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Fold uplift versus regional subsidence and sedimentation rate

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Fold uplifts compete during their development with regional subsidence in the frontal parts of thrust belts and accretionary wedges. Two cases exist in frontal thrust belts. In the first, more common case, the uplift rate of the external folds is higher than the subsidence rate of the foredeep. In the second case the fold uplift is less than the regional subsidence. The total fold uplift may be considered as the fold uplift rate minus the regional subsidence rate; this value can be either positive or negative. Positive total fold uplift occurs when folds rise faster than regional subsidence and the envelope of the fold crest rises towards the hinterland of the accretionary wedge. In the opposite case, negative total fold uplift, the envelope dips towards the hinterland because folds rise more slowly than regional subsidence. In the first positive case, the folds are deeply eroded and the onlap of the growing strata moves away from the fold crest if the sedimentation rate is lower than the fold uplift rate in marine or alluvial environments. In the second negative case, where folds rise at lower rates than the regional subsidence, the onlap moves towards the fold crest if the sedimentation rate is higher than the fold uplift rate. This is also the more favorable case for hydrocarbon traps where growth strata can seal the fold. Moreover the fast subsidence rates in the foredeep provide a higher thermal maturation. This second tectonic setting is commonly associated with accretionary wedges forming along west-directed subduction zones, which are characterized by high subsidence rates in the foredeep or trench, due to the fast 'eastward' roll-back of the subduction hinge (e.g. Apennines, Carpathians, Banda arc). © 1997 Elsevier Science Ltd

Keywords: fold uplift; regional subsidence; sedimentation rate

This paper aims to be a preliminary discussion on the interplay between local fold uplift, regional subsidence, and the sedimentation rate within active-margin settings. Studies on fold development have generally omitted the tectonic and geodynamic settings in which they formed. In particular, the regional subsidence of the foredeep interferes with the frontal folds of thrust belts and decreases the amount of fold uplift. Fold uplift and regional subsidence can be computed relative to the geoid. In the first part we assume that other factors such as sedimentation rate and eustasy are constant. However, syntectonic sedimentation is strongly variable in terms of amount and composition at the front of thrust belts and accretionary prisms. Moreover eustasy is independent of fold uplift, regional subsidence and sediment supply. All these parameters interfere in a variety of settings (Zoetemeijer *et al.*, 1992; Hardy and Waltham, 1992). A simple model that relates the different parameters will be illustrated using regional examples mainly from the Apennines and from the Italian Southern Alps. It will be shown that this analysis has some potential applications to hydrocarbon exploration.

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Fold uplift versus regional subsidence

The evolution of fault-bend and fault-propagation folds has been quantitatively modeled by Suppe (1983), Mitra (1986), Mitra (1990) and Suppe and Medwedeff (1990). Their models show how the hinge zones of different fold types migrate mainly assuming layer-parallel simple shear. Furthermore Medwedeff (1989), Mount *et al.* (1990) and Suppe *et al.* (1992) have modeled the forward propagation of the eroded hinges during fold growth and the upward decrease in width of the kink bands within synfolding strata. The latter observation was stressed by Suppe *et al.* (1992) as a useful tool to date and quantify rates of folding and faulting. Recently Torrente and Kligfield (1995) have computed the evolution of buckle growth folds with different sedimentation rates. However fold and thrust analysis should also incorporate the differences that exist among thrust belts which may determine different tectonic and stratigraphic settings.

Doglioni (1992a) observed that generally thrust belts associated with west-directed subduction zones differ from thrust belts associated with east- or northeast-directed subduction zones. Foredeeps associated with deep and steep west-directed subduction zones have high subsidence rates and the associated accretionary wedge has a low elevation and mainly sedimentary rocks are involved. On the other hand, foredeeps associated with

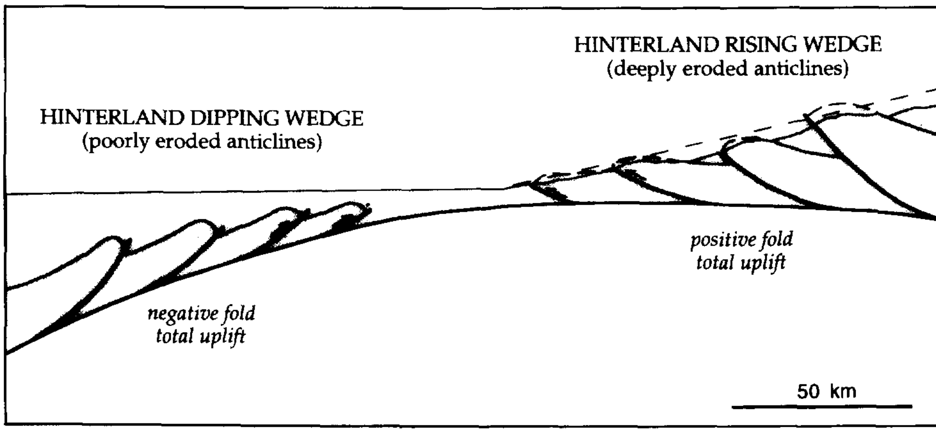

Figure 1 West-directed subduction zones can generate a hinterland-dipping wedge, characterized by well preserved growth anticlines above a steep basal decollement at the top of the regional basement, whereas east-directed subduction zones are mostly characterized by a hinterland rising wedge with deeply eroded anticlines and a regional basement with low dip. Compare *Figure 3* and *Figure 6* as end member examples

east- or northeast-directed shallow subduction zones have low subsidence rates, the associated orogen has a high elevation and thick slices of crustal metamorphic rocks are involved. These differences can be explained by the 'westward' drift of the lithosphere that implies a relative asthenospheric 'eastward' counterflow (Nelson and Temple, 1972; Doglioni, 1990; Ricard *et al.*, 1991). The asymmetry between west and east Pacific subduction zones has been interpreted in the past as controlled by the different age and density of the downgoing oceanic lithosphere. However we note that these differences exist even where the same lithosphere is subducting, e.g. the Ionian Mesozoic oceanic basin (de Voogd *et al.*, 1992) subducts almost vertically to the west down to about 550 km beneath the Apennines (Giardini and Velonà, 1991; Amato *et al.*, 1993), whereas below Greece it plunges at lower angles (15–30°) to the northeast at shallow depths (150–180 km, Christova and Nikolova, 1993). This global polarity controls the different behavior of the decollement planes along the opposite subduction zones, generating a variety of structural and lithologic variations in the two end-members. Imbricate thrust fans develop particularly in the external parts of accretionary wedges and the envelope to the fold crests may rise towards the hinterland or dip towards the hinterland (*Figure 1*), determining a hinterland rising wedge (HRW) or a hinterland dipping wedge (HDW). The hinterland rising fold crests envelope case is the typical situation in fold and thrust belts associated with east- or northeast-directed subduction zones both in the frontal thrust belt (e.g. Western Alps, Dinarides, Himalayas, Western Cordillera) and in the back-thrust belt (e.g. Southern Alps, Balkans, Pamir, Rocky Mountains, Doglioni, 1992a, 1994). The hinterland dipping fold crests envelope case (HDW) may be found in accretionary wedges related to west-directed subduction zones (e.g. Apennines, Carpathians, Banda Arc). Examples for the Apennines can be found in Pieri (1983), Schwander (1989) and Doglioni (1993); for the Carpathians in Roure *et al.* (1993) and for the Banda Arc in Crostella and Powell (1976). In the HRW case, folds are uplifted and deeply eroded whereas in the HDW case, they may be only partly eroded by sea-level falls, and they are associated with trenches or foredeeps up to several kilometers deep (*Figure 1*). These differences can be explained on a global scale as due to the westward drift of the lithosphere which is detected also in the hot-spot reference frame. This relative lithospheric drift with respect to the asthenosphere causes two different origins of foredeep basins (Doglioni, 1992a, 1994). Along east-northeast-directed subduction zones the orogenic load combined with the downward component of motion of the upper plate appear to be the main forces generating the basin. These forces contrast with the upward component of the relative 'eastward' asthenospheric flow which tends to sustain the overlying plates. Along west-directed subduction zones, the relative 'eastward' asthenospheric flow appears to be the main force acting on the foreland slab, determining its rollback and the consequent subsidence at the subduction hinge. In this case the push provided by the mantle is added to the slab pull and the lithostatic load. A strong asymmetry of geologic parameters is observed between foredeeps related to west-dipping subduction, and foredeeps related to east-northeast-dipping subduction. In the west-dipping case the area of the foredeep (filled or unfilled) is wider than the area of the mountainous ridge, whereas the foredeep areas are smaller in the east-northeast-dipping case (Doglioni, 1994). The west-dipping subduction zones have now, and in the past, the fastest subsidence rates and the deepest foredeep basins and trenches in the world, whereas paradoxically the foredeeps and trenches with the lowest subsidence rates are those associated with east-northeast dipping subduction zones which have the highest mountain ranges. This explains why foredeeps and trenches associated with west-directed subduction maintain deep marine environments for long periods of time, whereas the same basins associated with east- or northeast-directed subduction rapidly shallow upward changing from flysch to molasse facies.

Different geometries may develop in beds laid down contemporaneously with the imbricate fans in the frontal portion of accretionary wedges. In particular the onlap patterns generated in growth folds in different geodynamic environments can be distinguished. For example, within the Po Plain (*Figures 2 and 3*), an accretionary wedge related to west-directed subduction under the Apennines is buried beneath Pliocene to Quaternary clastic sediments (*Figure 3*). This foredeep is characterized by a high subsidence rate (up to about 1500 m My^{-1},

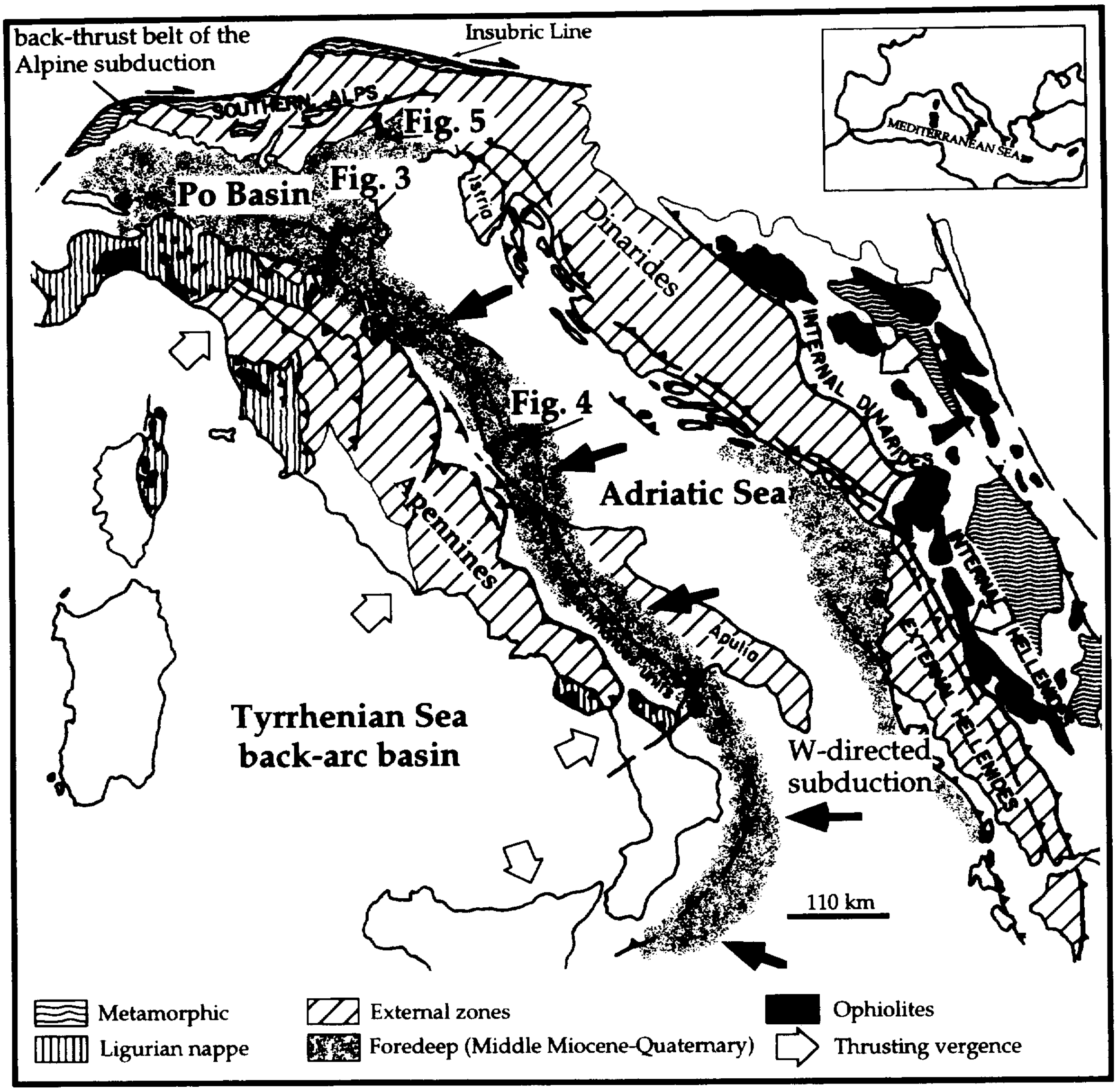

Figure 2 Tectonic sketch map of the Italian region, modified after Schwander (1989) and Bernoulli (1972)

Doglioni, 1993) and by an envelope to the fold crests dipping towards the hinterland. On all the anticlines of the accretionary wedge, the onlaps of the syntectonic sediments have a general trend of migration towards the fold crest, going up section, apart from opposite episodes likely generated by eustatic fluctuations. We infer that the rising anticlines were outpaced by regional subsidence, which created accommodation space for the syntectonic sediments.

In the Po Plain, a broad estimate of the fold uplift rate can be made using the age of the syntectonic sediments. Typically, a single fold of 1–3 km amplitude grew in an interval of 0.5–5 My (*Figure 3*), yielding an average uplift velocity there of 0.5–2 mm y^{-1}. These values are interpreted on the basis of the age range of the synfolding sediments. It must be pointed out that during their early development, folds may rise at higher velocities (up to 20 mm y^{-1}; Rockwell *et al.*, 1988), especially those located in transpressive regimes.

A similar geometry is displayed by the accretionary wedge of the Apennines in the central Adriatic sea (*Figure 4*, after Schwander, 1989). Like the previous example, the hinterland-dipping wedge is characterized by a fold uplift rate lower than the regional subsidence rate. Therefore no erosion occurred on the fold hinges and crests, which were uplifted well below sea-level. The syntectonic deposits, deep-sea turbidites of Pliocene age, covered the anticlines and the marine onlap migrated towards the fold crests. In both the Po Plain and in the Adriatic sea (*Figures 3 and 4*), the sedimentation rate was high because most of the clastic supply was sourced from the elevated Alpine chain and the Apenninic foredeep was thus rapidly filled by deep-sea to deltaic sediments. Since the sedimentation rate was higher than the fold total uplift (fold uplift minus the regional subsidence), the onlaps of the growth strata therefore migrated towards the fold crest.

A completely different relationship between fold uplift and regional subsidence rates may be inferred in the eastern part of the Southern Alps (*Figure 2*). This mountain chain represents the back-thrust belt of the main Alpine accretionary wedge, related to a east-directed subduction zone. The east–west trending central–eastern Alps are generally considered to be the dextral transpressive lateral ramp of the subduction zone (Laubscher, 1988, 1992), whereas the arc-shaped geometry of the western Alps represents the frontal ramp of the east-directed subduction zone. Therefore the deformation within the back-thrust belt is partitioned between dextral strike-slip move-

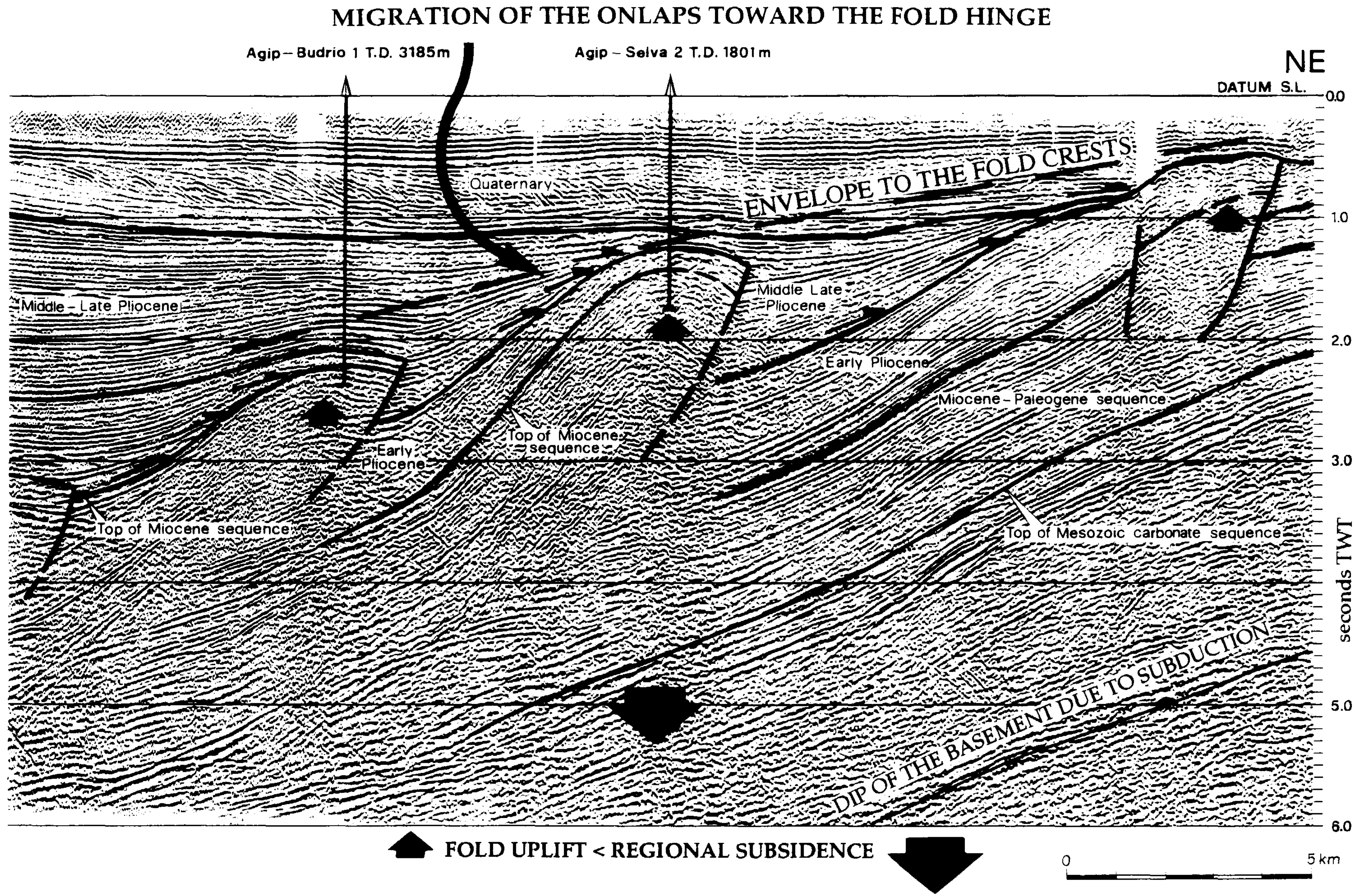

Figure 3 Example of fold uplift rate lower than the regional subsidence rate in a classic seismic section of the Po Basin in northern Italy. It shows the accretionary wedge associated with the Apenninic subduction zone. Note the steep dip of the basement. The subsidence rate of the basement was higher than the uplift rate of the folds and consequently the onlaps of the growth strata generally migrated towards the fold crests with time. Note the hinterland dipping envelope of the folds. This is an example of a hinterland dipping wedge. Seismic section after Pieri (1983). Location of the section is shown in *Figure 2*

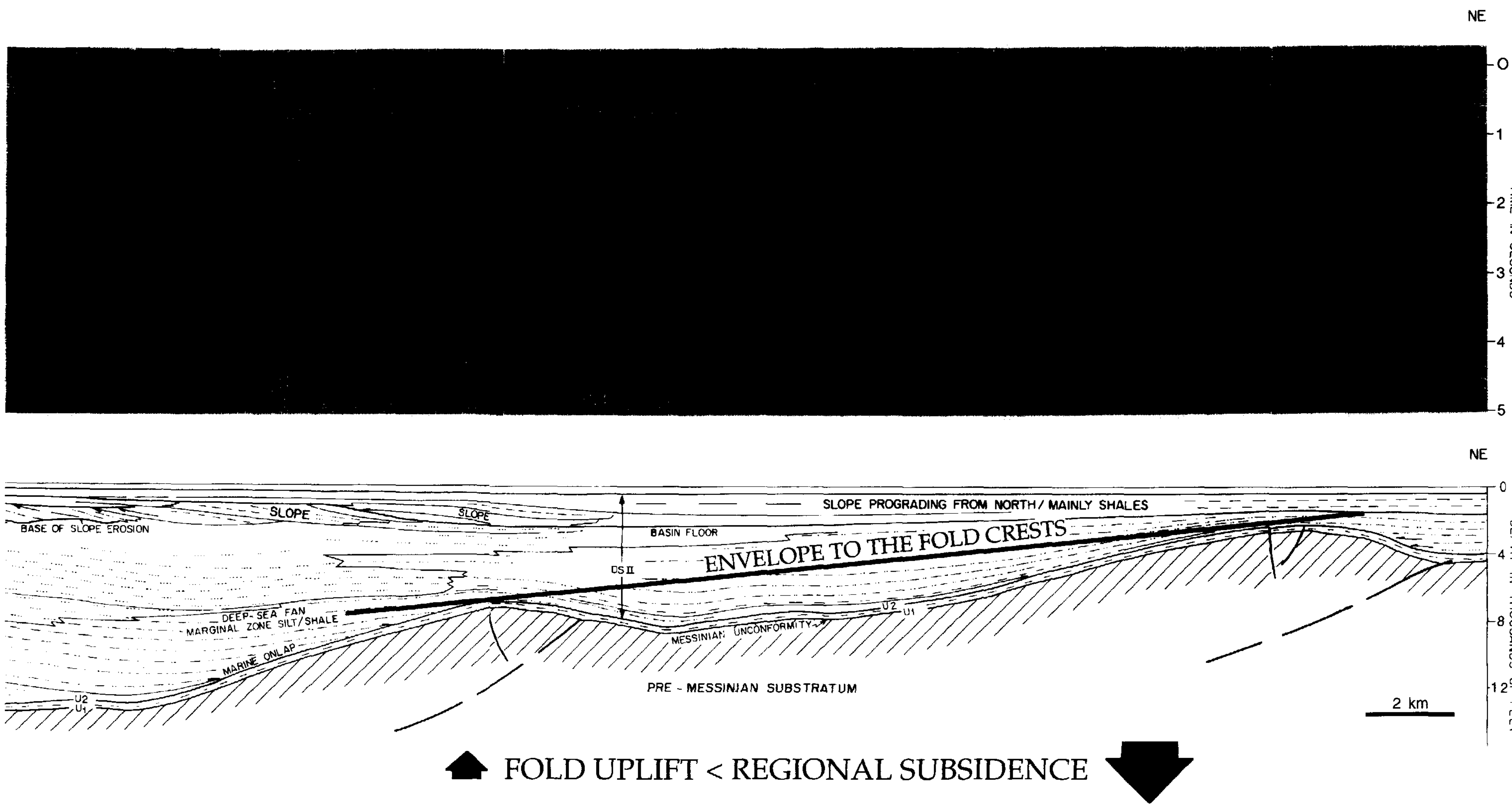

Figure 4 The hinterland-dipping wedge of the Apennines below the Adriatic Sea. The anticlines display no erosion and a marine onlap migrating towards the fold crests up-section. Seismic section and interpretation modified after Schwander (1989). Location of the section is shown in *Figure 2*

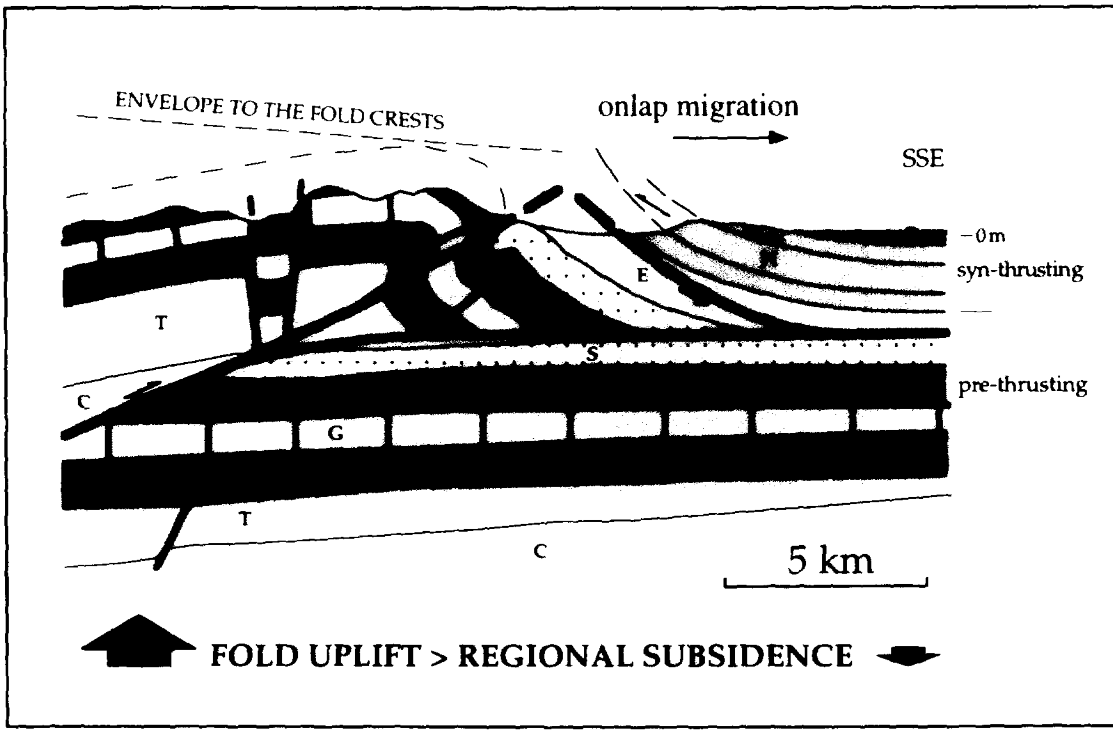

Figure 5 Progressive unconformity within the Upper Miocene–Quaternary continental deposits along the main front of the eastern Southern Alps. The fold crests envelope (only partly represented here: for a complete view of the section, see Doglioni, 1992b) is rising toward the hinterland. Abbreviations: C, Crystalline Hercynian basement; T, Late Permian–Lower and Middle Triassic formations; P, Late Triassic (Dolomia Principale); G, Jurassic basinal facies (Soverzene Formation, Igne Formation, Vajont Limestone, Fonzaso Formation, Ammonitico Rosso); B, Early Cretaceous (Biancone); S, Late Cretaceous (Scaglia Rossa); E, Paleogene (Possagno Marls, etc.); N, Late Oligocene–Neogene Molasse, including Tortonian and Messinian conglomerates and sandstones; Q, Quaternary. Location of the section is shown in *Figure 2*

ments along the Insubric line and SSE-verging thrusts. The frontal thrust of the eastern Southern Alps (*Figure 5*) exhibits a triangle zone, which is progressively covered by syntectonic deposits. The dip of the Tortonian conglomerates and sandstones exposed in the forelimb of the anticline decreases towards the foreland (Massari, 1978) and their onlap moves southward, away from the fold crest. Moreover the anticline is exposed and deeply eroded, indicating that the fold uplift rate was higher than the regional subsidence rate. The erosion is syntectonic as demonstrated by the composition of the Upper Miocene conglomerates that include the sedimentary succession exposed in the anticline.

Another example of onlap migrating away from the fold crest may be seen in the external folds of the active Cascadia accretionary wedge, an hinterland rising wedge related to the eastward-dipping subduction of the Juan de Fuca plate underneath the North American plate (*Figure 6*). In this area the regional subsidence is clearly lower than the fold uplift rates (see sections and maps by Clarke, 1992 and Hyndman *et al.*, 1993). These types of accretionary wedges may become exposed later and eroded and therefore growth geometries on the fold limbs are often lost. Therefore the regional subsidence rate of the foreland areas may be either lower or higher than the single fold uplift rate.

We might consider the fold total uplift as the single fold uplift rate minus the regional subsidence rate. This value can be either positive or negative. *Figure 7* illustrates this relationship and tentatively differentiates the two different tectonic fields during a steady state temporary moment of the evolution of the frontal Apennines and Southern Alps. In a foredeep where the basin margin slopes gently, the regional subsidence rate is lower than the fold uplift rate, i.e. regional subsidence rate of 0.1 mm y^{-1} (Doglioni, 1993), compared to fold uplift rate of 0.5–2 mm y^{-1}. In this classic case of positive fold total uplift the synsedimentary folds grow upward and the onlap of the sediments moves away from the fold crest if the sedimentation rate is also lower than the fold uplift (*Figure 8*). This latter condition may be present in both marine and alluvial environments. When the sedimentation rate in a marine environment is larger than the fold uplift, this generates a migration of the onlaps towards the crest zone even in a foredeep with gently dipping lower basin margin, where the general trend would be of onlaps moving away from the fold crest. This geometry is often eroded during the emergence of the fold or during a later sea-level drop in a coastal or alluvial environment where the syntectonic sediments may be cannibalized.

In the case where the regional subsidence rate is higher than the single fold uplift rate in deep foredeeps, the fold total uplift is negative. This trend implies subsidence and generation of accommodation space for syntectonic sediments (*Figure 9*). Within such a tectonic environment, the onlaps migrate towards the crest zone (*Figure 10*), providing the sedimentation rate is higher than the total fold uplift rate (*Figure 8*). Usually in deep foredeeps the regional subsidence rate is about 1–1.5 mm y^{-1}, often higher than the fold uplift rate (0.5–1 mm y^{-1}). On the other hand, the sedimentation rate may be higher (3 mm y^{-1}, e.g. in the Pescara basin along the Apenninic Adriatic foredeep), or lower (<0.1 mm y^{-1}, e.g. in the Mariana trench). The fold total uplift may vary during the history of a single fold from negative in the frontal

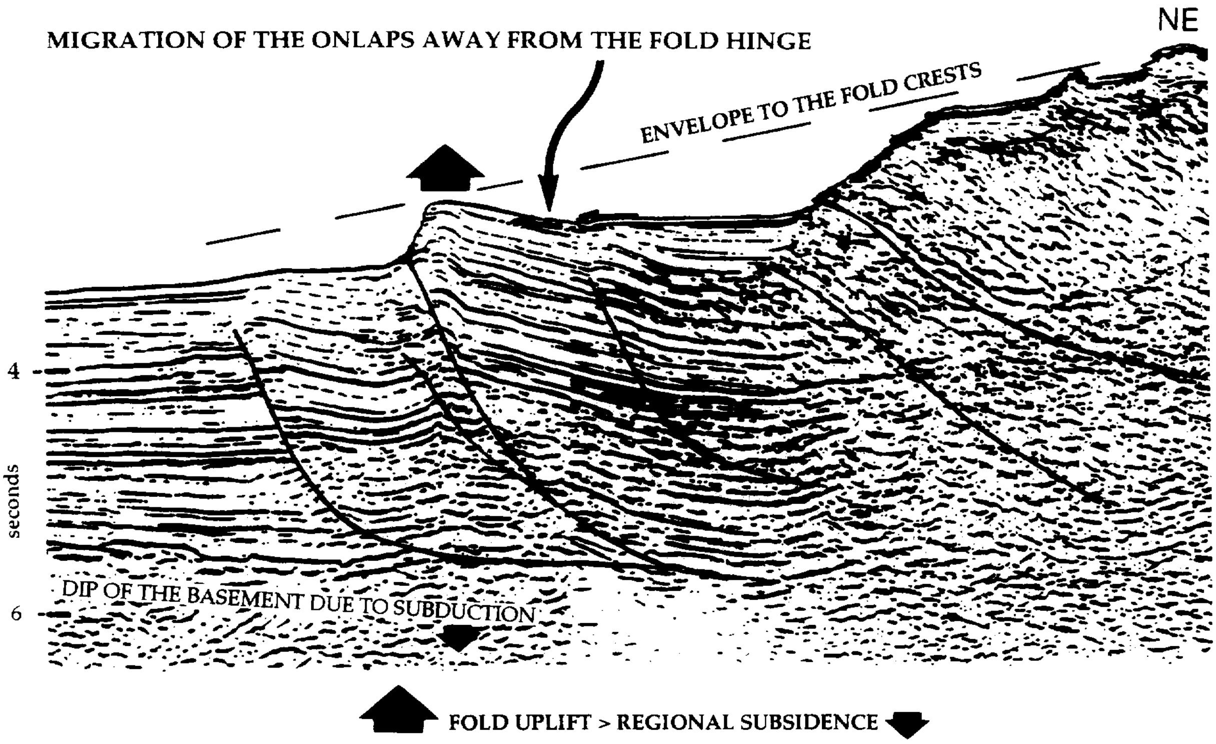

Figure 6 Example of fold uplift rates higher than the regional subsidence in the Cascadia prism offshore Vancouver Island. It shows the frontal thrusts and folds of the accretionary wedge associated with the Cascadia east-directed subduction zone. Note the minor dip of the basement compared to the west-directed subduction zone (*Figure 4*). The subsidence rate of the basement was lower than the uplift rate of the folds and therefore the onlaps of the growth strata migrated away from the fold crest. This situation is the least likely to be preserved because growth strata terminations are rapidly eroded during uplift, when both subaerial and submarine erosion may take place. Note the hinterland rising envelope of the folds. Seismic section after Hyndman *et al.* (1993)

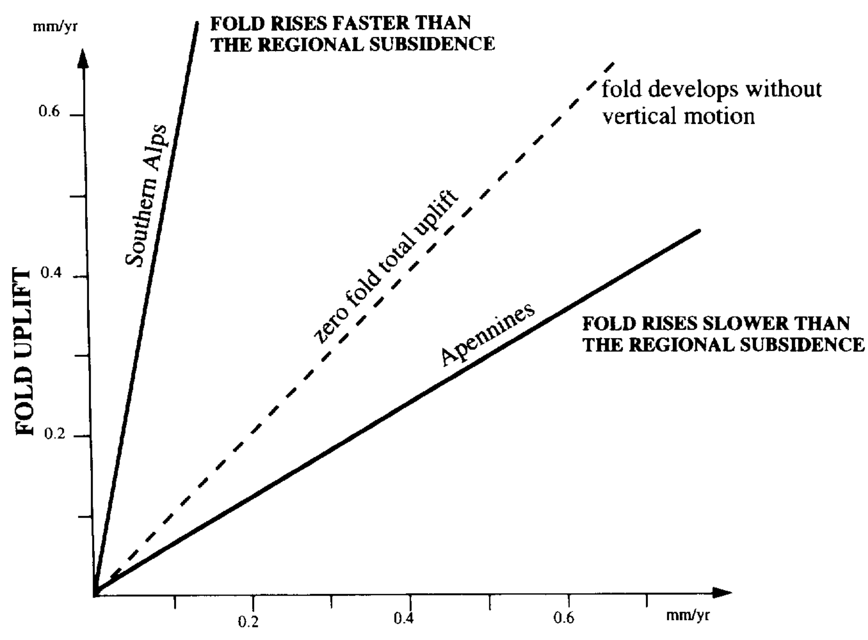

Figure 7 Fold uplift rate versus regional subsidence rate of the foredeep generates two fields in which one of the two parameters relatively prevails. The fold total uplift rate may be considered as the fold uplift rate minus the regional subsidence rate. The fold total uplift may be either positive or negative. The intermediate line represents the case in which the two parameters are equal and the fold develops without any vertical motion

parts, to positive more internally, where the fold and related thrust are detached and transposed in areas of lower regional subsidence rate.

Folds which grew faster than the regional subsidence rate, and were later covered by syn- to post-tectonic sediments, occur in the Pyrenees (Riba, 1973; Anadón *et al.*, 1986; Mutti *et al.*, 1988; Puigdefàbregas *et al.*, 1992; Hardy and Poblet, 1994). This thrust belt, formed by the rotation of the Iberian plate during late Cretaceous and early Tertiary time, shows some of the characteristics of an alpine-type orogen, i.e. wide involvement of basement, and a gently dipping base of the foredeep. Pyrenean folds

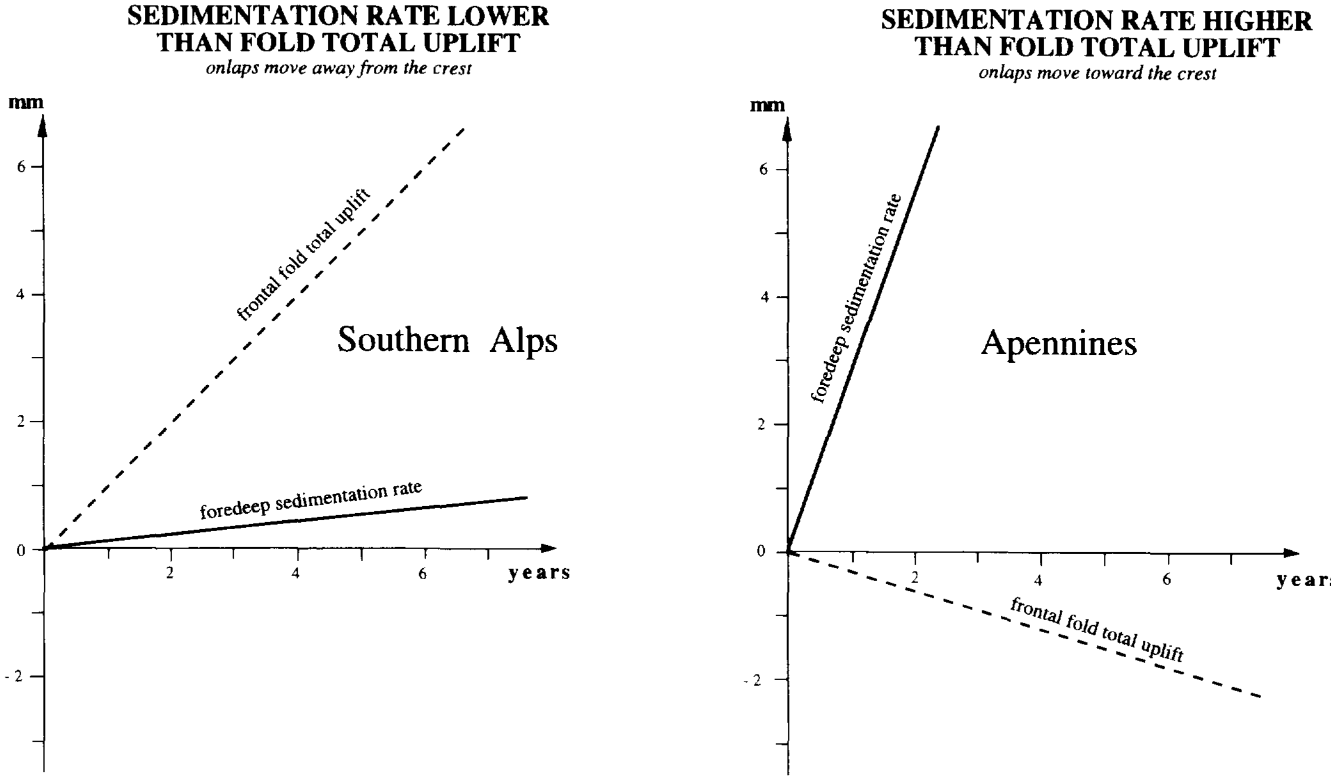

Figure 8 Sedimentation rate can be lower (e.g. Southern Alps) or higher (e.g. Apennines) relative to the fold total uplift of a given frontal structure of a thrust belt. In the first case the onlaps of the growth strata move away from the crest of the fold, whereas they migrate towards the fold crest in the second case

are draped by syntectonic alluvial deposits which display complicated onlap patterns. During early uplift, the onlaps moved away from the fold crest (Riba, 1973), which may be deeply eroded. Afterwards, when the fold stopped growing, the onlaps migrated up-section in the opposite direction. The kinematics of fault-bend folding (Suppe, 1983) and of progressive limb rotation (Hardy and Poblet, 1994) predict a decrease or cessation of the fold uplift rates at given geometric constraints. At the stage of arrival of the lower flat of the hangingwall of a thrust onto the upper flat of the footwall in a fault-bend fold, the kinematics show only forward propagation of the fold without any further uplift needed, at constant fault slip rates. When a fold finally stops growing upward, the onlaps will migrate towards the fold crest zone if the following conditions are met: (i) subsidence created sufficient accommodation space, or original thin crustal thickness determines a pre-existing basin; (ii) the sedimentation rate exceeds the regional subsidence rate; (iii) sea-level fall does not drop faster than the regional subsidence in coastal or alluvial environments.

Once a fold is deactivated it may be buried and passively transported at depth by west-directed subduction and later uplifted by normal faulting or, sometimes, by out-of-sequence thrusts. In east-dipping subduction it may be finally uplifted by deeper thrusts. On the other hand, a transgression of the same order of magnitude as the fold uplift generates a migration of the onlaps towards the crest zone even if the general trend of migration is away from the fold crest. This geometry is generally eroded during fold uplift or later regression and the syntectonic sediments may be cannibalized.

The occurrence of lateral facies variations within syntectonic deposits is mainly related to the superficial effects of a growing fold. However if the sedimentation rate exceeds the tectonic uplift rate, the topography is gradually levelled. In the opposite case, the irregular topography will be more and more enhanced by a sedimentation rate lower than the tectonic uplift.

Tectonics and eustasy

Subsidence or uplift rate versus sedimentation rate is an important parameter in discriminating tectono-sedimentary settings in different types of geodynamic environments. The long-standing debate about the relative importance of tectonics and eustasy in controlling sedimentation has generated significant research in the last several decades. Important insights have been developed by studying passive margins where no significant tectonic movements took place in the last 30 Ma, e.g. the New Jersey transect (ODP Legs 150, Mountain *et al.*, 1994), and comparison with areas where sedimentary sequences of similar Tertiary age are affected by deformation.

If eustasy is superposed on the local tectonic evolution, the onlap pattern may be influenced by sea-level variations, whether the regional subsidence rate is higher or lower than the local fold uplift (*Figure 7*). Several orders of sea-level fluctuation may be superposed on the tectonic movements; where the onlaps migrate towards the crest of a fold driven by subsidence, this migration will be a general trend, but within it sea-level fluctuations of 3rd, 4th or 5th order can generate intervals of sea-level fall in which the onlaps migrate away from the crest.

The stratigraphy of a growth fold depends on whether the fold grows in a deep marine environment or in a coastal environment (Torrente and Kligfield, 1995). In a deep marine environment, a low stand is recorded by the

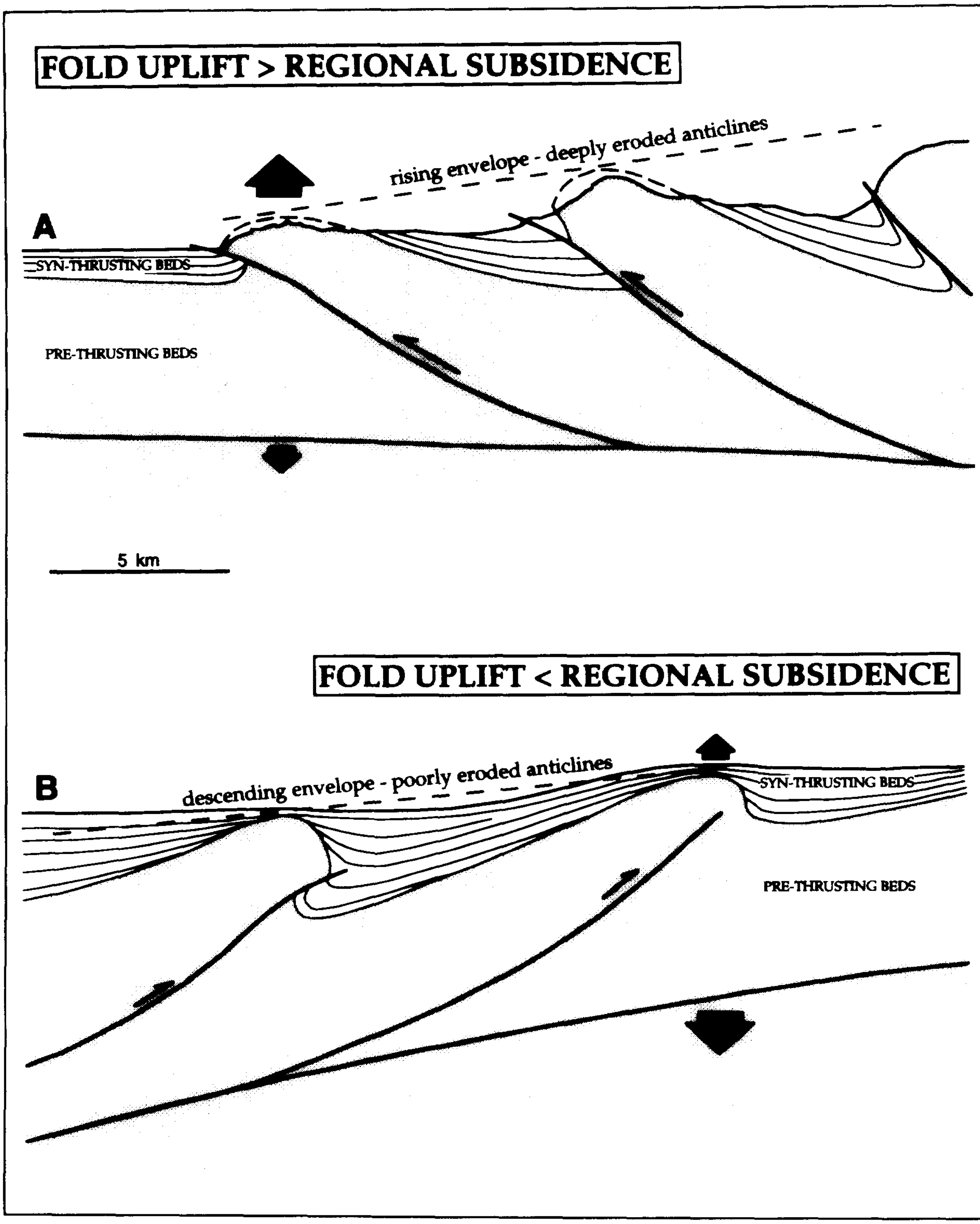

Figure 9 Fold uplift rates may be higher or lower than the regional subsidence of the foredeeps. In the classic case A, the envelope of the fold crests is rising towards the hinterland, and the anticlines are deeply eroded. In case B, the fold uplift rate is lower than the regional subsidence rate, as a result of which, the envelope to the fold crests descends towards the hinterland and the anticlines are not significantly eroded

larger arrival of clastics which may generate a migration of the onlap towards the fold crest. By contrast, in a coastal environment, a sea-level drop determines greater erosion and migration of the onlap of the growth strata away from the fold crest.

What is the uplift trend of a fold? Does it rise at stable rates or does it uplift episodically? Orogenic development correlates with plate velocities, that in general do not vary greatly as indicated by stable rates of sea-floor spreading (Hsü, 1992). Therefore uplift rates may be considered constant, at a given shortening rate, for the growth of any type of fold, but they may change during time, especially in transpressive regimes (Rockwell *et al.*, 1988). Folds are single features with their own history which is clearly one part of a more long-lived and continuous foreland propagating thrust belt. The growth of a tectonic structure, such as an anticline, may occur during any tract of a third-order cycle (low stand, transgressive, high

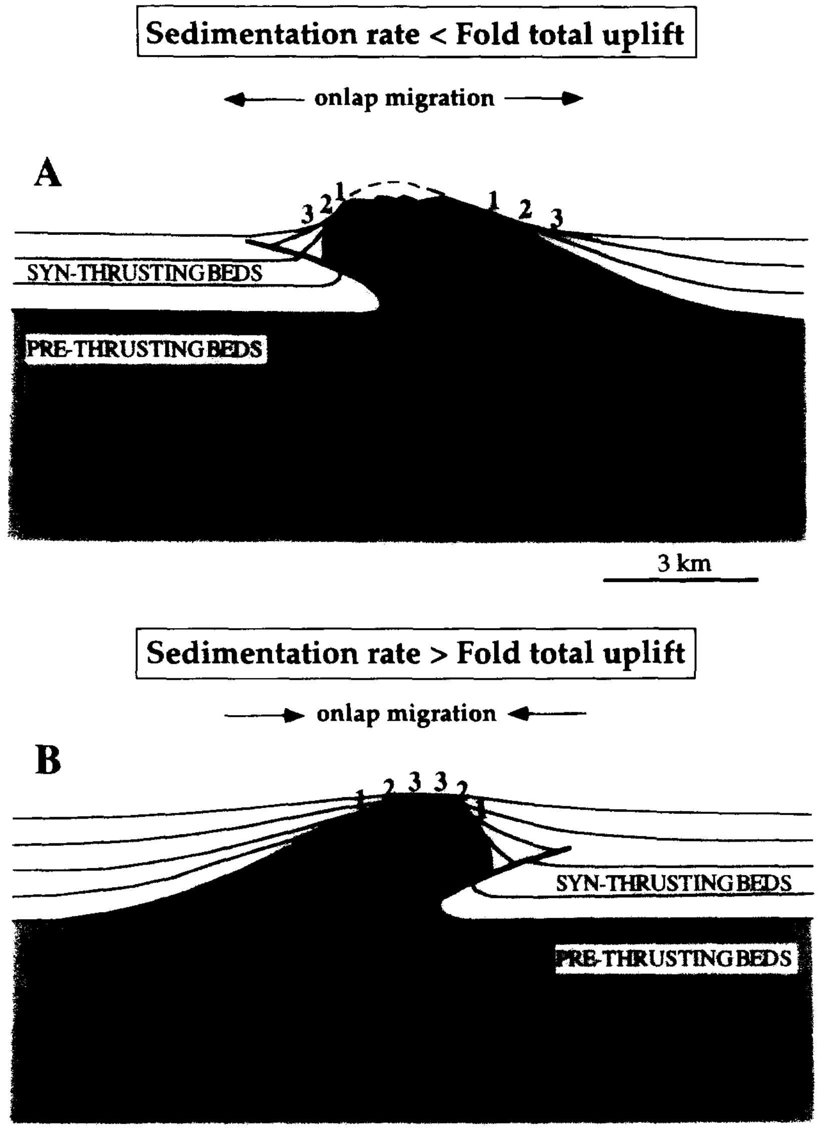

Figure 10 Where the fold uplift rate is greater than the regional subsidence rate, the onlaps of the syntectonic beds move away from the fold crest, and the sedimentation rate is lower than the fold total uplift (A). On the other hand, onlaps may migrate towards the fold crest where the fold uplift rate is less than the regional subsidence rate, and the sedimentation rate is higher than the fold total uplift (B). The two end members may alternate on the limbs of a fold when for instance in B, the fold uplift is lower than the regional subsidence, but the sea-level drops at higher rates exposing the fold

stand) and consequently the sedimentation patterns are a function of the random interaction between uplift rates and sea-level fluctuations.

Syntectonic sedimentation and erosion may be analyzed as a function of the relative fold uplift (i.e. the fold uplift decreased by the regional subsidence) and sea-level oscillations. During low stands, rates of uplift and eustatic sea-level fall combine to produce a relative sea-level fall. The erosion of the anticline may be at a maximum during this time interval if the fold is exposed above the sea-level in a foredeep with low subsidence rate and low dip of the foredeep base. During transgression, the effects of uplift may be partly or totally compensated by sea-level rise, and sea-level may remain almost constant relative to the growing anticline. Therefore fold erosion may proceed at very low rates during this time interval. The sediments deposited during the high stand lie unconformably on the fold limbs after a time of little or no deposition, representing the intermediate case in which the relative uplift rates of the fold are only in part or not compensated by sea-level rise. During the high stand, the erosion rate of a fold exposed above the sea-level is intermediate between the low-stand and the transgressive system tracts. Therefore every fold has a different history and a peculiar relationship to sedimentation as a function of how and when the sea-level fluctuations relate to the fold uplift rate. Furthermore this latter feature depends on four main variables: the geodynamic environment (i.e. west- or east-directed subduction), the shortening and related uplift rate, and the rheology of the deformed rocks which controls the distance between the thrust-ramps, the fold geometry and kinematics.

The onlap pattern and amount of erosion at the fold crest may result from the random superposition of the factors discussed above. Therefore, distinguishing between eustatic and tectonic controls on the syntectonic sedimentation may be sometimes difficult, if only one single fold is considered. The eustatic versus tectonic geometries can be worked out if a larger trend of onlap migration can be discerned on a regional basis, such as in the Po Plain (*Figure 3*). Therefore it is necessary to analyze the sedimentary evolution of a thrust-and-fold belt as a whole in order to recognize a general trend of onlap migration.

Possible hydrocarbon application

Folds with negative total uplift have larger potential for hydrocarbon traps with respect to folds developing with positive total uplift. They rise more slowly than the regional subsidence and are transported at depth and heated while they form. When they are associated with sedimentation rates of the growth strata higher than the fold total uplift, the growth strata migrate towards the fold crest and may provide seals to the structure. Petroleum exploration in Italy has been particularly successful in the Apenninic foredeeps, which are often characterized by negative fold total uplift, and sedimentation rates higher than the fold total uplift (*Figures 3 and 8*). Italian gas reserves are primarily found in Pliocene sand reservoirs of the Apenninic foredeep in structural traps formed by the external folds (Po Plain, Adriatic sea, Bradanic trough, Pieri and Mattavelli, 1986). The oil and part of the gas are mainly derived from black shales of Middle and Upper Triassic, and lower Liassic age. According to Pieri and Mattavelli (1986), petroleum generation began during the Mesozoic in the deepest parts of these basins, and heavy oil migrated into the adjacent Mesozoic carbonate platform reservoirs. Condensate and wet gas originated in the areas of major Tertiary subsidence and migrated into Neogene clastic reservoir often located in fold cores.

Conclusions

The stratal architecture at the front of thrust belts is a function of local factors, such as fold uplift, the regional subsidence rate, sedimentation rate and the eustatic history. The fold total uplift may be considered as the single fold uplift minus the regional subsidence. Therefore the fold total uplift can be either positive or negative, depending on whether the regional subsidence is lower or higher than the fold uplift. Negative fold total uplift means that in spite of folding and thrusting, the accretionary wedge subsides and generates accommodation space, unlike an outcropping mountain range. This occurs particularly in frontal thrust belts associated with west-directed subduction zones where the foredeep subsidence is controlled not only by the load of the thrust sheets, but is also incremented by the eastward rollback of the subduction hinge generated by relative eastward asthenospheric flow and slab pull (Doglioni, 1993).

The onlap of strata on limbs of growth folds migrates towards the fold crest if the sedimentation rate is higher than the fold total uplift. This is easier where the fold total uplift is negative and the system generally subsides providing accommodation space. This case may be frequently found within hinterland-dipping wedges related to west-dipping subductions. Conversely, where the fold total uplift is positive, the onlaps of the growth strata gradually migrate away from the fold crest in the common case of sedimentation rate lower than the fold total uplift. This is typical of east- or northeast-dipping subduction that has orogens mainly developed onshore. These general trends are complicated by sea-level oscillations and by variations in sedimentation rate. Eustasy independently interferes with the two end-members (HDW and HRW) determining temporary enhancements or lowering of the onlap migration during eustatic high-stand or low stand. Therefore it is possible to separate eustasy and tectonics where a general onlap pattern is recognized in several folds within a single thrust belt. This would be a first-order analysis in the discrimination of the tectonic signal with respect to the several orders of eustatic fluctuation. Variations in sedimentation rate may produce variations in the onlap pattern too, if enough accommodation space is present for the syntectonic deposition.

Tectonics controls the superficial topography only if sedimentation rates are lower than the velocity at which the local tectonic movements take place. This relationship may be observed by considering the uplift rate of an anticline and the sedimentation rate. Consequently, the facies types of the syntectonic deposits will not change across a growing tectonic structure if the sedimentation rate is faster than the local uplift rates.

We finally suggest the two following statements: (i) the ratio between local fold uplift and regional subsidence can be higher or lower than 1. Higher than 1 means a positive fold total uplift (HRW), and lower than 1 indicates a negative fold total uplift (HDW) (*Figures 7 and 9*); (ii) the ratio between sedimentation rate and fold total uplift can be higher or lower than 1. Higher than 1 determines migration of the onlaps of the growth strata towards the crest of the fold and gradual levelling of the tectonically induced topography. Lower than 1 generates migration of the onlaps away from the crest of the fold and enhances the tectonically induced topography (*Figures 8 and 10*). The geometry of the syntectonic deposits may be used to discriminate between the different accretionary wedges and thrust belts.

Growth folds progressively covered by syntectonic deposits may represent potential hydrocarbon traps, particularly if they are located within a deep foredeep, characterized by sedimentation rates higher than the fold total uplift rate.

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