Foredeep geometries at the front of the Apennines in the Ionian Sea (central Mediterranean)

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Abstract

A new regional seismic section in the Ionian Sea across the Apennines belt and related foreland shows how the present foredeep geometry may be an example for interpreting discontinuous, tilted and deformed earlier basins now incorporated in the internal parts of the accretionary wedge. Onlap stratal terminations of the foredeep sediments on the foreland monocline may simulate downlap geometries once involved and tilted by back-thrusting. The geometry of the Ionian foredeep is controlled by the dip of the regional monocline, and internally by the variable dip and length of the limb of the external fold, which may be either foreland-verging or hinterland-verging. The generation of a new fold within the foredeep splits the basin into a new foredeep toward the foreland and a thrust-top basin toward the hinterland. The thrust-top basin dimension is primarily controlled by the distance between the two folds and related thrusts at its margins. The foredeep, in its overall history, is composed by a series of concave heterogeneous lenses, progressively displaced and piled up toward the foreland to the east. The formation of each sedimentary lens is controlled by the development of a new fold and the contemporaneous retreat of the regional monocline which creates new accommodation space. The complex 3D geometry of the Apennines foredeep mainly results from lateral variations of the latter parameters, as well as variations in sediment supply and eustasy. © 1999 Elsevier Science B.V. All rights reserved.

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1. Introduction

Foredeeps are those basins located at the margin of orogens or accretionary wedges, and they are characterized by lens shaped clastic sedimentary sequences which are controlled by a number of well known factors, i.e., subsidence, sediment supply, eustasy and climate [1]. The internal geometry of these active margin basins is well differentiated from that of passive margin basins, both in terms of lithology and geometry of the basin. Foredeeps are located and propagate on top of a regional monocline [2] usually dipping toward the interior of the belt with angles ranging between 1° and more than 10° [3]. The internal geometries of foredeep basins are notoriously controlled by growth folds (e.g., [4,5]). The Apennines accretionary wedge presents a Plio–Pleistocene somewhere 8 km deep basin which underwent subsidence rates higher than 1 mm/yr. This
The Italian Peninsula, from Piemonte-Monferrato in northern Italy, down to the northern Africa-Maghrebides (Fig. 1). The arc formed on top of a west-directed subduction zone which retreated ‘eastward’ during the last 30 Ma [7–12]. The convex part of the arc is the area where the roll-back of the subduction hinge has been maximum. The most arcuate part of the Apennines Arc is Calabria. The arc migrated ‘eastward’ about 775 km during the Late Oligocene in a section crossing northern Calabria, the Tyrrhenian Sea, Sardinia, and the Provençal basin [12]. This value decreases moving either toward the northern Apennines or to the south, toward Sicily and the Maghrebides. The southern Apennines and Calabria,
Fig. 2. Regional seismic section Crop M5 of the Ionian Sea across the Apennines accretionary wedge and its Apulian foreland. See location in Fig. 1. Note that the accretionary wedge is lower than the foreland.
being located in the most arcuate part of the belt, travelled eastward at the fastest rates (3–4 cm/yr; [11,13,14]). The earlier foredeep stages were located more internally and to the west they are now abandoned due to the high speed of the roll-back. Within the southern Apennines and Calabrian Arc there are remnants of the earlier foredeep since the Early Miocene ('pre-Irpinian') [15], as it was observed in the central-northern Apennines [16]. The fast eastward advancement of the southern Apennines foredeep is clearly evidenced by highly shortened Plio–Pleistocene deposits, originally located in the internal side of the foredeep, or discovered in wells where the Pliocene sediments have been overridden by Mesozoic thrust sheets.

The Apennines foredeep has been interpreted as generated by the 'eastward' roll-back of the hinge of the subduction induced by the slab pull or by the relative eastward mantle flow [14,17]. There the subsidence is among the fastest on the Earth's surface and it exceeds 1 mm/yr [3]. The foredeep eastward migration in the Apennines should reflect the velocity of the roll-back of the Adriatic slab, which retreated faster in its southern part where the Ionian oceanic lithosphere was undergoing subduction, in contrast with the slower northern continental part. This appears to be true both for the early Neogene history of the foredeep but also for the later-to-present stages of the subduction [18].

3. Seismic section M5 in the Ionian Sea

This seismic section is one of the most complete lines across the Apennines front and its foreland. The line runs from offshore eastern Calabria (southern Italy) to the northeast, offshore southern Puglia. In the Calabrian part the section crosses extensional faults which are well known inland to the north in Campania and Basilicata to form grabens (e.g., the Vallo di Diano, Val d’Agri) and be responsible for the high seismicity of the southern Apennines [19]. Moving northeastward, the section exhibits an irregular seafloor, indicating active or very recent tectonic activity. Below the Messinian unconformity (Fig. 2) back-thrusts deform the Miocene sequences and they determine the formation of triangle zones in the central part of the section. The front of the accretionary wedge is marked by an eastward-verging thrust overriding the narrow foredeep deposits of the Taranto trench. (Fig. 3). The foreland is characterized by a steep westward dipping monocline made of continental crust with an about 6 km thick Mesozoic Apulian carbonate platform and a thin sequence of Tertiary calcarenites and limestone. A few normal faults also disrupt the seafloor of the foreland which is even more elevated than the accretionary wedge to the west (Fig. 2).

From the main section, two details have been extracted in order to have clearer views of the front of the accretionary wedge and the present foredeep (Fig. 3) and a more internal part of the wedge which was formerly the front of the belt, probably during the Late Miocene (Fig. 4). These data allow us to give a look into the complicated geometries of the accretionary wedge. Dating of sediments is based on projected unpublished Agip wells.

The frontal section (Fig. 3) shows a 8.5 km wide foredeep, with a seafloor about 2350 m deep, and sediments onlapping the westward-dipping monocline. The onlap shows a progressive eastward displacement. The accretionary wedge is composed of Plio–Pleistocene sediments. The internal detail of the section (Fig. 4) has been migrated and depth-converted. It is characterized by two main back-thrusts verging toward the southwest, generating two triangle zones. Between the two hinterland-verging ramps there is a basin which is made of two wedges, the lower pointing toward the foreland, the upper pointing toward the hinterland. The lower wedge appears as an earlier external foredeep now involved by the accretionary wedge, and it is limited at the base by apparent downlap stratigraphic terminations at about 5 km depth. The overlying upper wedge is a later thrust-top basin onlapping the lower wedge with stratigraphic terminations shifting in the opposite direction toward the southwest.

4. Discussion on the M5 section

Fig. 5 is an interpretation of the main features visible on Fig. 4. This spectacular section indicates that the two-stage basin shape is controlled by the distance between the two back-thrusts in the upper wedge, that this upper basin formed during the
Fig. 3. The frontal thrust and related fold of the Apennines accretionary wedge in the Ionian Sea with the related foredeep. Deep facies sediments onlap the foreland monocline. See location in Fig. 2.

growth of the two anticlines (in particular it pinches-out on the back-limb of the internal anticline to the southwest), and that the lower foreland pinching-out wedge has an apparent downlap of sediments toward the right. The Messinian unconformity eroded the two folds and post-dates the underlying sediments. The Miocene sequences are laterally displaced, with the younger one more to the right, toward the foreland, and laterally overlying the margin of the previous internal section. Therefore, the relative depocentres are progressively displaced toward the east. Fig. 6 proposes an interpretation of the kinematics of the geometries occurring in Fig. 4: the original foredeep sedimentary wedge (first stage) is incorporated and tilted by a back-thrust with syntectonic sedimentation (second stage). Original onlap
geometries are tilted to appear as downlap strata terminations. The first sedimentary wedge is thinning toward the foreland, whereas the second overlying basin is thinning toward the hinterland on the back-limb of the fold. Therefore, the first stage should correspond to the external foredeep located on the foreland monocline and limited to the southwest by the frontal fold of the accretionary wedge. The second stage of the basin formed instead on top of active thrusts, and the first-stage foredeep became a piggy-back basin confined by two hinterland-verging structures (Fig. 6). These geometries and kinematics may be a key to unravel along-strike inland deep geometries in the southern Apennines, e.g., the Sant'Arcangelo basin where onshore seismic data are of lower quality but the outcrops are spectacular [20,21].

4.1. Internal geometries of the thrust belt

Within a foreland-propagating accretionary wedge there may form back-thrusts. When associated to a basal decollement, a back-thrust forms a triangle zone [22]. This feature is well developed within the M5 seismic section (Fig. 5). The association of thrusts may generate different combinations of vergences which may be entirely or partly opposite to the accretionary wedge main direction of propagation (Fig. 7).
Fig. 6. Kinematic interpretation of the geometric structural and stratigraphic pattern of Fig. 4. The frontal early foredeep stage thinning toward the right is interpreted as the present setting at the front of the Apennines accretionary wedge. The front could have later been involved by a back-thrust. This generated the opposite pinching-out of the sedimentary packages associated with the two-stage evolution. Original onlap geometries then appear as a downlap plane. The intra-folds basin is contemporaneously filled by a wedge thinning toward the west. The shape and width of the basin is controlled by ramp distances and vergences.

Basin margins are shaped by the dip and evolution of the fold limbs: internal limbs are longer and less steep with respect to frontal fold limbs which are frequently short and overturned in fault-propagation folds [23].

In one of his classic papers on thrust belt structural analysis, Mitra [24] shows how the distance between the ramps and the ramp length control the final internal geometry of an imbricate fan or a duplex. When the distance between the ramps is large and the displacement of the associated thrusts small enough to maintain an undeformed flat sequence between the back limb of the external fold and the fore-limb of the internal fold, there may form a syn-folding basin, e.g., a thrust-top basin, or also called piggy-back basin [25]. In this respect, when the distance between the ramps varies, the basin dimension
Fig. 7. Two examples (A and B) in which M1 and M2 are sedimentary packages differentiated by the growth of the second fold which splits the basin into two sub-basins. The depocentre of M2 is shifted toward the foreland with respect to M1. The central piggy-back basin forms on top of older external foredeep sediments and it is controlled by the distance of the two ramps. (A) The fold vergences coincide with the regional vergence. (B) The fold vergences are opposed to the regional vergence. The foredeep sediments are thinning both toward the foreland monocline and toward the back-limb of the frontal fold which is longer and less steep with respect to example (A). The scale is based on the examples included in Fig. 2.

also varies. In other words, the shape and dimension of a piggy-back basin forming on the top of an accretionary wedge may be analyzed in terms of ramp distances. In Fig. 4 it is evident that the width of the basin (about 7 km) confined between the two anticlines is proportional and determined by the distance between the two folds which is in turn controlled by the distance between the ramps of the two main thrusts (about 11 km).

The foreland migration of the southern Apennines foredeep since the Miocene to recent times generated a variety of lens-shaped basins progressively
displaced eastward. This is evident inland, for instance for the Tortonian Gorgoglione Flysch [26], and it occurs at the front of the northern Apennines in the Po basin [6]. As already demonstrated by Ricci Lucchi [16] for the northern Apennines, the onlap on the regional monocline contemporaneously migrated toward the foreland to the east. The basins shapes are controlled by thrust-ramps distance, fold vergence, dip of the foreland monocline, and the along-strike variation of the former parameters. Two thrusts can laterally branch into a single thrust and the distance between the two ramps may decrease to zero; therefore, also the possible associated thrust-top basin narrows (see the example of the Gorgoglione Flysch [26]). Usually the distance among major ramps in the Apennines ranges between 5 and 25 km at the front of the accretionary prism. Large thrust sheets of more that 40–50 km of displacement have also been interpreted, which implies an equal amount of ramps distance. The Apennines foredeep sediments are sometimes so irregular to form several isolated sub-basins. This could partly explain the large number of formational names which have been introduced in the literature to describe the Neogene and Quaternary foredeep stratigraphy of this belt. This large variety may be explained by the frequent undulations of the thrust belt, along transfer zones induced by the inherited lateral variations in the rheological parameters of the pre-existing Mesozoic stratigraphy and the underlying basement.

4.2. Foredeep evolution

The foredeep basin is in general a sedimentary wedge bounded internally by the frontal thrust, while it expands laterally toward the foreland, with a progressive onlap of the foredeep sediments [27]. The formation of a new anticline within a foredeep basin may generate two sub-basins, a new more external foredeep sensu stricto, and a thrust-top basin (Fig. 7) which forms on top of the earlier frontal foredeep. From that moment on, the two basins are also differentiated in terms of sediment supply from the foreland monocline, the hinterland, or other external sources along the foredeep axis. This is usually contextual to a progressive retreat of the foreland monocline which determines subsidence and new accommodation space. The stratigraphic packages may be punctuated and differentiated in shape by the growth of the new fold, which has a given distance with respect to the pre-existing internal fold. The frontal fold may have either foreland vergence (Fig. 7A) or hinterland vergence (Fig. 7B). The main difference is the onlap on the frontal fold which occurs respectively on the forelimb or in the back-limb. Back-limb is less steep and longer with respect to the forelimb, and this generates different shapes of the internal margin of the basin. The schematic sections of Fig. 7 represent a model of the kinematics of foredeep propagation based on the geometries observed in the M5 seismic section. In particular Fig. 5 shows the effect of back-thrusting in generating an isolated sub-basin (Fig. 7B).

The development of a fold may start at any moment during a third-order sea-level fluctuation. Therefore, the eustasy-controlled depositional sequences [1] may be perturbed by the isolation of new basins which determine variations in the sediment supply and in the water depth in the area of the growing fold.

5. Conclusions

The seismic section M5 of the Apennines accretionary wedge in the Ionian Sea (Fig. 2) supports the interpretation that the geometry and kinematics of foredeep and piggy-back basins are primarily controlled by the dip of the foreland monocline, the distance between thrust ramps, and the vergence of the single folds with respect to the regional vergence which may be either in the same direction or opposite. Subsidence in foredeeps controls the dip and retreat rate of the foreland monocline, parameters which are primarily determined by the subduction type [3]. Different geometries of basins associated with active margins result by the combination and variation of these parameters and the other sedimentary factors such as sediment supply and eustasy. As it is a classic rule in geology, the present geometries of a foredeep may be powerful keys in illuminating and interpreting internal shortened complex parts of an accretionary wedge (Fig. 6). The example of the Ionian Sea foredeep allows us to predict other variable patterns of foredeep geometry and kinematics. A common feature in the Apennines
is the formation of concave lenses progressively displaced and piled up toward the foreland to the east (Fig. 7). The stratigraphic packages may be punctuated and differentiated in shape by the growth of a new fold, its vergence and distance with respect to the pre-existing internal fold. In this regard, tectonics could deeply influence depositional sequences, independently from eustasy.

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