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Normal faulting vs regional subsidence and sedimentation rate

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Abstract

Normal faults occur in a variety of geodynamic environments, both in areas of subsidence and uplift. Normal faults may have slip rates faster or slower than regional subsidence or uplift rates. The total subsidence may be defined as the sum of the hangingwall subsidence generated by the normal fault and the regional subsidence or uplift rate. Positive total subsidence obviously increases the accommodation space (e.g., passive margins and back-arc basins), in contrast with negative total subsidence (e.g., orogens). Where the hangingwall subsidence rate is faster than the sedimentation rate in cases of both positive and negative total subsidence, the facies and thickness of the syntectonic stratigraphic package may vary from the hangingwall to the footwall. A hangingwall subsidence rate slower than sedimentation rate only results in a larger thickness of the strata growing in the hangingwall, with no facies changes and no morphological step at the surface. The isostatic footwall uplift is also proportional to the amount and density of the sediments filling the half-graben and therefore it should be more significant when the hangingwall subsidence rate is higher than sedimentation rate.

Keywords: Extensional tectonics; Regional subsidence; Uplift; Sedimentation rate

1. Introduction

Extensional environments and associated normal faults are usually regarded as a class of tectonic features (e.g., Bally, 1983; Suppe, 1985), whatever their origin. This paper considers geodynamic setting and sediment supply as two factors that independently interfere with normal faulting, thereby giving rise to a variety of geological architectures. This statement might appear as obvious. However, while the interplay between normal faulting, geodynamics and sedimentation is fairly well understood, normal faults continue to be reported in the literature as a single class of tectonic features, in spite of very different regional associations of their independent parameters. Normal faults develop in numerous and different tectonic environments, such as passive continental margins, back-arc basins, intraplate rifts, etc. Normal faults are also associated with orogenic wedges or convergent zones in general, and they may form both during and after subduction. Each tectonic environment, where normal faults occur, may have particular subsidence rates (or uplift rates), different depth and meaning of the decollement planes, and a particular timespan of activity. Therefore different fluids may circulate along fault planes, depending on regional context, geothermal setting, etc. At least nine different types of convergent geodynamic settings generate syn- or post-subduction normal faults (Doglioni, 1995). Moreover, each geodynamic setting has its own sedimentation rates. This paper suggests a better definition of the interplay between the slip rates of single normal faults, the regional subsidence or uplift rates at which the faults develop, and the sedimentation rates of a given area, as has been done for convergent settings (Doglioni & Prosser, 1997). Therefore, apart from eustasy and climate, the above three parameters interfere with each other, thus generating a number of different relationships. This paper represents a preliminary approach to the interplay between these three factors, which may explain a number of geological observations, e.g., the generation of morphological gradients, facies changes, and differential footwall uplift rates. Field examples from the Southern Alps and seismic lines of other areas illustrate both facies changes and mere thickness variations across syn-sedimentary normal faults.

2. Normal faulting vs regional subsidence or uplift

The subsidence of the hangingwall of a normal fault is associated with the regional setting, which may have

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variable subsidence or even uplift rates. Regional subsidence may be tectonic or thermal in passive margins and back-arc basins (Tankard & Balkwill, 1989; Kastens et al., 1988). Regional uplift may be due to orogens or other geodynamic settings which experience uplift. The total normal fault subsidence may be defined as the single normal fault hangingwall subsidence rate and the regional subsidence or uplift rate (Fig. 1). Therefore, the total subsidence can be either positive or negative. It is positive when the fault subsidence is incremented by the regional subsidence, and it is negative when the normal fault subsidence is exceeded by a faster regional uplift. When the total normal fault subsidence is positive, the fault subsidence may be either faster or slower than the regional subsidence, or it may be faster than the regional uplift. When the total subsidence is negative, the regional uplift is clearly higher than the fault subsidence. The geoid may be taken as a reference line.

Single normal faults may have variable vertical slip rates, depending on hierarchy (e.g., length), dip, and geodynamic setting in which they arise. Although the vertical slip rates of single faults are variable, this paper assumes an almost constant velocity of about 0.2 mm/year for the sake of simplicity. This value was computed as an average of multiple growth faults. For a recent review of normal faults slip rates see Ravnås and Steel (1998). Single hangingwall subsidence has to be added to or subtracted from the regional subsidence or uplift rates which are deter-

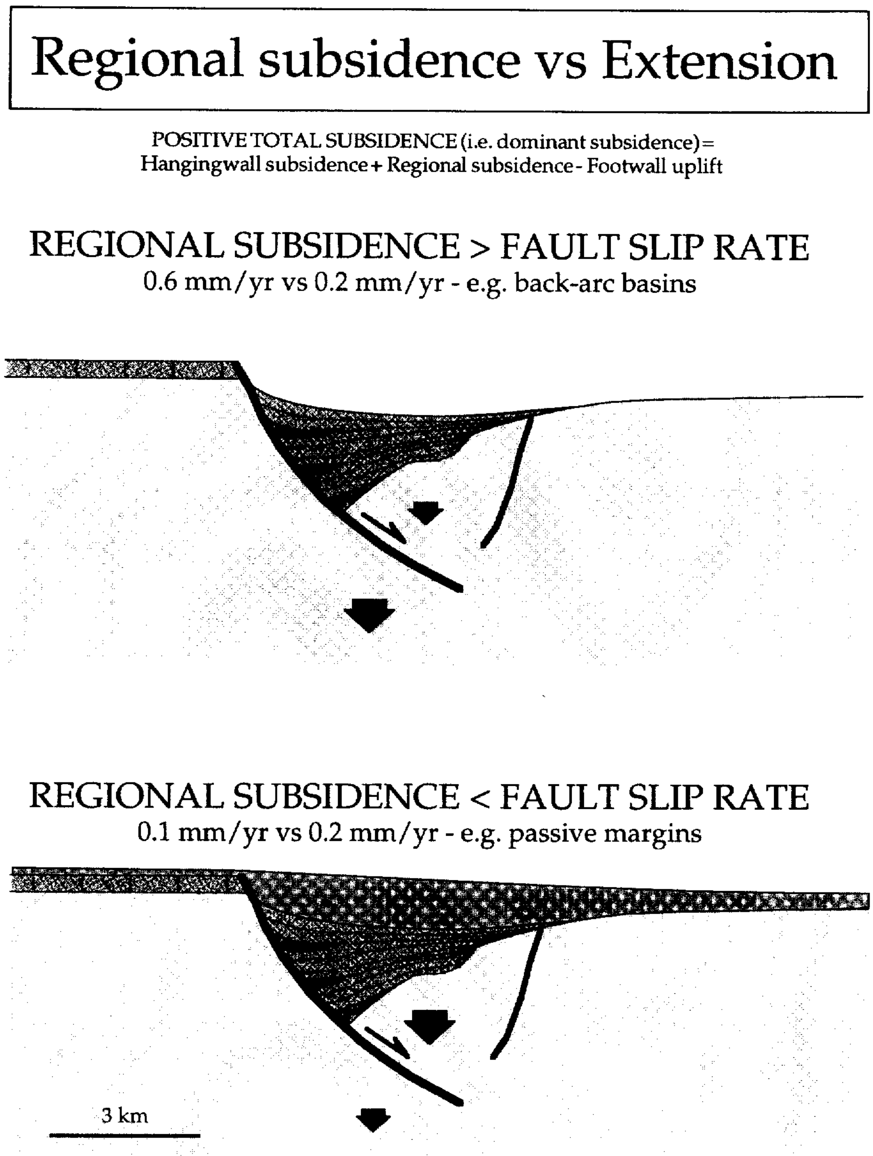

Fig. 1. Regional subsidence may be faster or slower than the fault slip rate. Regional subsidence is faster in back-arc basins with respect to passive continental margins. This might enhance an initially faster deepening-upward of the sedimentary succession in back-arc settings.

mined by the geodynamic framework. For instance, the Pliocene–Quaternary grabens of the Apennines belt were formed during a general uplift of the chain; instead, the grabens of the Tyrrhenian back-arc basin developed during times of very fast regional subsidence rates. Subsidence rates are usually very different in passive Atlantic-type margins (0.1 mm/year) with respect to back-arc settings, which feature much faster subsidence rates occur (up to 0.6 mm/year, Doglioni, 1995). Therefore, single normal faulting-related subsidence (e.g., 0.2 mm/year) may be lower or higher than regional subsidence (Fig. 1). In the first case, deepening-upward sequences may result from the generalised high rate of positive total subsidence of both the footwall and the hangingwall. Figure 2 is an example of the Tyrrhenian back-arc setting, in the hangingwall of the Apennine W-directed subduction zone. The larger regional subsidence will generate wider accommodation space in the entire basin as a whole. In the second case (passive margin), where regional subsidence is lower, a smaller accommodation space may be formed. However this space is larger in the hangingwall of the normal fault. Supposing a given value of sedimentation rate, the stratigraphic package in a back-arc basin should generally show a different upward evolution with respect to a passive margin characterised by a lower regional subsidence rate. Negative total subsidence may take place along rift shoulders, where normal fault subsidence competes with the regional uplift of the shoulders.

Normal faulting in a continental rift shows average horizontal extensional rates of 0.2 mm/year, whereas once the continental crust is completely stretched and the oceanic crust starts to form, the extensional rates immediately rise to 20–100 mm/year, more than one hundred times faster. The 5–10 km of horizontal displacement which were needed to open intraplate grabens during a period of 10–40 Ma (e.g., the East-African rift, the Rhine–Rhone graben system, the pre-Atlantic Late Permian–Early Triassic continental rift) indicate that complete stretching of the continental lithosphere enables rift zones to drastically accelerate the relative plate motion. This change occurs when the passive margin switches from the rifting to the drifting stage; the latter switch may originate from the differential drag that the asthenosphere induces at the base of the lithosphere.

Normal faults within active or inactive thrust belts have been widely described (e.g., Burchfield & Royden, 1985; Dewey, 1988; Selverstone, 1988; Ratschbacher et al., 1989; Buck, 1991). Normal faults that form within uplifting orogens (e.g., Andes, Himalayas, Alps) generally have hangingwall subsidence rates lower than the regional uplift (Fig. 3). Active orogens may have regional uplift rates higher than 10 mm/year. Uplift is recorded also in the hangingwall of W-directed subduction zones, west of the accretionary wedge, where extension prevails. Figure 4 is the example of the Gubbio graben in the Central Apennines in Italy, where normal faulting developed in a context of regional uplift. Here an eastward migrating wave with an uplift rate of about 1

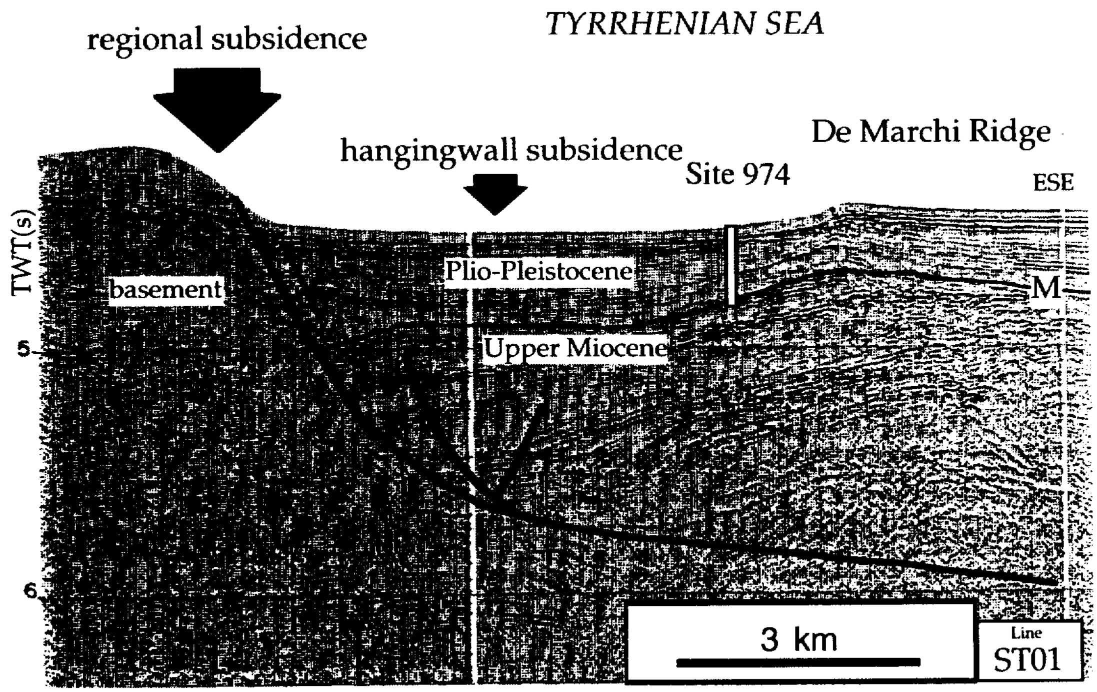

Fig. 2. Hangingwall subsidence along a listric normal fault adds to the regional subsidence to produce a positive total subsidence rate. This example comes from the central Mediterranean Tyrrhenian back-arc basin, where high subsidence rates developed from the Middle Miocene up to recent times. Seismic section after Kastens et al. (1987).

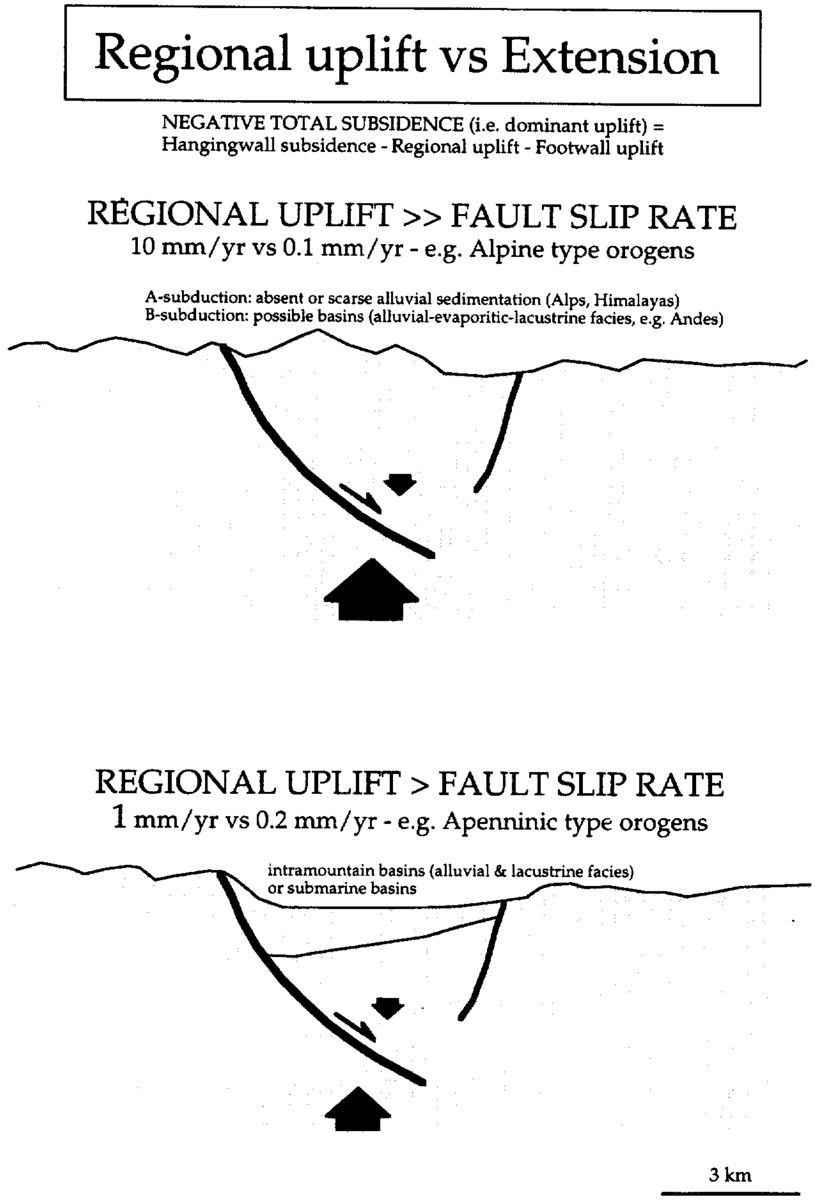

Fig. 3. Normal faults that develop in uplifting geodynamic settings may compete with high or very high regional uplift. Usually, the footwall is being eroded and the hangingwall may accommodate alluvial and lacustrine sedimentation.

mm/year is reported. Grabens are regularly spaced in this uplifting area. Clearly in these orogenic settings the total subsidence (regional and normal fault) is negative.

The above discussion infers that normal faults originate from variable geodynamic settings, with different regional subsidence or uplift rates (Fig. 5). As a result, each setting should be treated separately.

3. Normal faulting vs sedimentation rate

The stratigraphic architecture of rift-basins is clearly controlled by the interference of tectonics and sedimentation. Ravnås and Steel (1998) recently provided a useful summary of this interplay. A sketch of two different subsidence/sedimentation relationships is displayed in Fig. 6. When fault movement rate is faster than sedimentation, the fault becomes a significant morphological step which affects the facies and thickness of the two walls. On the other hand if the subsidence rate does not exceed the sedimentation rate, the same facies is maintained across the fault. In the latter case the growth fault will only control the differential thickness between the two walls of the fault, because the sediments are continuously levelling the fault scarp (Fig. 6). Examples and a discussion of this topic may be found in Christiansen (1983) and Xiao and Suppe (1992).

The occurrence of lateral facies variations within syn-

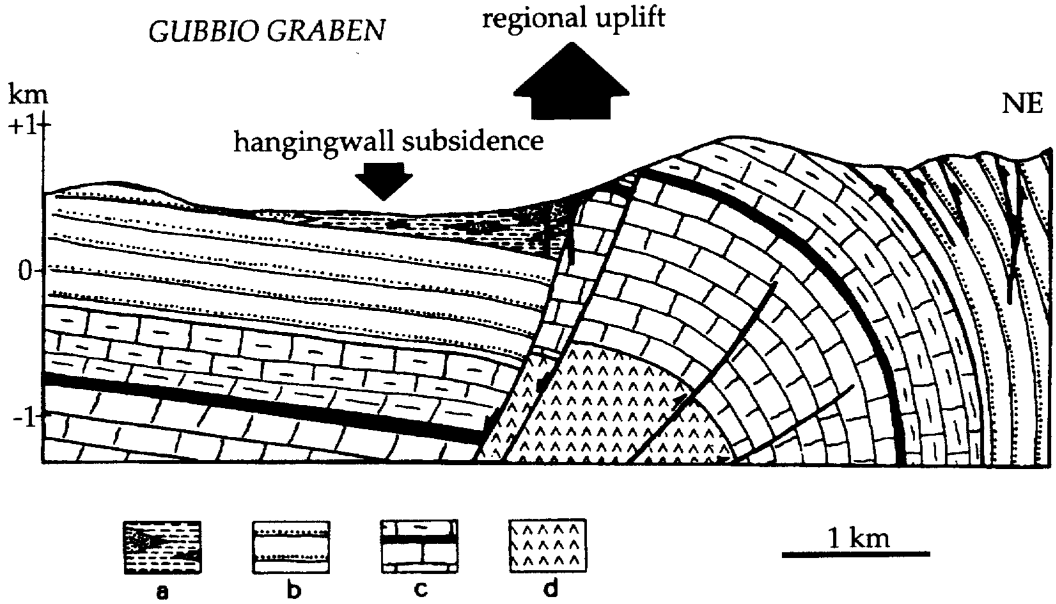

Fig. 4. Cross-section of the Gubbio half-graben, Central Italy, after Menichetti and Minelli (1991). Regional uplift was higher than the hangingwall subsidence and resulted into a negative total subsidence. The footwall of the normal fault is deeply eroded and the half-graben presents a limited thickness of the alluvial-lacustrine sedimentary fill. (a) Pleistocene fluvial-lacustrine continental deposits; (b) Langhian-Serravallian Marnoso Arenacea Formation; (c) Liassic-Oligocene Umbro-Machean pelagic carbonate sequence; (d) Triassic Burano evaporites.

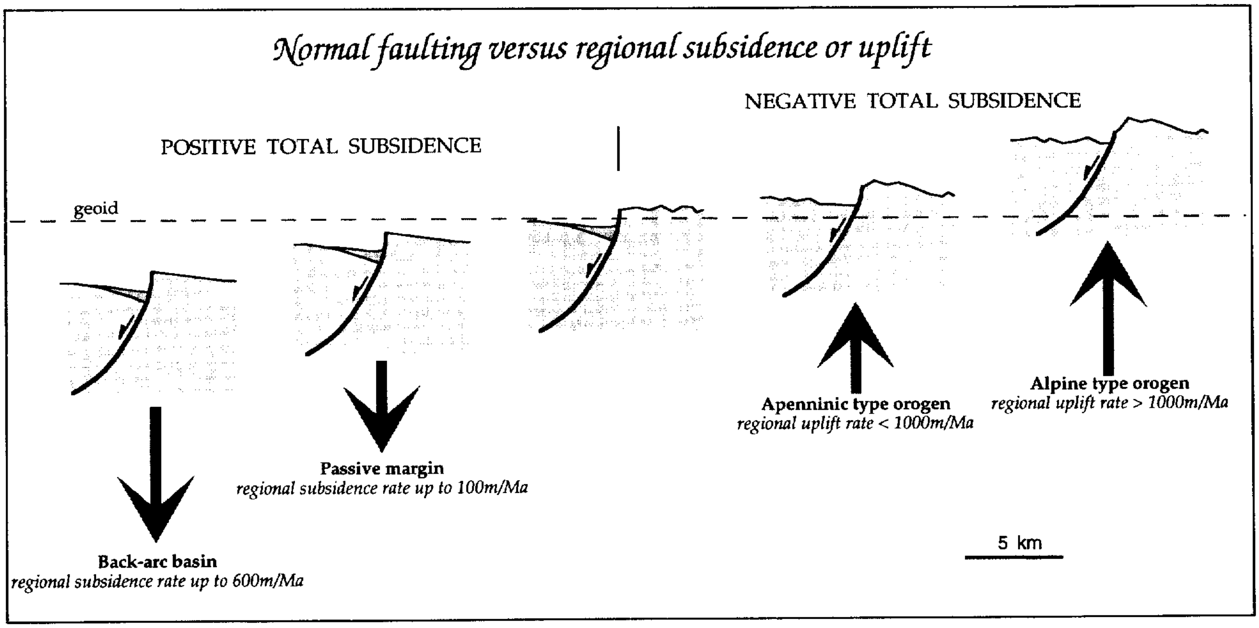

Fig. 5. Normal faults should be differentiated on the basis of their original geodynamic setting, because they may form in areas with different regional subsidence or uplift rates with respect to the geoid. Back-arc basins experience the fastest subsidence rates, whereas the Alpine-Himalayan type of orogens has the fastest uplift rates.

tectonic deposits is mainly related to the superficial effects of a growing tectonic structure. Lateral facies variations are controlled by variegated topography. When the sedimentation rate is lower than the total subsidence rate, submarine depositional environments may develop a carbonate platform in the footwall and pelagic sedimentation in the hangingwall (Fig. 6). A subaerial environment with negative total subsidence may experience erosion of the footwall and alluvial or lacustrine sedimentation in the hangingwall. Figure 7 is the example of the Sulmona graben in the Central Apennines. Narrow facies distribution and boundaries characterise subaerial settings of grabens where sedimentation does not compensate the tectonic offset. Where the sedimentation rate

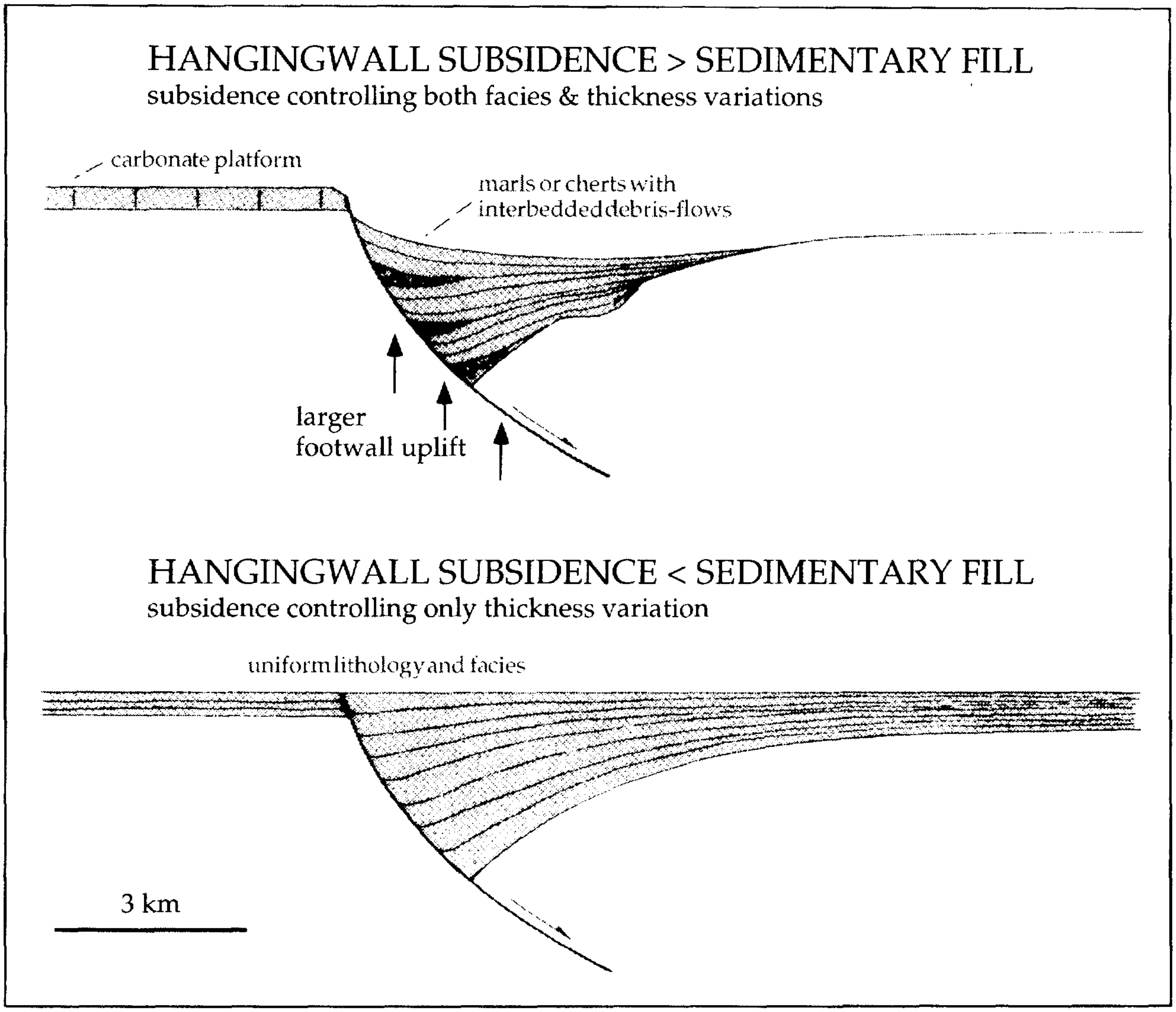

Fig. 6. Subsidence rates and sediment supply are independent factors that have different values in different geodynamic settings. When the subsidence rate along a fault is larger than the sedimentation rate, there is a morphological step at the fault and this may generate lateral facies changes. When the subsidence rate is lower than the sedimentation rate, the fault only controls the thickness of the syntectonic sediments and the morphological gradient is absent in any kind of sedimentary environment, e.g., both subaerial and shallow or deep marine facies. In the former case, a higher footwall uplift should be expected due to the mass deficit. Interbedded debris flows may be sourced both by the fault scarp and by the limb of the rollover anticline.

is higher than the subsidence rate, the topographic gradients are levelled by sediments, both in subaerial and submarine environments. As the sedimentation exceeds the tectonic rates, the topography becomes less and less irregular. The sedimentation rate controls the surface morphology during the growth of different tectonic structures. This feature may be easily analysed by considering the relationship between the sedimentation rate and the development of normal faults. Examples may be the listric normal growth faults in the northern margin of the Gulf of Mexico where high sedimentation rates sourced by the Mississippi and adjacent rivers have exceeded the total subsidence rate of the active normal faults. No significant morphological steps are observed in this setting, at the superficial expression either of the fault or of the related normal fault-propagation fold. Active faults cross-cutting the Earth's surface in subaerial environments generate significant topographic scarps (e.g., Cello et al., 1998), particularly in areas where the total subsidence is negative (see example of the Southern Apennines, Fig. 8).

Sediment supply and consequent sedimentation rate primarily depend on morphological gradient, climate, erosion rate and organic productivity (carbonate, silica, etc.). These parameters are variable all over the Earth and may interfere with the different subsidence rates of the various geodynamic settings. The Tyrrhenian sea, which is the back-arc basin of Apennine subduction

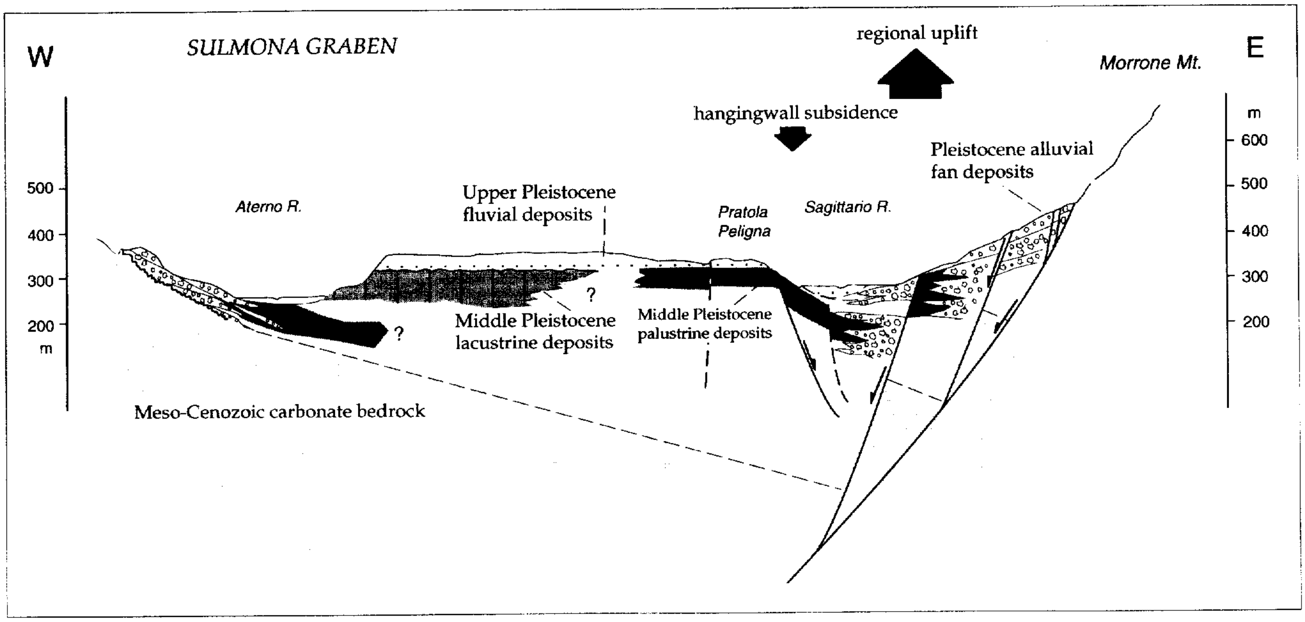

Fig. 7. The Sulmona basin in the central Apennines (after Cavinato & Miccadei, 1995) shows a typically narrow distribution of the facies associated to the fault growth. Syntectonic sedimentation occurred during a negative total subsidence because the regional uplift exceeded the normal fault subsidence. Sedimentation was unable to entirely fill the basin.

(Malinverno & Ryan, 1986; Kastens et al., 1988), is characterised by deep bathymetry (3–4000 m) and seamounts with condensed sedimentation (horsts and volcanoes). The Pannonian basin is a similar back-arc basin associated with the Carpathian subduction (Horváth, 1993; Linzer, 1996). However, this basin was rapidly filled with clastics transported by the Danube and other rivers; these clastics were sourced from the European craton and the surrounding orogenic belts. This terrigenous supply caused a sedimentation rate larger than the subsidence rate. In this case, the normal faults mostly produced only thickness changes between the hangingwall and footwall.

Sections from the Southern Alps in northern Italy, Tunisia, and two seismic sections from the western margin of the Black sea illustrate the two cases (sedimentation rate > subsidence rate and sedimentation rate < subsidence rate, Figs 9, 10, 11, 12 and 13). The Southern Alps were a passive continental margin that developed during Mesozoic times (Bernoulli et al., 1979; Winterer & Bosellini, 1981; Bertotti et al., 1993). Within the Alpine thrust belt, mainly north-trending syn-sedimentary normal faults are preserved. This area experienced both subsidence rates slower and faster than sedimentation rates. In the Dolomites (eastern Southern Alps) there are several examples of syn-sedimentary normal faults of Mesozoic age. The section in Fig. 9 shows a Ladinian pelagic and volcaniclastic succession, which thickens towards the eastern basin of the Dolomites. In this instance, the sedimentation rate was higher than the subsidence rate and the transition between horst and graben occurred with a thickness change but with no significant facies change. This setting is commonly observed on seismic lines of passive continental margins (e.g., Christiansen, 1983; Tankard & Balkwill, 1990; Xiao & Suppe, 1992).

Very frequently, along passive margins, normal faults will generate forced folds in the upper sedimentary cover, as clearly modelled by Withjack et al. (1990). They usually have open limbs. These folds may be misinterpreted as indicators of compressive tectonics, and they could rather be classified as normal-fault propagation folds (Figs 9, 10 and 12). With this kind of folding, growth related sedimentation will onlap the lower limb of the fold rather than a real normal fault.

Normal faults separating different facies domains were common during the late Triassic–Early Jurassic rifting event in the central Southern Alps (Castellarin, 1972; Doglioni & Bosellini, 1987; Bertotti et al., 1993). Figure 11 displays the normal fault system between the Trento horst and the Lombardy basin. Up to the Late Triassic, this boundary mainly controlled only thickness variations between footwall and hangingwall, because the hangingwall subsidence was lower than the sedimentation rate. During the Jurassic, this relationship was reversed and shallow-water carbonates developed on the Trento platform, while pelagic limestones were deposited in the Lombardy basin. The original tectonic setting was strongly modified during the Alpine compressional tectonics, but in places syn-sedimentary normal faults, sometimes with half-graben geometry, were preserved (Castellarin et al., 1993). It must be pointed out that a topographic step was maintained in this area by the combination of two factors: (1) overall subsidence rates exceeded sedimentation rates

Fig. 8. Active normal fault in the Southern Apennines, north of Polla, in Mesozoic carbonate platform rocks. Note its typical undulated shape and the morphological scarp cross-cutting the slope covered by Quaternary breccias. The regional uplift exceeds the normal fault hangingwall subsidence, and the sedimentation rate. Southeast to the right.

in the basin; and (2) the growth of the carbonate platform in the footwall of the normal faults further enhanced the topographic high (Castellarin, 1972). Rifting began in the Late Triassic (Norian–Rhaetian), but a well-defined north-trending boundary between platform carbonates and deep-water limestones developed during the Early Jurassic. At this time, the system underwent a transition process from a monotonous peritidal deposition in the passive margin (Norian Dolomia Principale), mostly characterised by thickness variations across syn-sedimentary normal faults (with sedimentation rates higher than the regional subsidence ones) to subsidence rates higher than sedimentation ones, which gave rise to both abrupt facies and thickness changes across the active normal faults. During the early Lias, the shallow-water limestones which were contained in the early-formed half-grabens, were occasionally replaced by deep-water sediments. A tectonic retrogradation of the Trento platform developed during the Late Lias and fragments of carbonate platform were incorporated into the basin. During the same time interval, carbonate platform facies were deposited on the footwall of the normal fault system. Debris flows and turbiditic calcarenites from the Trento platform are commonly interbedded within the pelagic limestones of the Lombardy basin, indicating episodic failure of the platform margin.

The effects of tectonics on the sedimentary package of a passive continental margin differs between rift and drift stages. During rifting, tectonic subsidence prevails while, during drifting, thermal and lithostatic subsidence are the most important factors in controlling basin development. Therefore, the slip rate of the fault planes is obviously faster in the first rift stage. During this stage the subsidence rate is often higher than the sedimentation one, determining frequent facies transitions across the growth fault.

Normal faults associated with convergent settings are usually characterised by negative total subsidence (the regional uplift being larger than the fault-related subsidence). This usually generates intermontane graben which may be filled by alluvial, lacustrine or evaporitic sediments. An example is the Basin and Range province, where high-angle listric normal faults bound grabens which are filled by clastic sedimentation (Carpenter & Carpenter, 1994). These features usually have sedimentation rates which are insufficient to cover both the footwall and the hangingwall of the normal fault, thus exposing the eroding footwall.

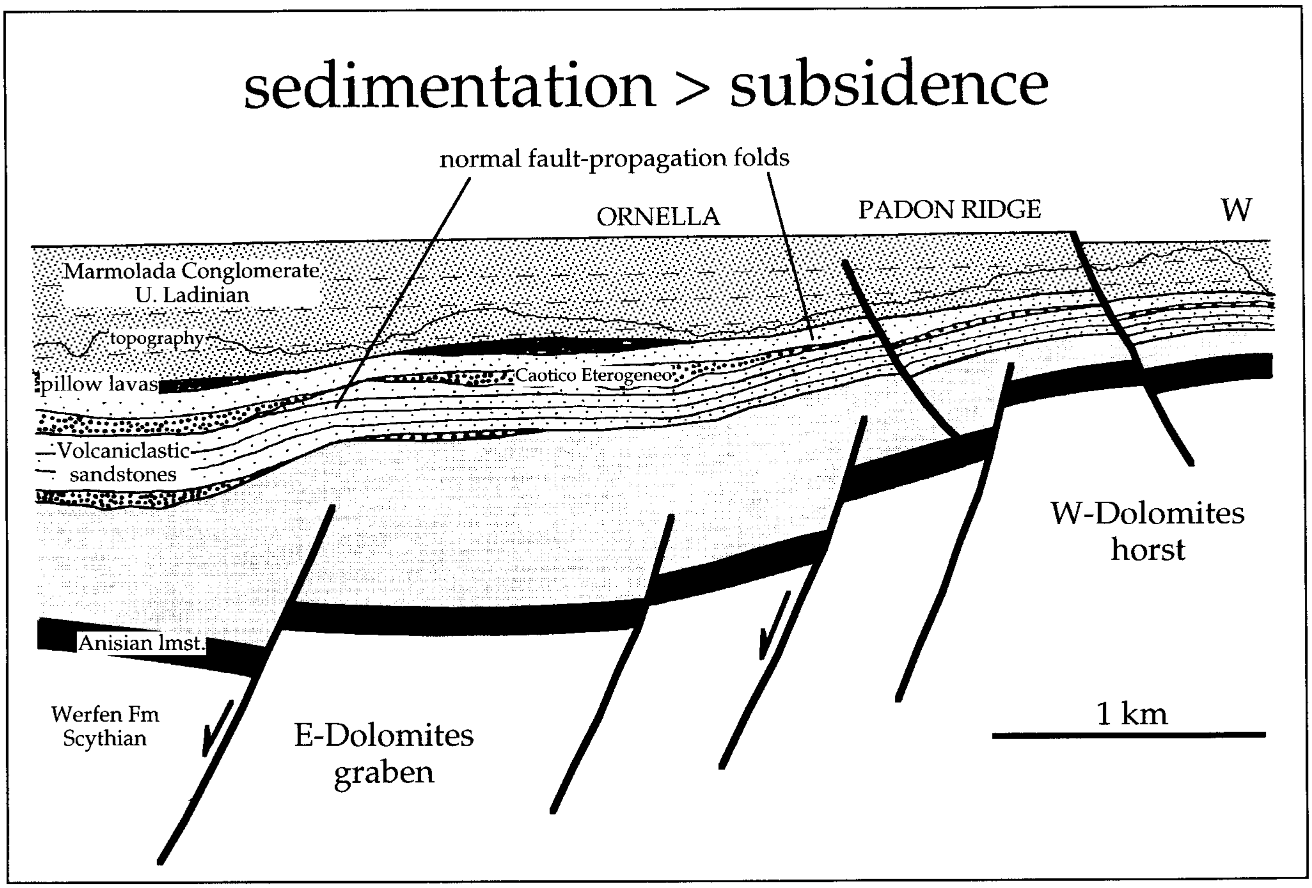

Fig. 9. Interpretative Late Ladinian E–W cross-section of the Padon Ridge in the central Dolomites (northern Italy). The subsidence rates in the eastern Dolomites Graben (or Carnico–Bellunese Basin) were lower than the sedimentation rate, and therefore the normal faults controlled only the greater thickness of the Ladinian sediments in the eastern side. Note also the bending of the cover on top of the deeper normal faults, this being interpreted as normal fault-propagation folds.

Another fundamental parameter which controls basin evolution is the distance between the ramps of the normal faults. This distance determines the width of the basin and therefore the facies association. For instance, a given stretching factor of the lithosphere and variable rheological parameters, may lead to either two large conjugate normal faults, or four smaller faults with a wider rift zone but a small subsidence for each fault. The two systems will generate different basin depths and widths, and therefore different facies evolution.

4. Sedimentation rate vs footwall uplift

Horizontal stretching of the crust through normal faulting implies the removal of the hangingwall from the footwall. This produces unloading of the footwall, which should be compensated isostatically by uplift of the footwall itself (e.g., Wernicke, 1985; Wernicke & Axen, 1988). Along a normal fault, the removed hangingwall material may be: completely compensated by the concurrent filling of the half-graben by sediments; partly compensated; or completely uncompensated in case of failing sedimentation (Fig. 6). In order to achieve complete compensation the sediments filling the half-graben should have the same density as the displaced hangingwall rocks, which seems very unlikely. Nevertheless there is a spectrum of possibilities of sediments which may either partially or not buffer the isostatic rebound of the footwall. The larger sedimentation along a normal fault where the sediments continuously compensate the subsidence should inhibit the footwall uplift or decrease its magnitude. The case in which the sedimentation rate is lower than the normal fault slip rate will generate a footwall uplift larger than the case in which the sedimentation rate is higher than the fault displacement. In effect, in the latter case, the sedimentation in the half-graben can only in part compensate the footwall unloading which generated the gravity anomaly.

Figure 14 shows the effect of variable-density sediments filling the half-graben vs the extent of footwall uplift. The resulting geometries were computed through the analytical solution of the thin-plate flexure equation by Bott (1996), describing the flexure associated with

Fig. 10. Early–Middle Cretaceous growth fault, sutured by the marls of the Fahdene Formation (F), Cenomanian in age. The footwall is constituted by sandstones of the Hauterivian Boudinar Formation (B); o: oysters beds. Sedimentation rate exceeded the subsidence rate. The normal fault only controlled thickness changes. Note the thinning of the oysters bed toward the footwall at the right. Kef El Hassine, Djebel Nara, looking northward, central Tunisia.

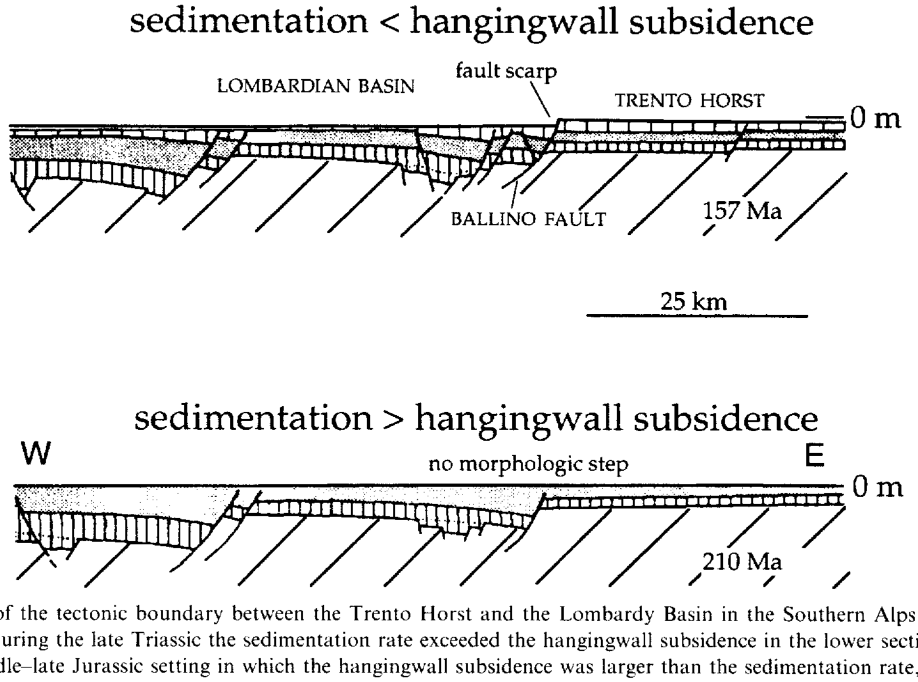

Fig. 11. Cross-section of the tectonic boundary between the Trento Horst and the Lombardy Basin in the Southern Alps (northern Italy), after Bertotti et al. (1993). During the late Triassic the sedimentation rate exceeded the hangingwall subsidence in the lower section, whereas the upper section depicts the middle–late Jurassic setting in which the hangingwall subsidence was larger than the sedimentation rate, with a morphological step generated by the fault scarp.

planar faulting with constrained plate edges on both sides of the fault. In the model, the basin depth and the effective elastic thickness were set at 1 and 10 km, respectively, in order to isolate the effect of sediment density. The density of the faulted upper crust and of the inviscid substratum is assumed to be 2750 kg m^{-3}. Increasing density has

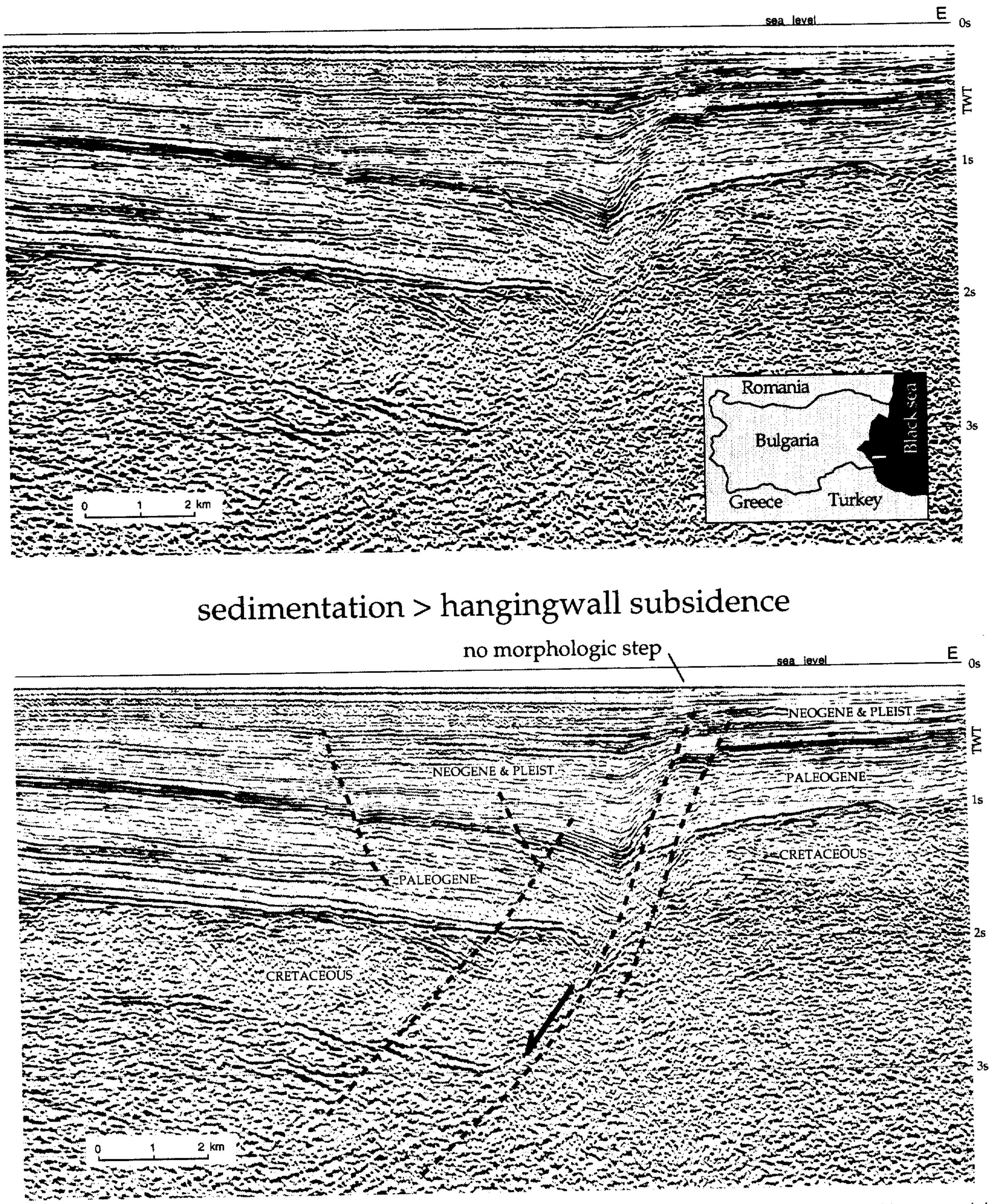

Fig. 12. Example of active normal growth fault in the southwest Black sea where the sedimentation rate exceeded the subsidence rate, inhibiting morphological evidence of the fault at the sea bottom (seismic section by Edison Gas).

two consequences: (1) decreasing the footwall uplift; (2) increasing the basin width. However, since normal faults may form in uplifting areas, some uplift rates which are interpreted as pertaining to the footwall may prove to be regional uplift rates.

5. Concluding remarks

The stratigraphic packaging along normal faults is generally consequent upon the following factors, i.e., the subsidence rate of the hangingwall due to single fault slip

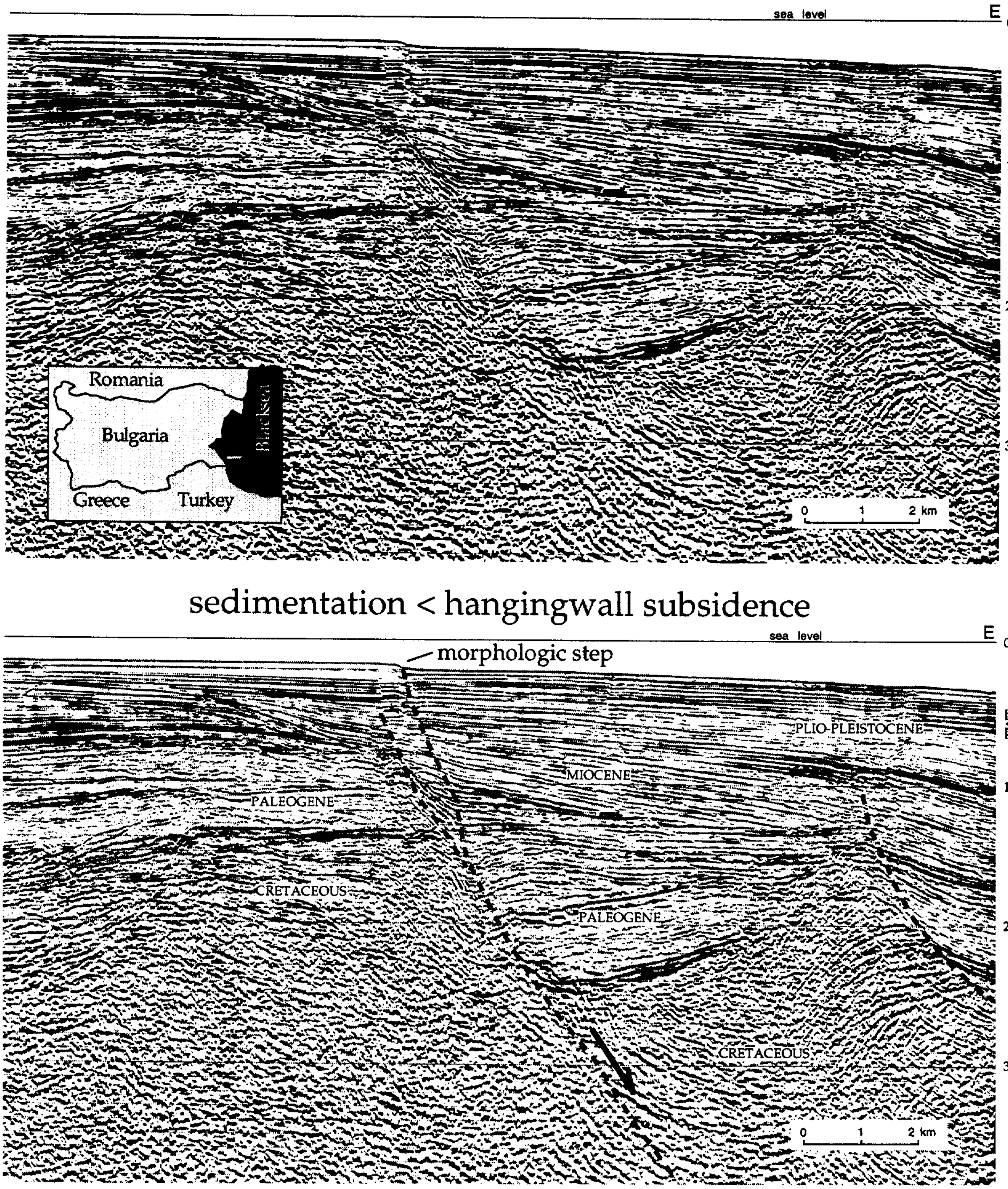

Fig. 13. Example of active normal growth fault in the southwest Black sea where the sedimentation rate was lower than the subsidence rate, generating a morphological evidence of the fault at the sea bottom (seismic section by Edison Gas).

rate, the regional subsidence/uplift rate, the sedimentation rate and the eustatic history. The subsidence rate of a normal fault may be higher or lower than the regional subsidence or even uplift rates (Fig. 5). The total subsidence of the hangingwall of a normal fault may be defined as the vertical slip rate of the fault and the regional subsidence (or uplift) rate. This value may be either positive (passive margins) or negative (orogens) where the regional uplift is larger than the single fault subsidence. The regional subsidence may locally be compensated by the footwall uplift. Moreover, the subsidence rate of the normal fault hangingwall may be higher or

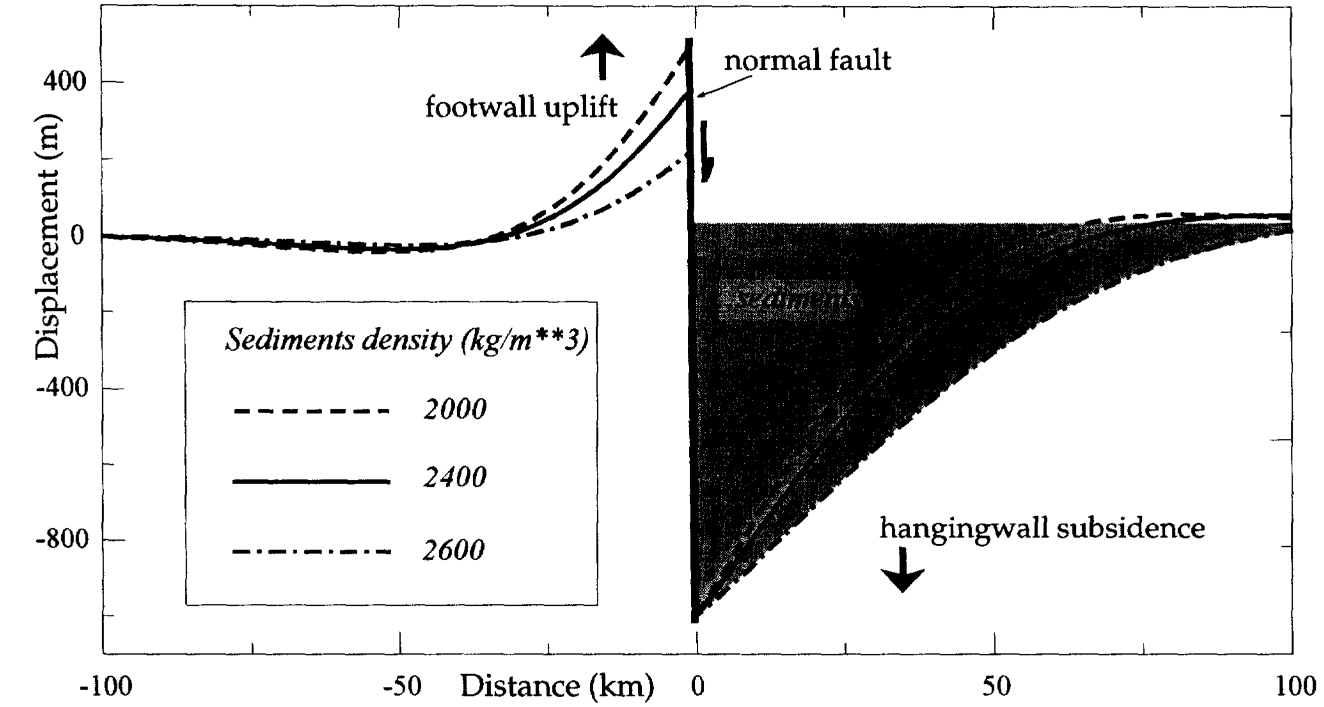

Fig. 14. The footwall uplift (positive elevation) is inversely proportional to the amount and density of the sediments filling the half-graben. The figure shows the effect of variable density of sediments infilling a half-graben. Geometries from an analytical solution of the thin-plate equation (see Bott, 1996 for details). Effective elastic thickness (*Te*) and basin depth set at 10 km and 1 km respectively. Density of the faulted upper crust and inviscid substratum set at 2750 kg m^{-3}. Increasing sediment density has a major effect on footwall uplift and basin width.

lower than the sedimentation rate (Fig. 6). Tectonics controls the superficial topography only if the sedimentation rate is lower than the velocity at which the local tectonic movements take place. This relationship may be observed by considering the average fault slip rate along a normal fault in the steady state. Consequently, facies types of the syn-tectonic deposits will not change across a growing tectonic structure if the sedimentation rate is faster than the local tectonic rates. Furthermore, the footwall uplift of a normal fault is also controlled by the amount and density of sediments partly or entirely filling the half-graben (Fig. 14). If the sedimentation rate is lower onto the footwall of a normal fault, this will further enhance the surface expression of a half-graben.

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