Foredeeps versus subduction zones

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ABSTRACT

The geologic characteristics of foredeeps and accretionary wedges suggest that these features are distinguishable on the basis of the direction of the associated subduction. East-northeast–dipping subduction-related accretionary wedges show high relief and broad outcrops of metamorphic rocks. They are associated with shallow foredeeps with low subsidence rates. In contrast, west-dipping subduction-related accretionary wedges show low relief and involve mainly sedimentary cover. The related foredeeps are deep and have high subsidence rates. This differentiation is useful both for oceanic and continental subductions, e.g., eastern vs. western Pacific subductions, or east-dipping Alpine vs. west-dipping Apenninic subductions. In a cross section of the Alps the ratio of the area of the orogen to the area of the foredeeps is at least 2:1, whereas this ratio is 0.22:1 for the Apennines. These ratios explain why foredeeps related to east- or northeast-dipping subduction are quickly filled and are bypassed by clastic rocks, whereas foredeeps related to west-dipping subduction maintain a deep-water environment longer. These differences support the presence of an "eastward" asthenospheric counterflow relative to the "westward" drift of the lithosphere detected in the hot-spot reference frame, even in the Mediterranean where no hot spots are present. In this interpretation, the Apennines foredeep was caused by the "eastward" push of the mantle acting on the subducted slab, whereas the foredeeps in the Alps were caused by the load of the thrust sheets and the downward component of movement of the upper Adriatic plate; these forces contrast with the upward component of the "eastward" mantle flow.

INTRODUCTION

The origin of foredeeps, including foreland basins and trenches in continental and oceanic lithosphere, respectively, has been linked to loading caused by an advancing orogen (Beaumont, 1981; Jordan, 1981; Quinlan and Beaumont, 1984). However Royden and Karner (1984) demonstrated that in the Carpathian and Apennine thrust belts the topographic load is insufficient to explain the deep foreland basins. Royden and Karner (1984) linked the origin of such foreland basins to roll-back of the subducting lithosphere due to slab pull. All these fundamental models of foredeep formation did not take into account the "westward" drift of the lithosphere (Le Pichon, 1968; Ricard et al., 1991), which implies a relative "eastward" counterflow of the asthenosphere. Dickinson (1978) noted that the Pacific trenches associated with west-dipping subduction (Mariana type) are deeper than those related to east-dipping subduction (Chilean type). This asymmetry may be related to eastward mantle flow (Nelson and Temple, 1972; Uyeda and Kanamori, 1979; Doglioni, 1990, 1991, 1993). In this paper I emphasize the differences between foredeeps associated to opposite subductions, using the contrast between the Alps and the Apennines as an example, and infer that these differences are due to the global relative motion between lithosphere and asthenosphere.

GLOBAL COMPARISON OF THRUST BELTS AND FOREDEEPS

The orientation of subduction relative to global plate motion and the "westward" drift of the lithosphere cause the decollement planes in the convergent systems to be in different locations and to behave differently from each others (Doglioni, 1992). The consequence of this asymmetry is that west-dipping subduction doesn't have decollement planes for uplifting deep-seated rocks; such uplift occurs only in east-northeast–dipping subduction zones. Rather than specifying west- or east-dipping subduction, it would be better to specify whether subduction follows or is opposite to the undulate flow that characterizes global plate motion, which is not regularly east-west. For example the gradual transition from east-west plate motion in the Atlantic to northeast in the Indian Ocean, to the north-northeast motion of Arabia and India follows the bending of plate motion in eastern Asia and the Pacific which trends west-northwest (Doglioni, 1993, Fig. 1). The major differences between thrust belts associated with subduction that is in the same direction or opposite to the "east-northeast" mantle counterflow are that subduction in the same direction of this flow has orogens with high structural and morphologic relief, deep crustal rocks, and shallow foredeeps. Thrust belts associated with subduction in the direction opposite to that of the mantle flow commonly have low structural and morphologic relief and sedimentary cover scraped off the top of the subducting plate, and the subduction zones have deep foredeeps and an east-verging arcuate shape and are always associated with back-arc basins.

Subsidence rates calculated from several foredeeps (Fig. 1) are a first estimation of the values, considering the age and facies evolution of the clastic sedimentary rate that fills the basin, or the absence of such fill. Taking the total thickness of the foredeep deposits in the depocenter and dividing that value by the time span in which they were deposited, we may obtain a rough maximum conservative estimate of the subsidence rate. Thus, for example, a 6-km-thick foredeep related to a west-dipping subduction zone that formed in 5 m.y. indicates an average subsidence rate of 1200 m/m.y. For an east-northeast–dipping subduction zone foredeep of 6 km depth and formed in 50 m.y., we determine an average maximum subsidence rate of 120 m/m.y. This is the common difference between subsidence rates of foredeeps related to west-dipping and east- or northeast-dipping subduction zones. The

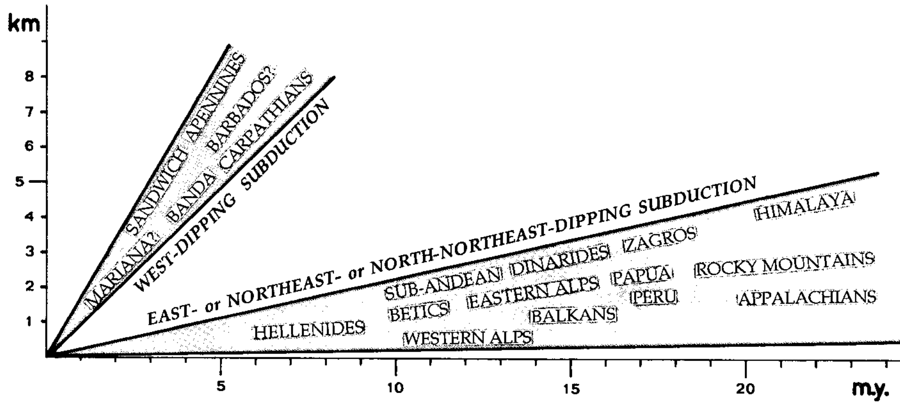

Figure 1. Foredeeps (including trenches and foreland basins) show two main fields of subsidence rates. High rates, up to 1600 m/m.y., characterize foredeeps related to west-dipping subduction. Rates about one order of magnitude slower are observed for foredeeps associated with east-northeast or north-northeast–dipping subduction, both for frontal and back-thrust belts.

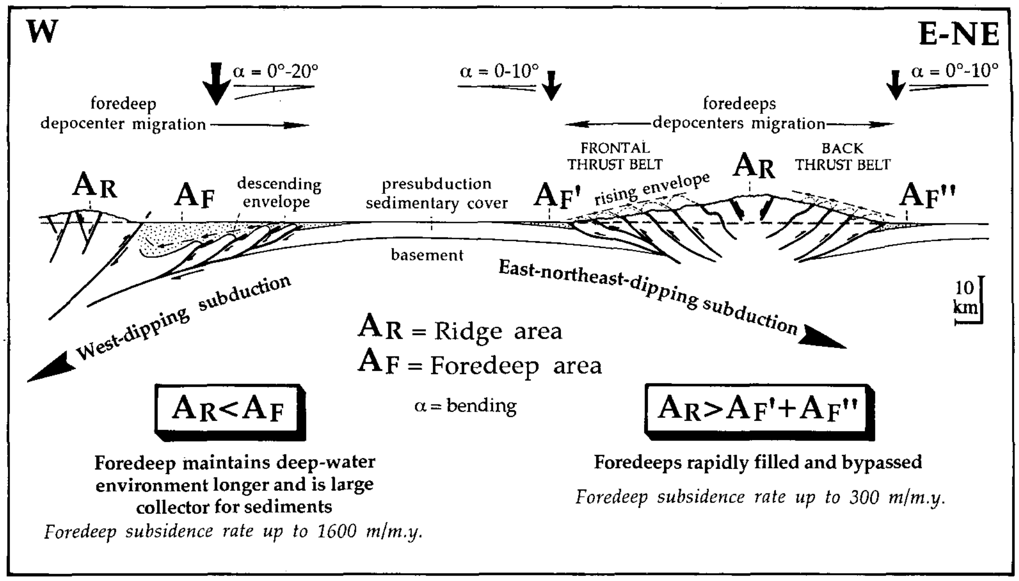

Figure 2. Strong asymmetry of geologic parameters is observed between foredeeps related to west-dipping subduction (left), and foredeeps related to east-northeast–dipping subduction (right). In west-dipping case, area of foredeep (filled or unfilled) is wider than area of mountainous ridge, whereas foredeep areas are smaller in opposite direction of subduction.

two fields differ by about one order of magnitude of subsidence rate, both in oceanic and continental environments. There are two very distinct fields, one with subsidence rates ranging from 800 to 1600 m/m.y., and a second one with rates of 0 to 300 m/m.y. The first field includes only foredeeps (both trenches and foreland basins) related to west-dipping subduction (Carpathians, Apennines, Banda, Barbados, Sandwich, and probably Mariana and other western Pacific trenches). The second field includes only foredeeps in front of frontal thrust belts related to east-dipping (northern and southern Cordilleras, Alps, Urals, Appalachians), northeast-dipping (Dinarides, Hellenides, Taurides), north-northeast–dipping subduction zones (Zagros, Himalayas, Indonesian arc, New Zealand), or foredeeps related to their back-thrust belts (e.g., European southern Alps, Balkans, Pontides, Pamir, Rocky Mountains, Sub-Andean thrust belt). Subsidence rate is clearly distinguished from sedimentation rate, and the two types of subsidence in foredeeps differ both if the foredeep is filled by sediments and if it's not. Sedimentation rates may be high in front of east-dipping subduction (e.g., Taiwan) where an earlier deep oceanic basin formed the collector and in which subsidence rates were low. Unfilled deep trenches that formed in response to west-dipping western Pacific subduction zones can have high rates of subsidence (e.g., Mariana). Moreover, the ratio between the area of the elevated ridge and the area of the foredeeps is >1 in case of east-northeast-dipping subduction zones, whereas it is <1 for west-dipping subduction zones (Fig. 2).

COMPARISON BETWEEN ALPS AND APENNINES

The Alps and the Apennines provide a unique geodynamic setting in which to compare structural differences between thrust belts associated with east- vs. west-dipping subduction zones (Fig. 3). The Alps and Apennines formed at the margins of the same plates: between the Adriatic plate to the east or southeast, and the European plate to the west or northwest. In the Alps, the Adriatic plate thrust the European plate, whereas in the Apennines the same Adriatic plate represents the footwall of the subduction zone. Note that the two orogens are diachronous and have very different rates of evolution. The Alpine subduction began during Early Cretaceous time and continued until the Pliocene. In contrast, the Apenninic subduction formed during the past 10–15 m.y. Evidences for the subducted Adriatic and European lithospheres have been proposed by several authors (e.g., Panza et al., 1982; Cattaneo and Eva, 1990; Giardini and Velonà, 1991). Laubscher (1988) described the main differences between the western Alps and northern Apennines, pointing out the striking distinctions between the two orogens. He proposed calling the Alps a "push arc" and the Apennines a "pull arc." Royden and Burchfiel (1989) and I (Doglioni, 1990, 1992) arrived at similar conclusions in comparing the Alps and the Carpathians and the Mediterranean orogens in general. The Alps are more elevated relative to the Apennines and have a much higher structural relief, as also indicated by the outcrops of high-grade metamorphic rocks. Erosion eliminated a large part of the uplifted thrust sheets, which would have reached some tens of kilometres of altitude if they had stayed in place. The Apennines, on the other hand, have extensive outcrops of sedimentary cover (Bally et al., 1986) and only a few scattered outcrops of metamorphic rocks, mainly relicts of the earlier Alpine phase. In contrast with the Alps, the Apennines did not have a thick pile of a few tens of kilometres of nappes that were eroded. Moreover, only to the west of the Apennines did a back-arc basin form—i.e., the Tyrrhenian Sea. Another unexpected difference between the Alps and the Apennines is that paradoxically the Alps have a shallow foredeep with low subsidence rates, in spite of the high topographic relief and consequent higher lithostatic load compared to the Apennines. In the Alpine foredeep (Homewood et al., 1986; Pfiffner, 1986) the Oligocene base reaches 4000 m (Bigi et al., 1989). Subsidence rates in the Alpine foreland range from 0 to 200 m/m.y. The southern Alps are the back-thrust belt of the Alpine orogen. The Southalpine foredeep (Massari, 1990) subsided at rates that rarely exceeded 300 m/m.y., determined by dividing the total thickness of the flysch and molasse deposits by duration of the deposition (2–6 km of sediment deposited in 15–40 m.y. or more). The average area of the entire Alpine orogen above sea level is about 300 km^2, and the sum of the areas of the foredeeps of the frontal and back thrust belts is estimated as 150 km^2. Thus the ratio of the area of the orogen to the area of the foredeeps is 2:1 in this case. It is regularly >1, as in thrust belts related to east-northeast–dipping subduction. It is from

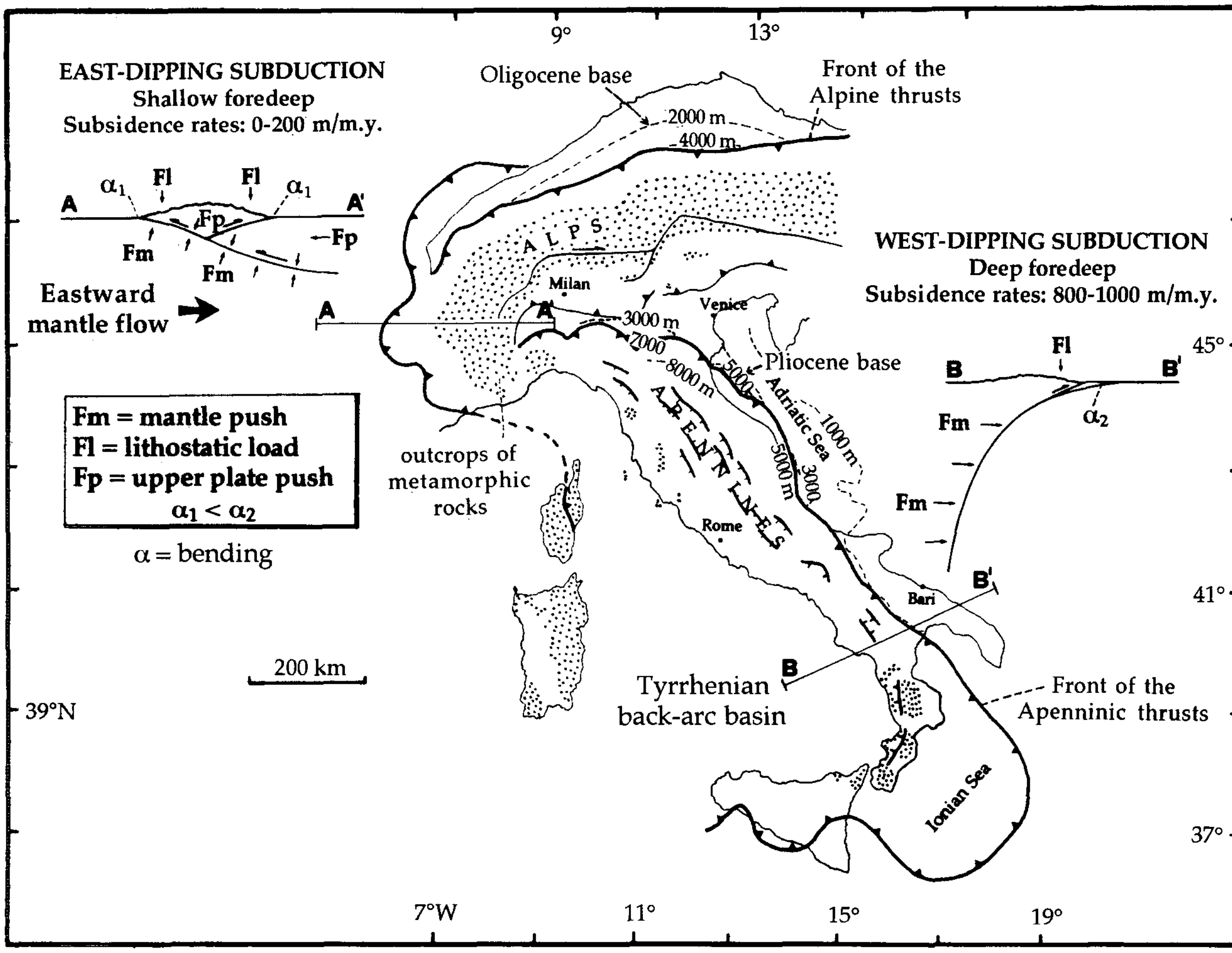

Figure 3. Alps and Apennines are thrust belts with very different characters: Alps have shallow foredeep, broad outcrops of metamorphic rocks, and high structural and morphologic relief. Apennines have deep foredeep, few outcrops of basement rocks (partly inherited from earlier Alpine phase), low structural and morphologic elevation, and Tyrrhenian back-arc basin. These differences mimic asymmetries of Pacific east-dipping Chilean and west-dipping Marianas subductions. For east-dipping subduction foredeep, origin may be interpreted as controlled by lithostatic load and downward component of upper plate push, minus upward component of "eastward" mantle flow. For west-dipping subduction, where subsidence rate is much higher, foredeep origin may instead be interpreted as due to horizontal mantle push and lithostatic load.

the Alps that the terms flysch and molasse were introduced, describing early and later stages of foredeep filling. Flysch and molasse are in general synonymous with deep and shallow clastic facies, respectively. The initial stages of subduction occurred when there was a deep-water environment collector for turbidites coming from the uplifting and eroding wedge. The foredeep was quickly filled, however, because the amount of sediment coming from the orogen was much larger than the area of the foredeep. As a consequence, the foredeep changed to molasse shallow-water conditions, and once the basin was filled, the foredeep was bypassed, and clastic sedimentation occurred in remote areas: for the Alps, in the Rhone delta, and in the North Sea and the Black Sea, by means of the Rhine and Danube rivers, respectively. This bypassing occurred because the subsidence rate in the foreland basins around the Alps was insufficient to keep the sediments coming from the orogen. This low subsidence rate did not occur in thrust belts related to west-dipping subduction, where the subsidence rate was always greater relative to the amount of volume eroded from the internal elevated ridge.

The Apennines are characterized by a frontal active accretionary wedge below sea level, whereas the main elevated ridge is the result of uplift and extension. These different tectonic fields are still moving eastward, expanding the Apenninic arc at velocities of 1 to 7 cm/yr, rates comparable to those of other arcs related to west-dipping subduction (e.g., the Banda arc; Veevers et al., 1978). The eastward rollback of the Adriatic lithosphere (Malinverno and Ryan, 1986) accompanies this migration. In the elevated Apenninic ridge, what was previously accreted in the frontal part (mainly Mesozoic cover and deep foredeep deposits) has been uplifted and crosscut by the eastward-propagating extensional wave. Seismic data from the accretionary wedge of the Apennines (Pieri, 1983; Schwander, 1989) show that the envelope around the fold crest may dip toward the hinterland. Thus, the folds did not form during upward movement, but rather developed as fault-propagation and fault-bend folds due to underthrusting of the footwall—i.e., the subducting lithosphere. As a result, growth folds are little eroded, and clastic sedimentary rock of the foredeep onlaps the limbs of these folds. In the Alps, on the other hand, the envelope of the fold crest rises toward the hinterland. The front of the thrust belt rises, and growth folds are uplifted and deeply eroded during the forward propagation of the orogen, an evolution opposite to that of the folds of a west-dipping, subduction-related accretionary wedge (Fig. 2).

In contrast to the Alps, the Apennines have a very pronounced foredeep; the Pliocene base reaches 8.5 km (Bigi et al., 1989), indicating subsidence rates of 800–1600 m/m.y. Much of the Apenninic foredeep (e.g., Ori et al., 1986; Royden et al., 1987; Casnedi, 1988) is located on top of the accretionary wedge, not to its front. Thus, the so-called piggyback basin is commonly the foredeep for the Apennines. Clastic material in the Apennines is provided not only by their ridge but also by the Alps and Dinarides surrounding the Adriatic plate. The average area of the elevated ridge of the Apennines above sea level, from the water divider eastward, is 40 km^2; the area of the foredeep is 180 km^2, so the ratio is 0.22:1. This ratio is always <1, as in all west-dipping subduction settings.

SUMMARY AND CONCLUSIONS

There appear to be global differences in the characters of foredeeps: Those related to west-dipping subduction have high subsidence rates (Fig. 1) and a steep basal monocline (up to 10°–20°). Those associated with east- or northeast-dipping subduction are shallower (1–5 km for ages of 10–20 m.y.), have lower subsidence rates (100–300 m/m.y. or less), and have a lower dip of the basal monocline (up to 5°–10°). In foredeeps associated with west-dipping subduction zones, subsidence rates are high and sediment supply rates from the associated accretionary wedge are low. In the foredeep linked to west-dipping subduction zones, the source of clastic sediments is the extensional, main uplifted ridge behind the accretionary wedge; very little comes from the accretionary wedge itself (Fig. 2). Foredeeps associated with east- or northeast-dipping subduction zones are in front of both frontal and back-thrust belts and have low rates of subsidence and high rates of sediment supply. Thus, in those settings, foredeeps are filled rapidly, the flysch deposits passing upward to the shallow molasse. These foredeeps are usually bypassed by clastic sediments from the orogen; the sediments are transported far away to remote deltas (e.g., the Rhone delta for the Alps, or the Ganges and Bengal deltas for the Himalayas). Apennine-type foredeeps tend to maintain deep-water conditions with abundant flysch deposits, owing to the high subsidence rates (Royden, 1993). Alpine-type foredeeps shallow upward more rapidly (flysch-molasse transition) and are bypassed by sediments because the rate of subsidence is insufficient to accommodate the high rate of clastic supply (Fig. 2). These differences may be explained by the different forces acting along opposite subduction zones, due to the global "westward" drift of the lithosphere relative to the asthenosphere (Fig. 3).

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