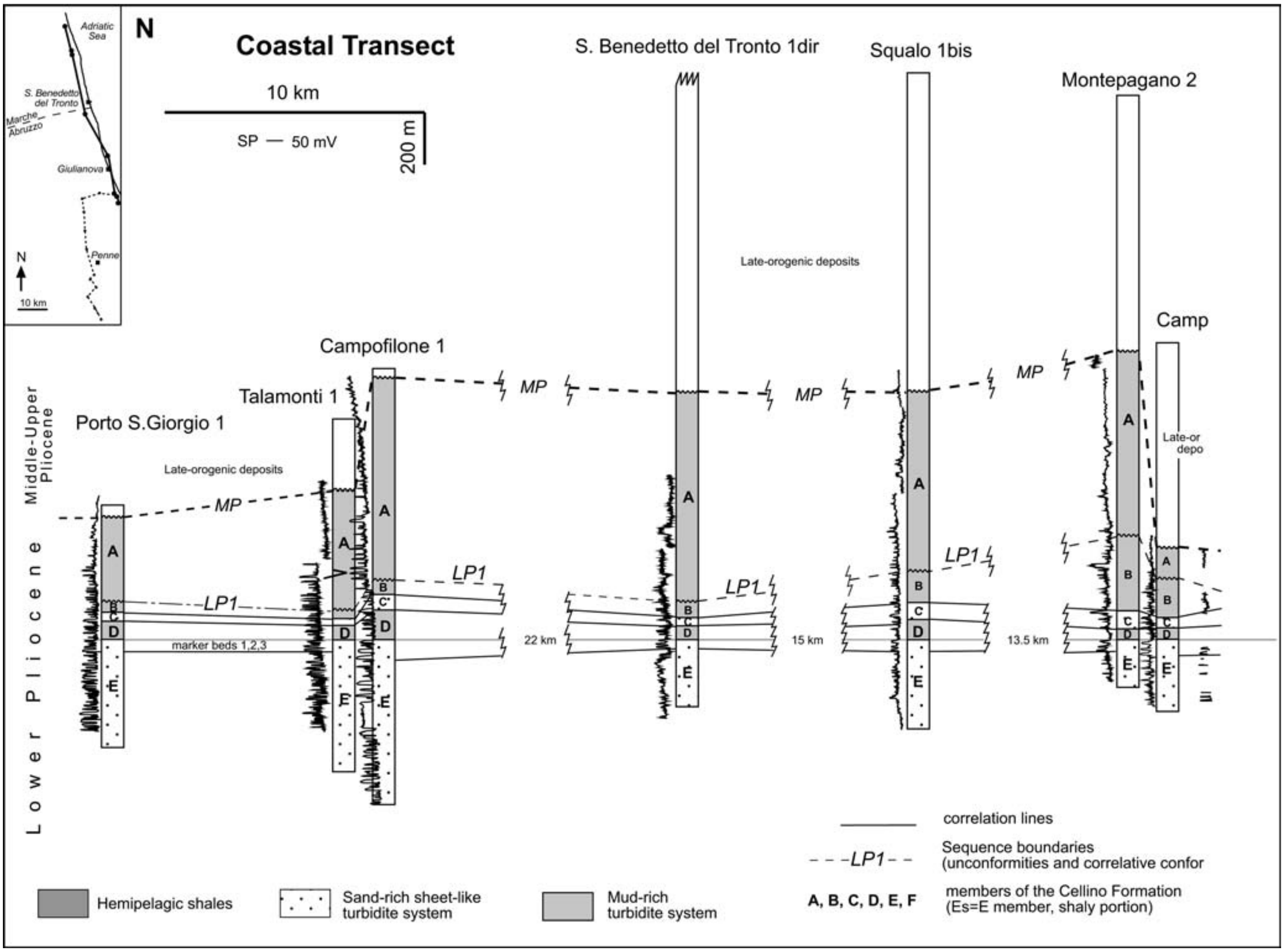


**Fig. 9** Well-log correlation of the Cellino Formation along the Coastal Structure up to the central Marche (Porto S. Giorgio 1 well)

The well log correlation along the northern part of the Coastal Structure (Fig. 9) confirms the remarkable longitudinal extension of the Cellino Basin. The sand bodies of the E and C members are correlatable from the southern margin of the basin in Abruzzo (Cigno High, near the Maiella mountain) to the central Marche (Porto S. Giorgio 1: Fig. 9), outcropping northward near Ancona (Ori et al. 1993). The Cellino Basin therefore extended longitudinally for at least 150 km.

## Balanced structural cross-section

By integrating all the interpreted data we were able to draw a restorable and balanced geologic section across the southern Cellino Basin, illustrating the Apennine-foredeep belt structure and evolution. The section (Fig. 10) is 30 km long, stretching W–E from the Teramo Flysch outcrops to the coastline a few kilometers north of Pescara.

The wells on the section provide very important but spatially limited constraints. In the offshore, the Fratello 1 well (Figs. 1b and 10) allowed the Gessoso-Solfifera Formation reflections to be identified. Wells on the Coastal Structure provided the calibration of the Lower and Middle Pliocene tops. On the Internal Structure, the Roccafinadamo 1 revealed an upper Miocene clastic succession (which we refer to as Teramo Flysch) below the Argille a Colombacci Formation, whereas the Villadegna 1 well demonstrates that the Argille a Colombacci Formation directly overlying the carbonate units (Fig. 10).

Besides the information from wells, the balanced cross-section takes into account the regional structural style inferred from field observations and other evidence from nearby seismic sections. It should be noted that the identification of the pre-Pliocene deep horizons is available only in the southern part of the basin (Villadegna 1 and, partly, some other wells out of the plane of this section). The Villadegna 1 well provides velocity information for the entire stratigraphic succession down to the Upper Triassic evaporites. Other interval velocity values constrain only to the uppermost clastic Pliocene above the Internal and Coastal structures. This limited seismic velocity information could represent an inadequate source for depth conversion in such a complex tectonic setting: the geological cross-section of Fig. 10 is therefore likely to be a simplified picture of the subsurface, representing the possible overall structural setting of this sector of the foredeep.

The seismic image of the Internal Structure is generally qualitatively inferior to that of the Coastal Structure. Only a few seismic profiles across the Internal Structure have an acceptable signal-to-noise ratio. The combination of seismic data with some deep wells (Villadegna 1, T.D. 6,907; Caramanico 1, T.D. 5,075 m) drilled in the southern area provided important constraints, revealing that the Triassic-Miocene carbonates are involved in the deformation. In particular, the Villadegna 1 well indicates that the Liassic succession (Calcari di Castelmanfrino) is tectonically repeated.

According to our interpretation, the Internal Structure is formed by a major fault-related anticline (Villadegna Anticline) involving the entire carbonate-clastic succession; it is probably detached in the Triassic evaporites (out of the section of Fig. 10, to the west) and after having climbed up a ramp in the carbonate sequence is thrust over an upper flat in the undeformed Messinian evaporites (Villadegna Thrust). This flat becomes the basal detachment of the Coastal Structure eastward. An upper tectonic surface (Cellino Thrust) cuts the Villadegna Anticline and forms the basal detachment for two smaller anticlines chiefly involving the clastic Pliocene. Therefore, the Internal Structure is a breached fault-bend fold: the Cellino Thrust divides it into the Villadegna Unit and the overlying Cellino Unit.

In the Villadegna Unit, no extensional structures are visible because of the poor seismic image. It probably is a normal fault system involving the carbonate substratum of the Teramo Flysch Basin, interpretable in the overlying Cellino Unit, west of the Roccafinadamo 1 well (Fig. 10).

On the basis of the available data, we cannot completely exclude backthrusting to occur in the Villadegna Structure between the carbonates and the clastic Pliocene (Bally et al. 1986). However, this structure, if present, seems to be of minor importance compared to the forward displacement due to the Cellino Thrust.

A tectonic surface (Teramo Thrust) caused the overthrusting of the Teramo Flysch onto the Cellino Unit. Associated splays revealed by surface geological mapping partly involve the Cellino Formation, which is steeply dipping and is strongly deformed in its western part.

It is possible to detect the termination of the Teramo Flysch on the seismic image (Fig. 10), which tapers eastward along a basal unconformity (compare Paltrinieri et al. 1982). This unconformity between the Teramo Flysch and the foreland ramp (Schlier) reflectors visible to the west of the Cellino Anticline is interpreted as an

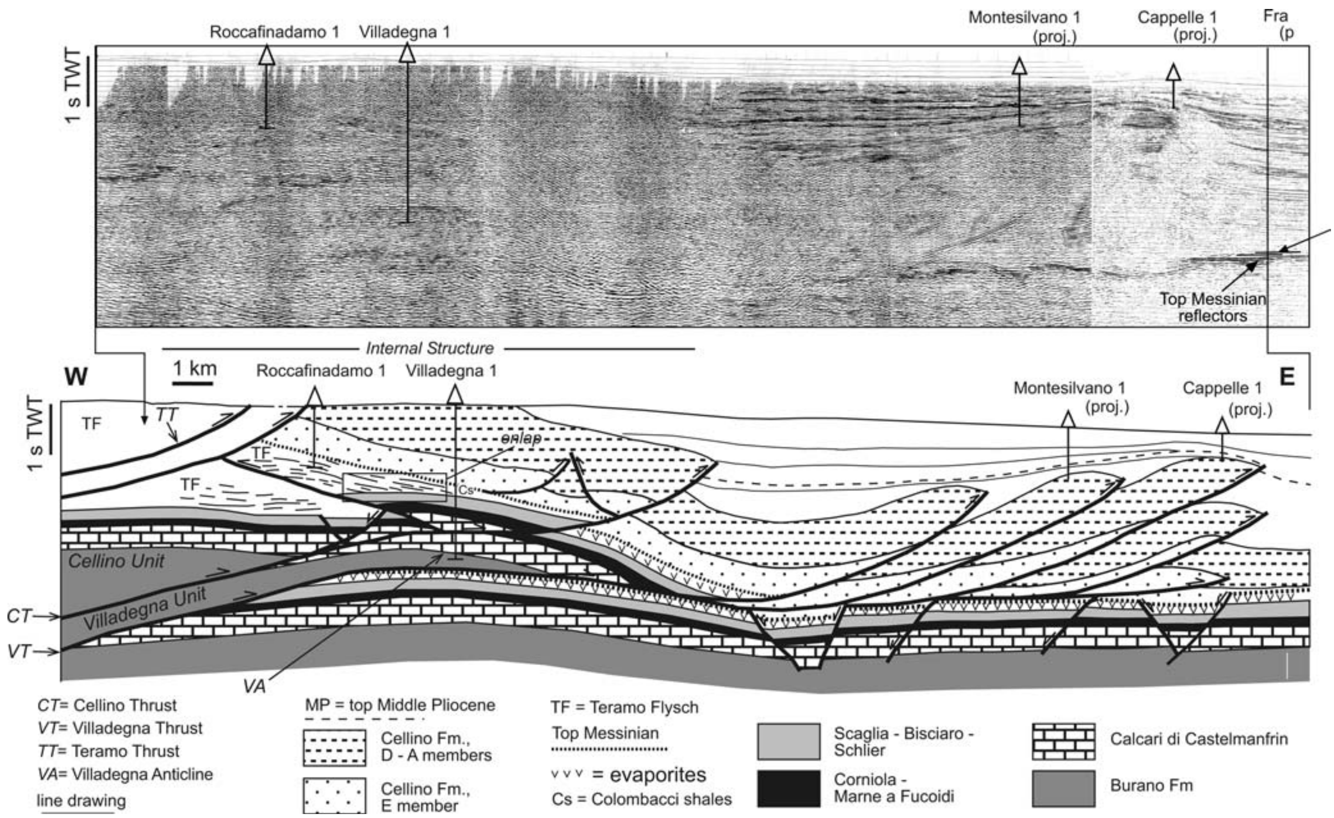


**Fig. 10** Seismic section in time (**a**) and geologic interpretation (**b**) across the southern Cellino Basin (location in Fig. 1)

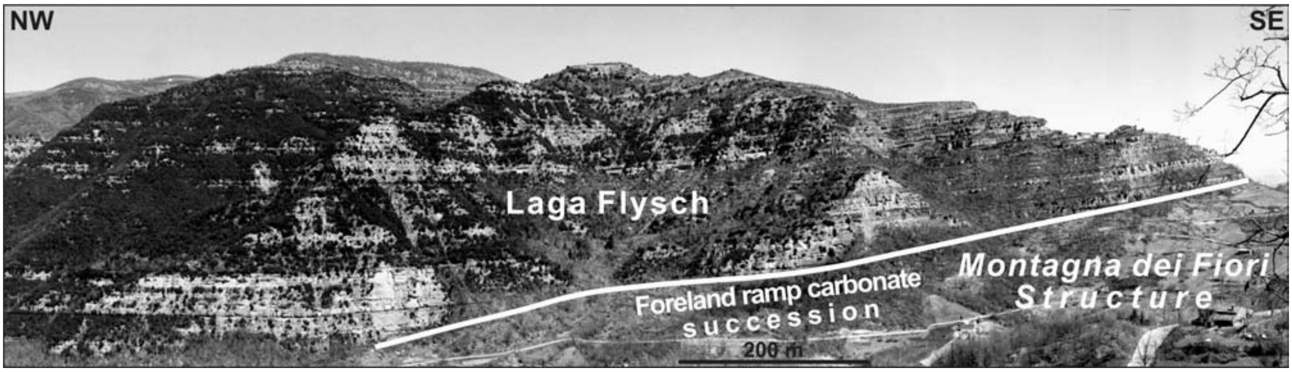


**Fig. 11** Onlap of the Laga Flysch turbidites against the Montagna dei Fiori Structure (location in Fig. 1). The onlap angle is about 10°

onlap surface of the Teramo Flysch onto the foreland deposits.

The tapering of the Teramo Flysch is also confirmed by the wells' stratigraphy: there is no Teramo Flysch on the crest of the Internal Structure (Villadegna 1, Colle Tavo 1 wells), while it is found to the west (Roccafinadamo 1, Pietra Rossa 1). The high angle (about 12°) of the unconformity could indicate that the clastic Teramo Flysch pinched out against a developing (or already developed) foreland structure.

Support for this interpretation also comes from other foredeep basins in the area. The undeformed, horizontal turbidite beds of the Laga Flysch spectacularly onlap against the deformed carbonate substratum of the Montagna dei Fiori Structure, with an angle of about 10°(Fig. 11). In the Adriatic Sea foreland (Fig. 12), the uppermost deposits of early Pliocene age (A member) terminate against an undeformed foreland ramp with an onlap angle of 1°–2°. By contrast, the Middle to Upper Pliocene foredeep sediments shows progressive onlaps (up to 8°) against embryonic compressional structures (Carruba et al., in press). This perfectly preserved basin configuration can represent the analogue of the eastern Teramo Flysch margin in the upper Messinian, as well as illustrating the eastern boundary of the more recent foredeep basins.

It can be inferred from the section of Fig. 10 that the Coastal Structure is formed by several east-vergent thrust-related anticlines, all involving the sandy E member of the Cellino Formation.

After depth conversion (Fig. 13a), the section was restored in two steps to account for the foredeep substratum tilting over time. The first step (Fig. 13b) illustrates the foredeep structure at the end of deposition of the E member. At this stage, the embryonic Villadegna Anticline formed the external border of the Teramo Flysch Basin to the west. The tabular sand bodies of the lower Cellino Basin deposited over a foredeep basin filled with Teramo Flysch to the west and a carbonate sequence cut by normal faults to the east. The turbidites

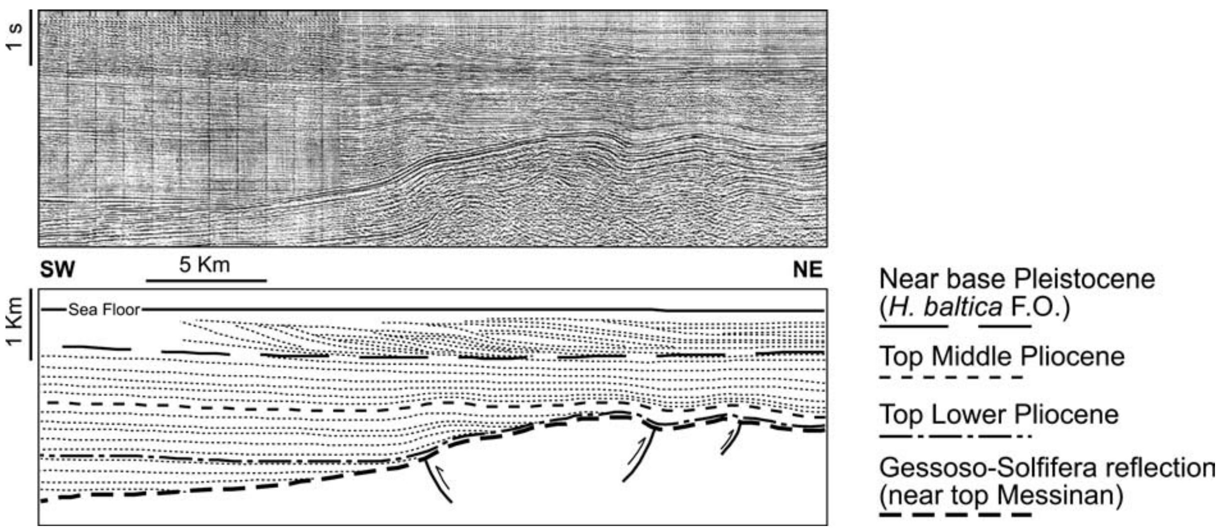


**Fig. 12** Seismic interpretation of the Periadriatic foredeep in the offshore Abruzzo (location in Fig. 1), showing the onlap of the Middle Pliocene clastic deposits against an embryonic compressional structure of the foreland (onlap angle of about 8°)

of the E member onlap onto a foreland plate dipping 3° westward. The shortening is about 37% (12.6 km). According to this reconstruction, the substratum high detected by the Colle Tavo 1 well (Fig. 7) could represent a local culmination of the Villadegna Anticline rather than a basement horst as suggested by Vezzani et al. (1993).

In a second step (Fig. 13c), we restored the section to an undeformed, sub-horizontal stage before the involvement of the Adria Plate in the foredeep downbending (Tortonian, deposition of the Schlier marls).

The total shortening along this transect across the Apennine foreland basin system is 39% (13.4 km).

The thick syntectonic succession deposited above the upper thrust sheets of the Coastal Structure shows several unconformities, allowing the phases of deformation to be reconstructed and dated. This area, limited westward by the Internal Structure and eastward by the anticlines of the Coastal Structure, forms a thick piggyback basin (Notaresco Basin) developed above by deforming thrusts.

We recognized at least six seismic sequences bounded by unconformities correlatable through the basin (Fig. 14). A seventh, uppermost sequence is visible only on a few sections but its correlation throughout the basin was not established.

Unit 1 comprises most of the Lower Pliocene succession overlying the M unconformity. This unit is divided into two subunits, 1a and 1b. The top of subunit 1b corresponds to the base of the A member of the Cellino Formation (LP1), marked by a local seismic unconformity (Morro D'Oro Structure, Internal Structure) and related correlative conformity, calibrated with wells (Morro d'Oro 1 and Fino 1, respectively). On the seismic profiles, the bases of the sandy members E and C of the Cellino Formation did not reveal seismic uncon-

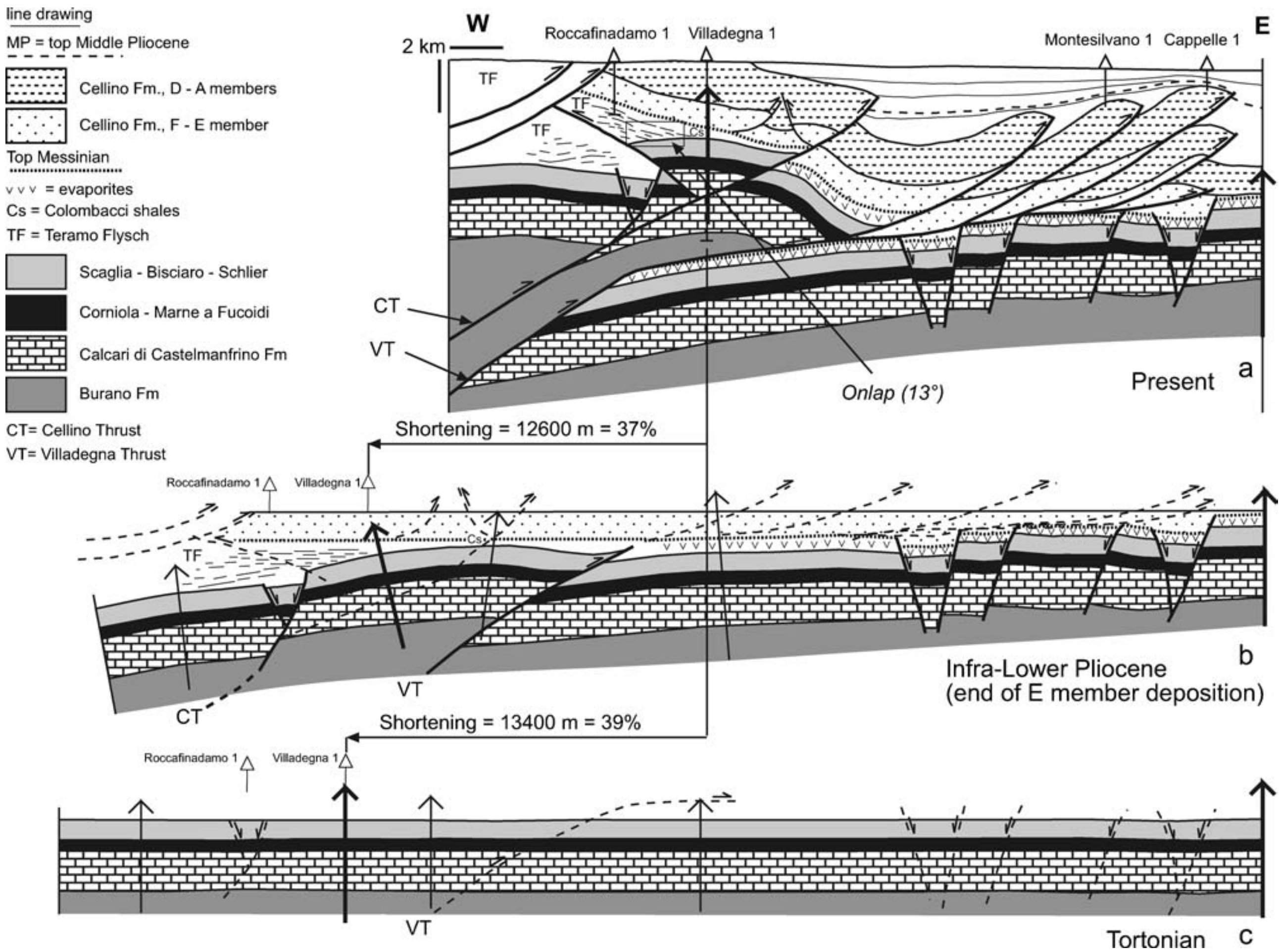


**Fig. 13 a:** Balanced depth cross-section of the profile of Fig. 10b. The section was restored at a time corresponding to the end of the E member deposition (**b**) and to the undeformed stage (**c**). The restoration illustrates the structural features of the Cellino Basin substratum, characterized by normal faults in the hinge zone of the downbending Adria lithosphere in the external areas and by an embryonic compressional structure (Villadegna Anticline) in the inner zone. The turbidites of the lower Cellino Basin replaced the Teramo Flysch sediments west of the Villadegna Anticline and were deposited over the evaporites of the Gessoso-Solfifera Formation to the east

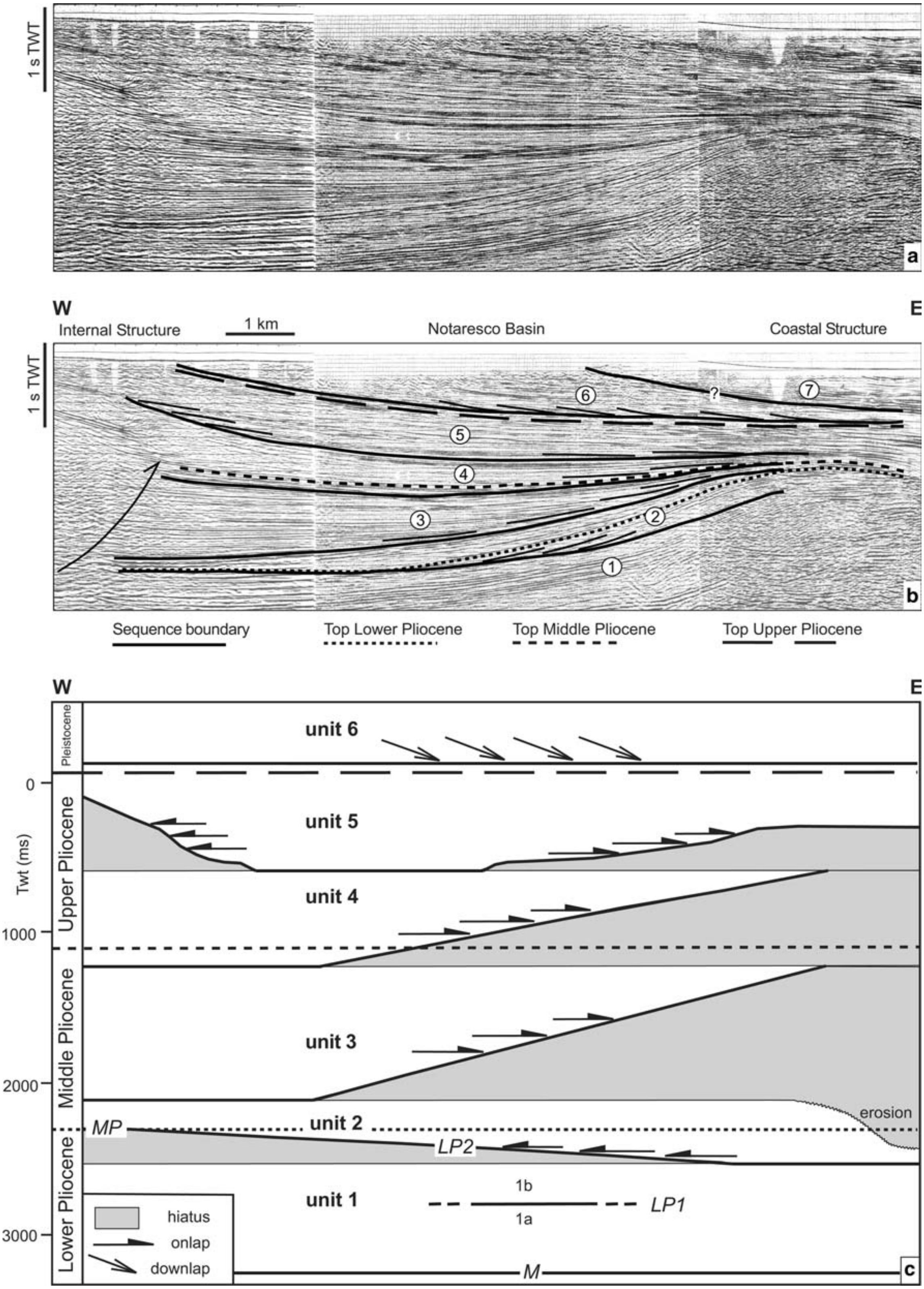


**Fig. 14 a,b** Seismostratigraphic units detectable in the Plio-Pleistocene succession of the study area. The basinal extension of Unit 7 was not ascertained. **c** Chronostratigraphic diagram of the seismostratigraphic units revealing the timing of deformation of the Internal and Coastal structures. The base of Unit 1 is the M unconformity (top Messinian); Unit 1 can be locally subdivided into two sub-units (1a and 1b) related to the Morro d'Oro Structure development. The LP1 and LP2 unconformities found in the wells were correlated with the seismic unconformities. Chronostratigraphic framework from Ghisetti et al. (1994)

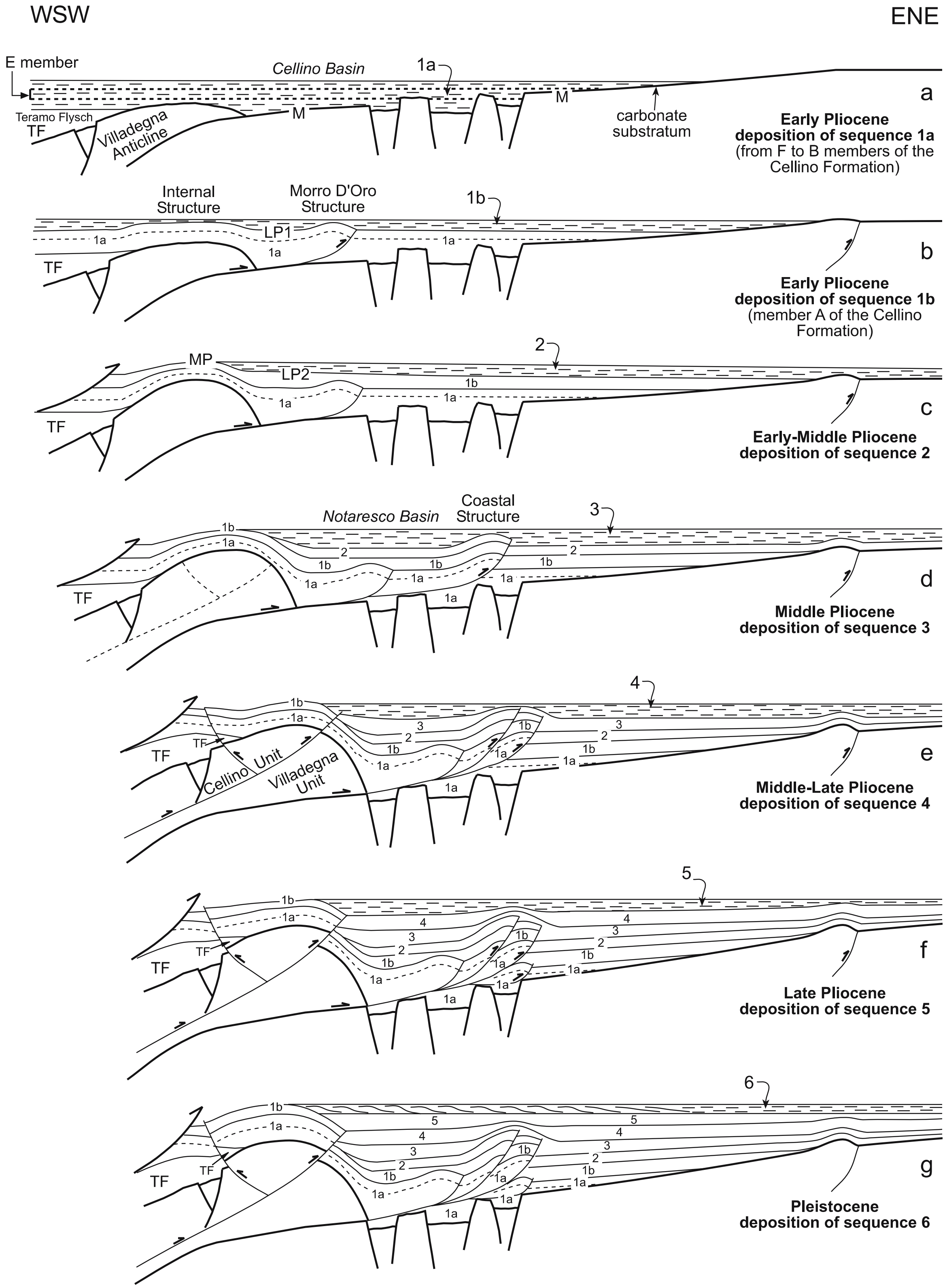


**Fig. 15** Schematic cross sections (not to scale) illustrating the Periadriatic foredeep evolution in the northeastern Abruzzo region of Central Italy from the early Pliocene (Cellino Basin, **a**) to the Pleistocene (end of the foredeep deepening, **g**) The six sequences correspond to the seismostratigraphic units drawn in Fig. 14 Details in the text. The diagrams account for the foredeep evolution in a E–W profile, even if longitudinal tectonics played an important role in the development of the basin, particularly in the Lower Pliocene (see text)

formities, confirming their significance as correlative conformities disclosed by well correlation and field surveys. Unit 2 developed in the upper Lower Pliocene–basal Middle Pliocene; its base (near the base of the Montefino Body?) is highlighted by westwardly tilted onlaps, becoming younger to the west (MP unconformity). The onlapping beds are interpreted (Casnedi and Serafini 1994) as deposited onto an eastward-dipping surface due to the developing Internal Structure, subsequently tilted by the rise of the Coastal Structure. Unit 3 (Fig. 14) is Middle Pliocene in age and is characterized by eastward onlaps against the growing Coastal Structure. Onlap also occurs on the base of the units 4 (Middle–Upper Pliocene) and 5 (Upper Pliocene–basal Pleistocene), which record subsequent phases of Coastal Structure thrusting. Additional evidence, including local onlaps on the Coastal Structure anticlines and folding of the overlying beds, indicate out-of-sequence growth of the different thrust sheets of the Coastal Structure. To the west, onlaps against the Internal Structure visible within Unit 5 show the out-of-sequence reactivation of the Internal Structure. The base of Unit 6 is a downlap surface that is the base for the Pleistocene, eastward-prograding deltaic deposits. This last unit appears to overlap the Coastal Structure deformations in the northern area (Giulianova) while it is folded by the early Quaternary tectonic activity of the structure in the south.

## Basin evolution

In the Periadriatic Foredeep in Central Italy, deposition started in the early Messinian with the deep-water, coarse-grained turbidites of the Laga Flysch of northern provenance. These accumulated onto the carbonate substratum of the Adria Plate continental margin, dipping westward under the uplifting Apennines and forming an asymmetric basin. In the late Messinian, the depocenter migrated toward the foreland, being placed east to the rising Laga Basin and Montagna dei Fiori Structure. The turbidites of the Teramo Flysch accumulated in this new basin, onlapping to the east onto a slightly deforming ramp (Fig. 15a).

During the Messinian–Pliocene transition, flexural extension occurred in the hinge zone of the downbending Adria Plate. In this area, normal fault systems defined a series of horst and graben elongated in a N–S direction and parallelling the trend of the Apennine structures. The deeper structural troughs acted as minor depocenters for sandy turbidity currents flowing from the north. The basin floor rose southward and eastward, where it was characterized by areas of different elevation and dip, reflecting foreland deformations linked to the Adria Plate flexure.

The foredeep depocenter gradually migrated eastward and Unit 1a (from F to B members of the Cellino Formation) was deposited (Fig. 15a). This Lower Pliocene succession started with hemipelagic and fine-grained turbidites conformably overlying the Teramo Flysch turbidites to the west and the Gessoso-Solfifera Formation evaporites to the east. The Cigno High had not yet developed, allowing conglomerates to enter the basin from the south (carbonate unit of Maiella, Casnedi and Mosna 1992).

After a starved interval with deposition of shales (Member F, upper part), a phase of oversupply began. The related coarse-grained sediments (E member) deposited over a substratum almost smoothed, but onlapped against the eastern and southern foreland margins (Fig. 15a). They were represented by the eastward-rising foreland ramp and the growing Cigno Structural High. The basin was narrow (approx. 30 km?) and stretched in an approx. N–S direction for many tens of kilometers (at least 150). Strong tectonic activity occurring in the adjacent areas to the north led to the deposition of large volumes of turbiditic sands. Every turbiditic event was characterized by huge volumes of sediments associated with high flow efficiency due to the high clay content (Mutti 1999). These elements favored the turbidity current flows along the entire narrow basin, reaching its margins. The result was a sheet complex, consisting of an aggradation (vertical stacking) of tabular confined sedimentary bodies of basin extent.

Fine-grained (D member) and, subsequently, tabular sandy turbidites (C member) followed. Significant intrabasinal deformations were absent in this period. During the deposition of the overlying B member, the basin was affected by southward tilting and consequential deepening.

Subsequently, compressional structures started developing at the western margin (Internal Structure) and, locally, inside the basin (Morro d'Oro Structure). Unit 1b (A member of the Cellino Formation) was deposited above the LP1 unconformity (Fig. 15b). Sedimentation of fine-grained turbidites and fan deposits of the A member occurred while the depocenter migrated eastward, extending the Lower Pliocene sedimentation to the east, in the present Adriatic offshore, where the foreland ramp was affected by incipient compressional deformations (Fig. 15b).

Between the end of the Lower Pliocene and the beginning of the Middle Pliocene, the Internal Structure continued developing and deformation of the Morro d'Oro Structure ceased. Unit 2 was deposited above the LP2 unconformity (Fig. 15c).

During the sedimentation of Unit 3 (Middle Pliocene), tectonic activity became stronger in this sector of the foredeep. The imbricate Coastal Structure developed in different phases, with syn-tectonic sedimentation in the overlying piggy-back basin (Fig. 15d). The depocenter of this basin shifted westward (towards the Apennines) as a consequence of the Coastal Structure uplift. Gentle folds developing in the eastward rising foreland delimited foredeep sedimentation.

During the deposition of Unit 4 (Middle Pliocene p.p.–Upper Pliocene p.p.), the Coastal Structure continued its growth in the southern sector, the Notaresco piggy-back basin was progressively filled, and the main depocenter migrated east of the Coastal Structure (Fig. 15e).

In the Upper Pliocene, the Internal Structure was reactivated out-of-sequence and the Coastal Structure continued to grow. Unit 5 onlapped these structures and filled the entire basin (Fig. 15f).

Since the Pleistocene, a relatively thin prograding deltaic system (Unit 6) extended over the whole central Adriatic (Ori et al. 1986), indicating the end (or interruption) of Adria Plate flexure and tilting (Fig. 15g).

## Conclusions

The Lower Pliocene sediments of the Periadriatic foredeep in central Italy were deposited into a long (at least 150 km) and narrow (about 40 km) foredeep basin stretching in a roughly N–S direction. The basin had a complex substratum morphology that strongly affected the distribution of the lowermost deposits. This substratum was characterized by significant variations in depth due to its general southward rise and due to a NNW-trending horst and graben system created by flexural extension in the hinge of the underthrusting Adria Plate. The graben formed local fault-controlled depocenters, in which a considerable amount (several hundreds meters) of Upper Messinian–basal Pliocene, possibly coarse-grained turbidites was deposited, smoothing the substratum relief. The overlying coarse-grained turbidites of the lower Cellino Basin (E member) were deposited by large-volume turbidity currents confined to the basin. The turbidites pinched out against the eastward-rising foreland ramp and the southern foreland structural highs, forming thick tabular sand bodies extending across the whole basin.

The foredeep succession was involved in the subsequent and partly syn-sedimentary later stages of the Apennine deformation, forming two main N–S trending, east-vergent thrust systems with a composite geometry and evolution.

The western Internal Structure is a breached fault-bend fold detached at depth, probably in the Triassic evaporites. It started as an emergent, low-relief foreland structure in the late Messinian, bordering eastward an older foredeep basin (the Teramo Flysch basin). Subsequently, it developed after the deposition of the Cellino Formation at the end of Lower Pliocene and was reactivated out-of-sequence in the Upper Pliocene.

The outer Coastal Structure is an imbricate fan composed of several overlapping thrust sheets detached over the Messinian evaporites and developed out-of-sequence during the Middle-Late Pliocene. The thrusts of the Coastal Structure were probably localized by the structural irregularities of the faulted substratum.

**Acknowledgements** This study was supported by MIVR (PRIN).

## References

Artoni A, Casero P (1997) Sequential balancing of growth structures, the late Tertiary example from the central Apennines. Bull Soc Gèol France 168:35–49

Bally AW, Burbi L, Cooper C, Ghelardoni R (1986) Balanced sections and seismic reflection profiles across the Central Apennines. Mem Soc Geol It 35:257–310

Bigi G, Cosentino D, Parotto M, Sartori R, Scandone P (eds) (1983) Structural model of Italy, 6 sheets, 1/500,000. Cartographie: CNR (Italian National Council of Researches), Rome

Bigi S, Calamita F, Paltrinieri W (1995) Modi e tempi della strutturazione della catena centroappenninica abruzzese dal Gran Sasso alla costa adriatica. Studi Geologici Camerti, volume speciale 1995(2):77–85

Boccaletti M, Coli M, Decandia FA, Giannini E, Lazzarotto A (1980) Evoluzione dell'Appennino Settentrionale secondo un nuovo modello strutturale. Mem Soc Geol It 21:359–373

Bolis G, Carruba S, Casnedi R, Perotti CR, Ravaglia A, Tornaghi M (2003) Compressional tectonics overprinting extensional structures in the Abruzzo Periadriatic Foredeep (Central Italy) during Pliocene times. Boll Soc Geol It 122:251–266

Bradley DC, Kidd WSF (1991) Flexural extension of the upper continental crust in collisional foredeeps. Geol Soc Am Bull 103:1416–1438

Calamita F, Cello G, Centamore E, Deiana G, Micarelli A, Paltrinieri W, Ridolfi M (1991) Stile deformativo e cronologia della deformazione lungo tre sezioni bilanciate dall'Appennino umbro-marchigiano alla costa adriatica. Studi Geologici Camerti, volume speciale 1991(1):295–314

Carruba S, Casnedi R, Felletti F (2004) From seismic to bed: surface-subsurface correlations within the turbiditic Cellino Formation (central Italy). Petrol Geosci 10:131–140

Carruba S, Casnedi R, Perotti CR, (2005) Mechanism and timing of the Pliocene-Pleistocene foredeep migration in the Abruzzo offshore area (central Adriatic). In: Finetti IR (ed). CROP – Deep seismic exploration of the Mediterranean region. Elsevier, Amsterdam (in press)

Casnedi R (1983) Hydrocarbon-bearing submarine fan system of Cellino Formation, Central Italy. Am Ass Petrol Geol Bull 67:359–370

Casnedi R (1991) Hydrocarbon accumulation in turbidites in migrating basins of the southern Adriatic foredeep (Italy). In: Bouma AH, Carter RM (eds) Facies models in exploration and development of hydrocarbon and ore deposits. Proceedings of 28th International Geological Congress, VSP, Utrecht, 9–19 July (1989), pp 219–224

Casnedi R, Mosna S (1992) Natura e provenienza di conglomerati basali del Pliocene inferiore abruzzese (Avanfossa Periadriatica). Atti Ticinensi di Scienze della Terra 35:135–143

Casnedi R, Serafini G (1994) Interpretazione geologica della sezione sismica nella valle del Vomano (Abruzzo). Atti Ticinensi di Scienze della Terra, serie speciale 2:45–49

Casnedi R, Moruzzi G, Mutti E (1978) Correlazioni elettriche di lobi deposizionali torbiditici nel Pliocene inferiore del sottosuolo abruzzese. Mem Soc Geol It 18:23–30

Crescenti U, D'Amato C, Balduzzi A, Tonna M (1980) Il Plio-Pleistocene del sottosuolo abruzzese-marchigiano tra Ascoli Piceno e Pescara. Geol Romana 19:63–84

DeCelles P, Giles KA (1996) Foreland basin systems. Basin Research 8:105–123

Doglioni C (1991) A proposal for the kinematic modelling of W-dipping subductions—possible applications to the Tyrrhenian-Apennines system. Terra Nova 3:423–434

Ghisetti F, Vezzani L (1991) Thrust belt development in the central Apennines. northward polarity of thrusting and out-of-sequence deformations in the Gran Sasso chain (Italy). Tectonics 10:904–919

Ghisetti F, Follador U, Casnedi R, Vezzani L (1994) Assetto tettonico delle zone esterne dell'Appennino abruzzese: elementi di

analisi stratigrafico-strutturali. Atti Ticinensi di Scienze della Terra, serie speciale 2:5–43
Kligfield R (1979) The northern Apennines as a collisional orogen. Am J Sci 279:676–691
Marsden D (1992) V0-k method of depth conversion. Geophysics: The leading edge of exploration, pp 53–54
Mutti E, Tinterri R, Remacha E, Mavilla N, Angella S, Fava L (1999) An introduction to the analysis of ancient turbidite basins from an outcrop perspective. Am Ass Petrol Geol Course Note 39:1–93
Ori GG, Friend PF (1984) Sedimentary basins formed and carried piggyback on active thrust sheets. Geology 12:475–478
Ori GG, Roveri M, Vannoni F (1986) Plio-Pleistocene sedimentation in the Apenninic-Adriatic Foredeep (Central Adriatic Sea, Italy). In: Allen PA, Homewood P (eds). Foreland basins: special publication no. 8 of the International Association of Sedimentologists, Blackwell, Oxford, pp 183–198
Ori GG, Serafini G, Visentin C, Ricci Lucchi F, Casnedi R, Colalongo ML, Mosna S (1993) Depositional history of the Pliocene-Pleistocene Adriatic Foredeep (Central Italy) from surface and subsurface data. In: Spencer AM (ed). Generation, accumulation and production of Europe's hydrocarbons III. Special publication of the European association of petroleum geoscientists, Springer, Berlin Heidelberg USA, pp 233–258
Paltrinieri W, Zanchini G, Martini N, Roccia L (1982) Evoluzione del bacino torbiditico marchigiano-abruzzese a partire dal Messiniano in base a lineazioni profonde. Mem Soc Geol It 24:233–241
Patacca E, Scandone P (1989) Post-Tortonian mountain building in the Apennines. The role of the passive sinking of a relic lithospheric slab. In: Boriani A, Bonafede M, Piccardo GB, Vai GB (eds) The lithosphere in Italy. Atti Accademia Nazionale dei Lincei 80. Rome, pp 157–176
Ricci Lucchi F (1986) The Oligocene to Recent foreland basins of the northern Apennines. In: Allen PA, Homewood P (eds) Foreland basins. Special publication no 8 of the International Association of Sedimentologists, Blackwell, Oxford, pp 105–139
Royden L (1988) Flexural behavior of the continental lithosphere in Italy: constraints imposed by gravity and deflection data. J Geophys Res 93:7747–7766
Scisciani V, Calamita F, Tavarnelli E, Rusciadelli G, Ori GG, Paltrinieri W (2001) Foreland-dipping normal faults in the inner edges of syn-orogenic basins: a case from the Central Apennines, Italy. Tectonophysics 330:211–224
Vezzani L, Casnedi R, Ghisetti F (1993) Geological map of the north-eastern Abruzzo region, 1 sheet, 1/100,000. Cartographie: SELCA, Florence
Vezzani L, Ghisetti F, con la collaborazione di BigozzI A, Follador U, Casnedi R (1998) Carta geologica dell'Abruzzo, 2 sheets, 1/100,000. Cartographie: SELCA, Florence