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Foreland and Hinterland basins: what controls their evolution?

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ABSTRACT

Compressional systems are usually characterized by a positive topography above the sea level, which is continuously modified by the conjugate effects of tectonic contraction or post-orogenic collapse, thermo-mechanical processes in the deep lithosphere and asthenosphere, but also by climate and other surface processes influencing erosion rates.

Different types of sedimentary basins can develop in close association with orogens, either in the foreland or in the hinterland. Being progressively filled by erosional products of adjacent uplifted domains, these basins provide a continuous sedimentary record of surficial, crustal and lithospheric deformation at and near plate boundaries.

Selected integrated basin-scale studies in the Circum-Mediterranean thrust belts and basins, in Pakistan and the Americas, are used here to document the effects of structures inherited from former orogens, rifts and passive margins, active tectonics and mantle dynamics on the development and long term evolution of synorogenic basins.

Introduction

Flexure of the oceanic lithosphere as a response to the tectonic loading by accretionary wedges and slab pull has been well described in the vicinity of active subduction zones (Karig 1974; Karig & Sharman 1975; Leggett 1982; Watts et al. 1982; von Huene 1986; von Huene & Sholl 1991). Intra-oceanic flexural moats developing as a response to the load of intraplate volcanoes have been carefully studied in Hawai (Watts et al. 1980). An extensive literature deals with the significance of foreland flexural basins, which are known to develop on continental lithosphere as a response to the load of both collisional and Cordillera-type orogens. Thermo-mechanical controls, associated with the thermal state and layered composition of the lithosphere and accounting for spatial and temporal changes observed in the width and depth of foreland basins, have also been widely studied (Beaumont 1981; Royden & Karner 1984; Kusznir & Park 1984; Kusznir & Karner 1985; Kruse & Royden 1987; 1994). Although most erosional products sourced by the orogens are likely to be trapped in adjacent foreland basins, recording successively marine and continental sedimentation, differential uplift and subsidence associated either with a negative inversion of former thrusts (post-orogenic collapse) or with the development of back-thrusts can also account for dominantly isolated, discontinuous depocenters in the hinterland. Ultimately, a part of synorogenic/synkinematic sediments does not reach the autochthonous foreland, being trapped in thrust-top or piggyback basins (Ori & Friend 1984; DeCelles & Giles 1996).

This study is focused on the control exerted on foreland basin evolution by pre-existing structures such as low-angle faults inherited from former orogens and high-angle faults inherited from the former rift architecture, as well as by lateral thickness and facies variations which are likely to occur in the post-rift sequences of former passive margins.

We will describe how active tectonics can induce the development of thrust-top and hinterland basins, and how post-orogenic mantle dynamics can impact the uplift and erosional history of the orogen itself, but also of adjacent foreland basins.

1 Lithological controls of passive margin series on the localization of decollement levels

Whereas the North American Cordillera and especially the Canadian Rocky Mountains show little evidence of major lateral thickness and facies variations in the pre-orogenic series, the current architecture of Circum-Mediterranean and Alpine foothills is dominantly controlled by the Tethyan rifting which

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operated in Triassic and Liassic times (Bernoulli & Lemoine 1980; Bernoulli 1981; Lemoine et al. 1981, 2000).

For instance, the occurrence or lack of Triassic salt have a strong influence on the development of transfer zones in the Jura Mountains and Sub-Alpine Chains (Guéllec et al. 1990; Philippe 1994; Philippe et al. 1996).

The marked contrasts in structural style among Mediterranean and Alpine thrust belts derived from the deformation of former passive margins of the Tethys are clearly related to the distribution of Cretaceous platform to basin transitions, as well as passive margins versus continental series. Seemingly, Mexican cordilleras such as the Zongolica and Sierra Madre thrust belts are also derived from the reactivation of Jurassic rift margins with wide Cretaceous prograding platforms, and share many similarities with Tethyan thrust belts from the other side of the Central Atlantic (Ortuño et al. 2003).

1.1 Architecture of platform to basin transitions in Albania

The Ionian Basin in Southern Albania is made up of dominantly Mesozoic thin-skinned tectonic units which have been detached from the infra-Triassic substratum along the basal Triassic salt. These thrust units involve relatively thin (about 1 km-thick) Mesozoic series of basinal affinities. Each unit is made up of Toarcian blackshales, Middle Jurassic cherts, Late Cretaceous carbonate turbidites and Eocene Scaglia-type fine-grained pelagic limestones, which are overlain by Oligocene siliciclastic synflexural series (Roure et al. 1995; 2004; Carminati et al. 2004). Farther north, these Mesozoic basinal series still belong to the autochthon in the Peri-Adriatic Depression, the main décollement of the northern Albanian foothills being located within Cenozoic series.

Up to 2 to 3 km-thick prograding Cretaceous platforms were built on both sides of the Mesozoic Ionian-Adriatic basin, accounting for the shallow water carbonate facies of the Sazani-pre-Apulian Platform domain in the west, and of the Kruja zone in the east (Roure et al. 1995; 2004).

Due to rheology contrasts between the massive platform carbonates and finely layered basinal series, but also between Mesozoic carbonates and siliciclastic Oligocene flysch, triangle zones have developed along these paleogeographic boundaries, accounting in both cases for the development of a regional backthrust and deeply buried duplexes (Fig. 1a, b).

In the northern transect (Fig. 1a), the Kruja units, made up of Cretaceous platform carbonates and Oligocene flysch, have been thrust over the siliciclastic series of the Peri-Adriatic Depression during a pre-Messinian thrusting episode. Subsequent deformation during the Pliocene involved the tectonic accretion of deeper platform duplexes, deformation propagating forelandward along a blind thrust, antithetic from a shallower east-verging backthrust.

In the southern transects (Fig. 1b), the foreland propagation of the frontal thrust is only visible in the northwestern side of the Sazani promontory (section 1), whereas farther south, it accounts for a west-verging blind thrust, propagating in the opposite direction from a shallower east-verging conjugate backthrust.

Both areas are yet underexplored, although they are likely to host hydrocarbon reserves in slope breccias near the transition between the Kruja and Sazani platform domains (known for their good reservoirs) and the Ionian and Peri-Adriatic basins (likely to have a good source rock potential; Roure et al. 1995, 2004).

1.2 The architecture of platforms to basin transitions in the French Alpine foreland

In southeastern France, triangle zones have also developed along the northern border of the Provençal Platform, accounting for the large backthrusts of the La Lance and Ventoux-Lure carbonate platforms, which are made up of Urgonian reefal facies and are widely thrust over coeval basinal facies of the Vocontian Trough (Roure et al. 1992, 1994a; Roure & Colletta 1996; Fig. 2).

La Lance structure

The deep architecture of the La Lance structure is related to the reactivation of a former Liassic basement-involving high-angle fault. A basal décollement is located in the Triassic salt series in the Vocontian Basin in the north, but in Jurassic blackshales in the south. A basement short-cut is evidenced at depth, with a south-verging reverse fault transporting passively the crest of the former Jurassic tilted-block (Fig. 2a). A blind antithetic north-verging backthrust has detached the Urgonian (Aptian) platform series, connecting the intra-Jurassic décollement in the south with a shallower décollement in the north, which propagated within the Lower Cretaceous basinal series of the Vocontian domain as far north as the Saou syncline.

Lateral thickness and facies variations of the Barremian-Aptian series can be clearly recognised on the seismic profiles, where the transition between thick prograding Urgonian series and thinner, isopachous basinal sequences can be picked very accurately.

Actually, regional-scale basinal inversion is also evidenced by the current position of the top Jurassic horizon, which is higher within the currently inverted basinal domain in the north, than in the ajdacent paleo-horst where Urgonian carbonates have been deposited in the south.

Although the seismic profile crossing the La Lance structure is of average quality at depth, the overall architecture of this structure fits quite well with the geometry expected for such localization of thin-skinned tectonics and wedging, associated with the reactivation of a deeper basement-involving fault, as predicted by analogue models (Fig. 2b).

The Ventoux-Lure structure

The Ventoux-Lure is a west-trending platformal unit which constitutes the eastern prolongation of the La Lance thrust sheet. As the latter, it is thrust northward over coeval basinal facies of the Vocontian Basin (Fig. 2). Although the surface ar-

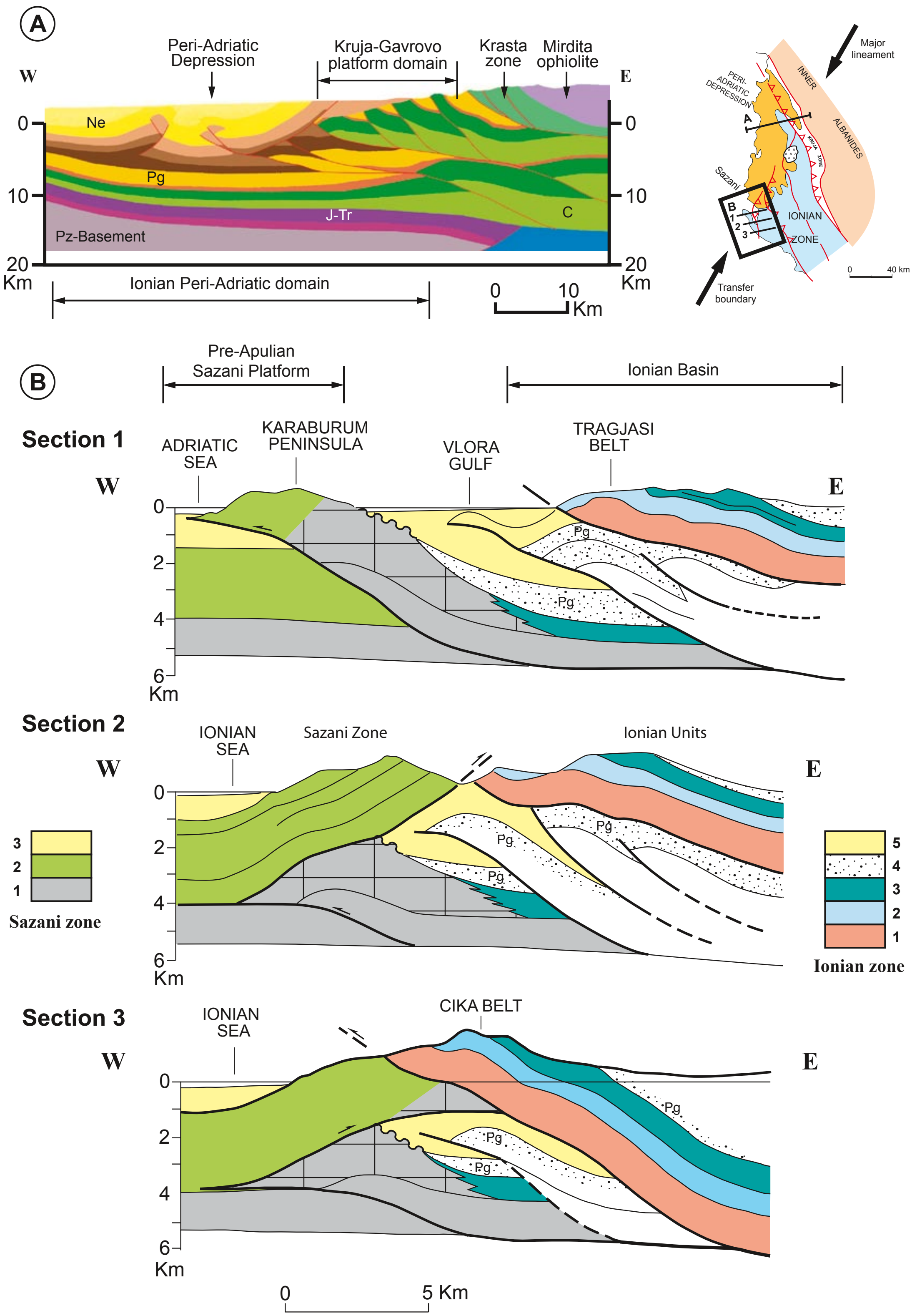

Fig. 1. Thin-skinned deformations associated with Mesozoic platform to basin transitions in Albania: a) Kruja duplexes and associated backthrust developing at the transition between the Kruja-Gavrovo Platform and the Ionian-Peri-Adriatic Basin; b) Serial sections in the Vlora area, outlining the lateral changes in thrust architecture at the transition between the Sazani-Pre-Apulian Platform and the Ionian Basin, with a progressive stacking of Ionian duplexes and development of a triangle zone. The Sazani units are made up of Mezozoic platform carbonates (2) and Neogene siliciclastic series (2). The Ionian units are detached along the Triassic salt (1), and comprise Jurassic (2) and Cretaceous (3) to Eocene basinal series, overlain by Oligocene turbidites (4) and Neogene clastics (5).

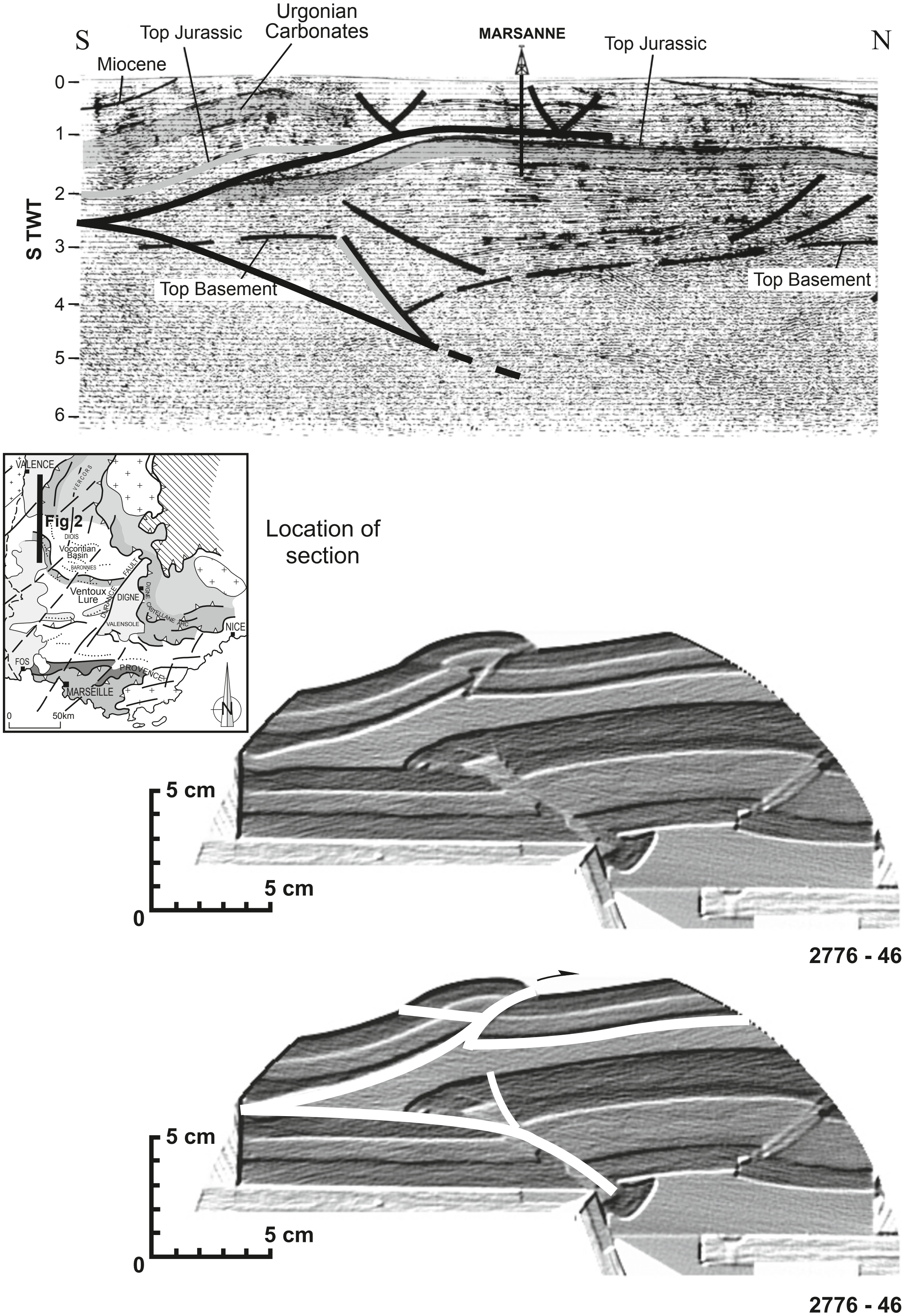

Fig. 2. Thin-skinned deformations associated with Mesozoic platform to basin transition in the French Alpine foreland basin: Basement short-cut and antithetic thin-skinned thrusts in the La Lance structure (French Alpine foreland basin). Top: Seismic profile across the La Lance anticline; Bottom: Sand box experiment outlining the development of a basement short-cut and passive transport of former normal fault during the transpressional inversion of a pre-existing graben.

chitecture of the Ventoux-Lure backthrust is very similar and more or less continuous with the one of the La Lance unit, a debate still remains for its deeper controls. Reprocessing of seismic profiles could not demonstrate the occurrence of high-angle normal faults in the basement, leaving open alternative hypotheses whereby the triangle zone is only controlled by the lateral motion and wedging of basinal series beneath the Cretaceous platform, the Jurassic mud pile acting as a smooth indenter which progressively opened the mouth of the "crocodile" (Meissner 1989; Ford & Stahel 1995).

1.3 The architecture of platform to basin transitions in the Zongolica thrustbelt

In Southern Mexico, the Cordoba Platform constitutes the easternmost tectonic units of the Zongolica thrustbelt. It is made up of 2 to 3 km-thick Lower Cretaceous shallow-water carbonates, which have been thrust eastward during the Late Cretaceous-Paleocene Cordilleran orogeny over coeval basinal sequences of the Veracruz Basin (Ortuño et al. 2003; Ferket et al. 2004).

As in Albania, numerous duplexes made up of Mesozoic carbonates have been stacked at the platform to basin transition, and constitute the main oil-productive structures in these areas (Fig. 3).

Worth to mention, slope breccias account here for the best reservoirs, whereas the main source rocks are likely to be found in the adjacent basinal series.

Lateral shifts in décollement layers between dominantly brittle platform domains and adjacent basins are the main parameter accounting for the deformation style and development of such triangle zones. Platform horses override poorly deformed basinal sequences when the deformation migrates from the platform towards the basinal domain (case of the Albanian/Kruja and Mexican examples), whereas an antiformal stack of basinal duplexes develop in the footwall of a major backthrust of the platform domain when the deformation front migrates from the basin toward the platform (case of the Albanian/Sazani/Ionian and La-Lance/Ventoux examples). All these transitional domains between former platforms and basins constitute major objectives for petroleum exploration, as they display excellent structural closures with good reservoirs, likely to be charged by oil generated in the adjacent basinal domains.

2 Basement architecture and foreland inversions

As already discussed in the case of the La Lance structure, the crustal architecture inherited from the rifting episodes exerted a strong control in localizing subsequent thin-skinned deformations:

2.1 Infra-salt basement controls and late-stage inversion beneath the Jura Mountains and Salt Range-Potwar Basin

The Ecors deep seismic profile and exploration wells in the Molasse Basin and Jura Mountains have evidenced the occurrence of Carboniferous basins beneath the basal, intra-Triassic décollement (Laubscher 1986; Guéllec et al. 1990; Philippe et al. 1996). Seismic imagery documents the late stage inversion of these basins, which post-dates the main Messinian-Pontian episode of westward lateral displacement of the Mesozoic cover toward the Bresse Graben. Therefore, the current topography of the High Jura (Grand Credo; Guéllec et al. 1990; Philippe 1994; Philippe et al. 1996; Fig. 4) cannot be only interpreted as the result of thin-skinned stacking, but in part is accounted for by vertical Plio-Quaternary uplift associated with basement inversion.

In Pakistan, timing of the Salt Range emplacement was erroneously attributed to the same Plio-Quaternary episode of deformation which is well documented by magneto-stratigraphy in the Siwalik molasse deposits of the Potwar Basin (Burbank et al. 1986, 1988). However, the Salt Range is devoid of Neogene series, and is known to rest directly on top of Miocene stata, with no Pliocene evidenced in the lower plate. Worth to mention also, Infracambrian and Paleocene blackshales of the Salt Range are still thermally immature, which means they were never buried deeply beneath the Siwalik series, as should be expected if thrusting operated only during the Plio-Quaternary (Grelaud et al. 2002).

In fact, there are many features on seismic profiles to demonstrate that the base of the Infra-Cambrian salt is not flat beneath the Potwar Basin, but is locally offset by high-angle faults operating in the infra-salt substratum. Most (if not all) outcropping anticlines of the Potwar Basin are indeed underlain by reactivated basement faults, providing strong support for another interpretation and timing of the deformation than the one proposed earlier (Jaswal et al. 2004; Fig. 5):

- Between 10 and 20 km of shortening have been accommodated by the southward thin-skinned translation of the sedimentary cover of the Potwar Basin, most of this motion being Miocene in age, i.e., synchronous with the deposition of the Siwalik molasse. The Salt Range thrust front was continuously uplifted and eroded during this stage, accounting for the low maturity of its source rocks (Grelaud et al. 2002).
- During the Plio-Quaternary, paleostress directions have been slightly modified, inducing the transpressional reactivation of east-trending faults in the infra-salt substratum. Shallow anticlines in the Potwar Basins are related to local in-situ thin-skinned accommodation features (fish tails and pop-up structures) which are directly controlled by the underlying ongoing basement inversion. Alternatively, lateral thickness variations of the salt pillows could also account for a subsequent localisation of the deformation, even in areas where no basement normal fault can be identified in the seismic profiles.
- Further evidence of this late stage transpressional event is recorded in recent outcrops provided by the new Islamabad-Lahore highway, at the crossing with the Hari-Murat thrust. Slicken-sides on the major thrust plane are indeed

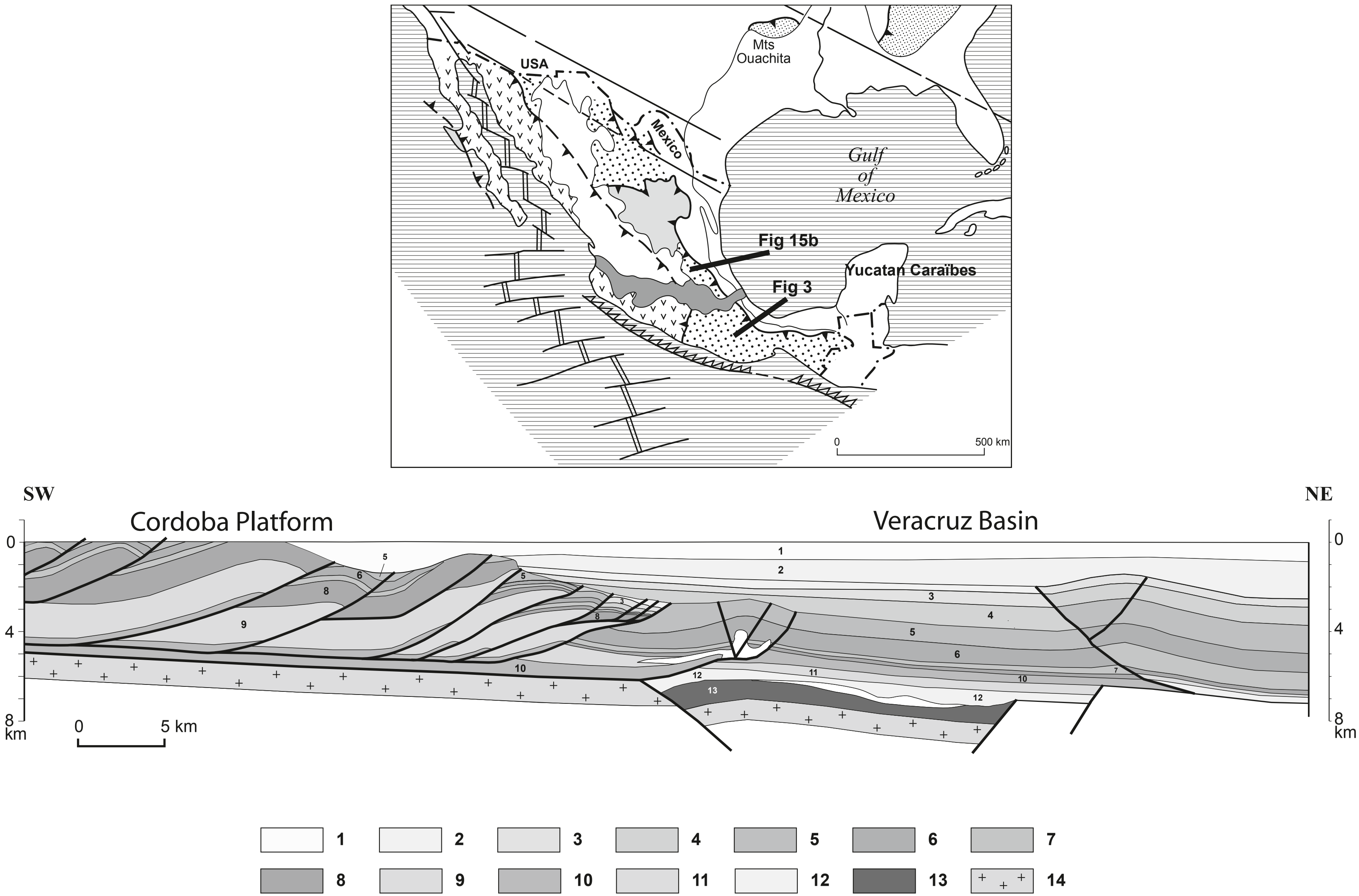

Fig. 3. Thin-skinned deformations associated with Mesozoic platform to basin transition in southeastern Mexico. This transect (modified from Gonzalez-Mercado 2007) crosses the Cordoba Platform and Veracruz Basin, and shows a discontinuous intra-Cretaceous decollement level accounting for a progressive stacking of platformal units. From top to bottom, the lithostratigraphy of the Veracruz Basin is made up of (1) Plio-Pleistocene series, (2 and 3) Miocene series, Paleogene series (4, 5 and 6), Jurassic to Cretaceous basinal series (7 to 12), Upper Jurassic salt (in white), Middle Jurassic red beds (13) and underlying crystaline basement (14). From top to bottom, the lithostratigraphy of the Cordoba units is made up of Plio-Pleistocene unconformable series (1), erosional remnants of Late Cretaceous to Paleogene flysch series (5 to 7), thick Cretaceous platform carbonates (8 and 9), and Jurassic continental red beds (10).

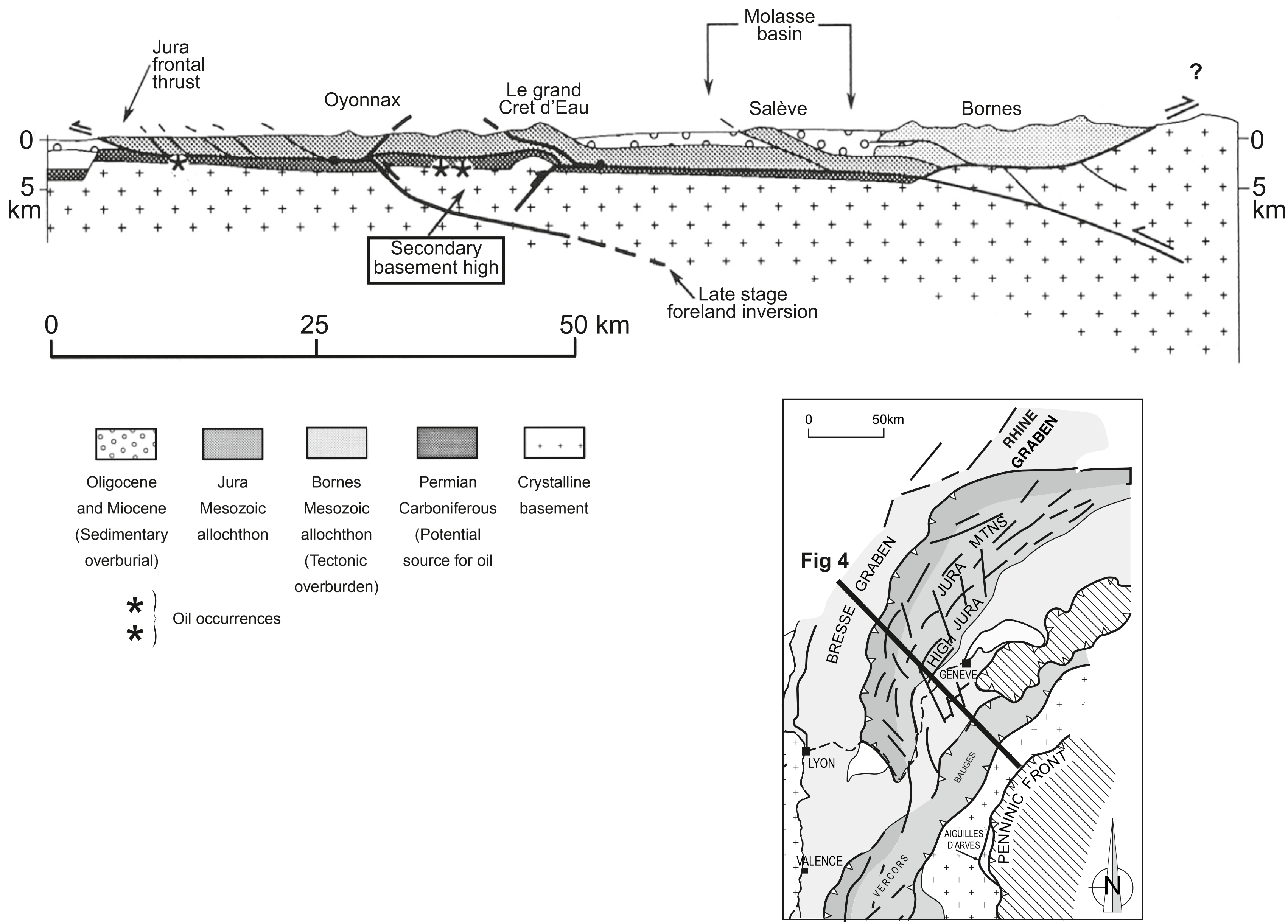

Fig. 4. Infra-salt Paleozoic basins and localisation of Neogene deformation in the Jura Mountains (modified after Roure et al. 1994).

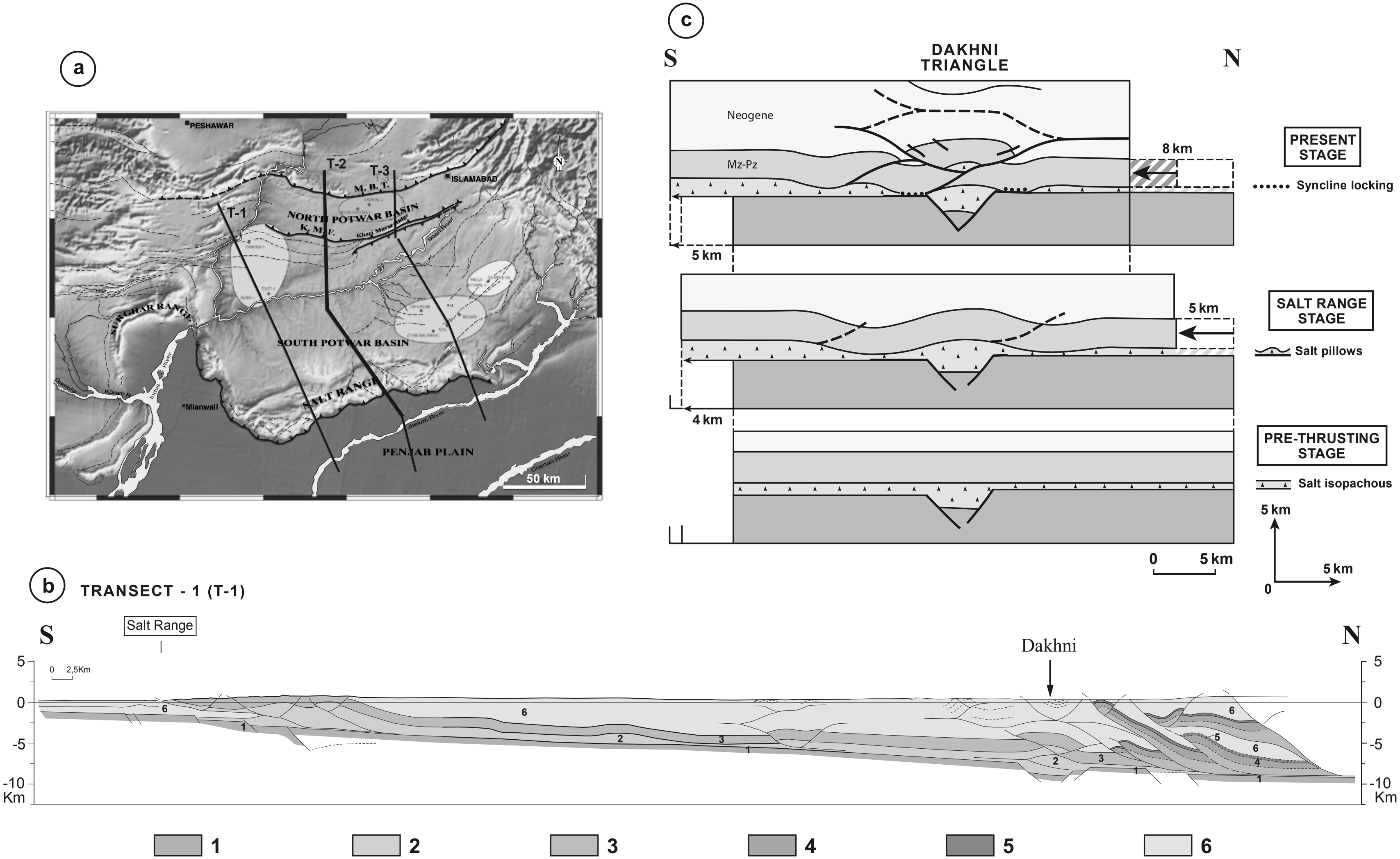

Fig. 5. Infra-salt Precambrian basins and localisation of Neogene deformation in the Potwar Basin (Pakistan): a) Location map; b) Regional section across the western part of the Potwar Basin from the Salt Range in the south to the Dakhni field in the north (modified after Grelaud et al. 2002); c) Evolutionary diagrams of the Dakhni structure, accounting for a first episode of thin-skinned tectonics, coeval with the thrust emplacement of the Salt Range frontal structure, and subsequent transpressional reactivation of basement structures (modified after Jaswal et al. 2004). Mz-Pz: Mesozoic and Paleozoic. The lithostratigraphy of the Salt Range-Potwar Basin comprises an infra-salt Precambrian substratum (1), Eo-Cambrian salt series (2), a Paleozoic sandstone and carbonate platform (3), Mesozoic to Eocene series (4 and 5), and Neogene Siwalik siliciclastic deposits (6).

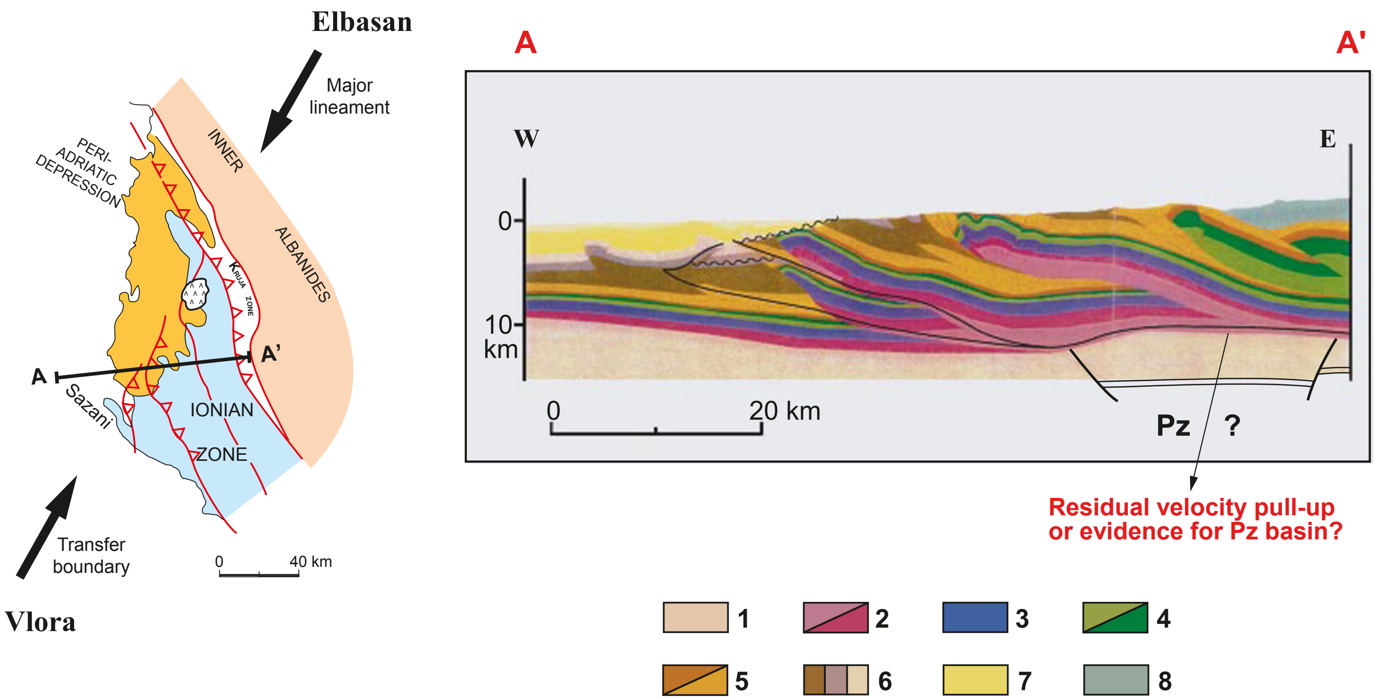

Fig. 6. The Vlora-Elbasan lineament in Albania: a lateral ramp connecting intra-Triassic and Cenozoic décollement levels.

almost horizontal, thus attesting for the late-stage, dominantly strike-slip motion along these former south-verging thrust contacts.

2.2 What is controlling the development of lateral ramps?

Scaled analogue models of thrust deformation have documented the influence of brittle-ductile coupling and thickness variations of décollement layers on the location of the active thrusts (Smit et al. 2003). Seismic profiles across lateral ramps and transfer zones do not differ too much from profiles crossing the frontal structures, although they accommodate a lot of "out-of-the-plane" motion. In Albania and in Eastern Venezuela, they provide a key for better understanding the deep controls accounting for the localization of the deformation along two well known transfer zones, namely the Vlora-Elbasan lineament and the Urica Fault:

Vlora-Elbasan lateral ramp (Albania)

The Vlora-Elbasan transfer fault constitutes a southwest-trending tectonic feature which separates the inverted Ionian Basin in the south from the Peri-Adriatic Depression in the north. It is related to a major lateral shift in the depth of the basal décollement, which is localized within the Triassic salt and evaporites in the south beneath the Ionian Basin, but ramps upward into the Oligocene and Neogene clastics of the flexural sequence further north beneath the Peri-Adriatic Depression (Roure et al. 1995, 2004).

Two different hypotheses have been proposed to account for this localization of the deformation (Fig. 6):

1) either the Vlora-Elbasan structure is located along a major paleogeographic facies boundary, accounting for the lack of Triassic salt in the north, the base of the Triassic remaining flat beneath the ramp;
2) or the main control is exerted by a high-angle fault in the basement, accounting for a vertical offset of the base of the Triassic series.

The latter explanation involving a southwest-trending fault may eventually be validated by depth migrating the time sections crossing the transfer zone. At this stage, an apparent antiformal deformation can be noticed below the basal intra-Triassic décollement, but there is not enough control on seismic velocities at depth yet to perform a confident depth migration of the lines. If still preserved after depth migration, this infra-salt doming would rather account for the reactivation of basement structures or inversion of a Paleozoic basin. Unfortunately, the resolution of potential data such as gravimetry is not sufficient to discriminate among the various hypotheses, due to the high density of shallow carbonates, and no deep seismic is yet available to document the presence or absence of an infra-salt basin.

Seismic profiles across the lineament account for a major change in the structural style, with a basal decollement located in the Triassic salt in the southeast, and in the Oligo-Miocene siliciclastics in the northwest. At intermediate depth (i.e. be-

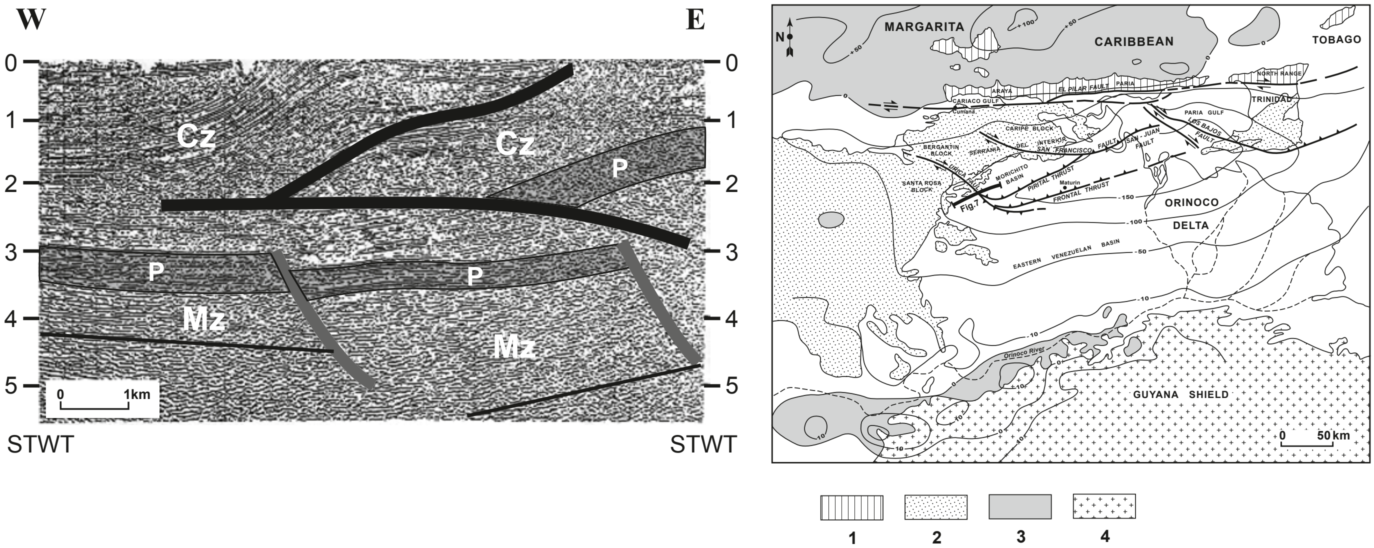

Fig. 7. The Urica transfer zone in Eastern Venezuela: a lateral ramp connecting Lower Cretaceous and intra-Miocene décollement levels (modified after Roure et al. 1994).

tween 4 and 8 km), the Vlora-Elbasan structure is best described as a lateral ramp). Deeper controls are still conjectural, being either related to a lateral change in the Triassic facies, or to a pre-existing Mesozoic or Paleozoic high-angle fault. The slight deformation observed at the base of Triassic series in the eastern part of the section could either be related to a velocity pull-up (underestimation of the seismic velocities during time-to-depth conversion of the section), or indicate inversion of a Paleozoic graben.

Urica lateral ramp (Eastern Venezuela)

The Urica Fault is a southeast-trending tectonic feature which constitutes the western border of the Serrania. At the surface, it is connected laterally with the regional north-verging backthrust of the main Eastern Venezuelan tectonic front. East-trending seismic profiles across the Urica zone help constraining its architecture at depth (Roure et al. 1994b; Fig. 7):

- To the east, the basal décollement beneath the Serrania is located in the Mesozoic series of the former passive margin, i.e., in Lower Cretaceous coal measures of the Barranquin Formation or in even deeper synrift Jurassic (?) series;
- To the west, the basal décollement is shallower, being located in the synflexural siliciclastic series of the Carapita Formation;
- The surface trace of the Urica Fault is related to an east-verging thin-skinned backthrust which roots within the intra-Carapita décollement;
- The deep control of the Urica trend consists in a south-southeast-trending high-angle normal fault which crosses the Mesozoic series and the basement. Although it guides the Late Miocene to Pliocene tectonic inversion of the Serrania, this fault still preserves its normal offset at basement level. This deep Urica fault was inherited from the Mesozoic rifting and accounts for an abrupt thickening of the Mesozoic series toward the northeast.

Figure 7 shows the rapid thickening of the Mesozoic rift sequence in the footwall of the thin-skinned detachment. At shallower level, the surface expression of this structure consists in a regional backthrust, whereas at deeper level, it is related to the reactivation and inversion of a Mesozoic high-angle fault system. The main Mesozoic depocenter is now inverted and dissected into numerous thrust sheets which account for a number of productive east-trending ramp anticlines at and near the main deformational front (i.e., the El Furial and Orocual trends), which are still deeply buried beneath the Neogene synorogenic series, and for the Serrania topography.

2.3 Inversion processes in Western Venezuela: From intra-plate basement short-cuts to foreland basement uplifts

Western Venezuela and Colombia are characterized by the occurrence of a Jurassic rifting episode which accounts for the development of north- and northeast-trending normal faults associated with Jurassic grabens. Outcrops in the Merida Andes and Sierra de Perija in Venezuela, and in the Eastern Cordillera of Colombia, help to study the Jurassic synrift sequences, which are dominantly made up of continental red beds and volcanics of the La Quinta Formation. The same series were also identified from subsurface drilling in the Maracaibo Basin, where industry seismic profiles helped to better understand the successive steps of basin inversion, from almost undeformed grabens still located at 2 or 3 km below the sea level along the western side of the Maracaibo Lake (Colletta et al. 1997; Roure et al. 1997; Fig. 8), up to the area of major foreland basement uplifts such as the Merida Andes and Eastern Cordillera, where

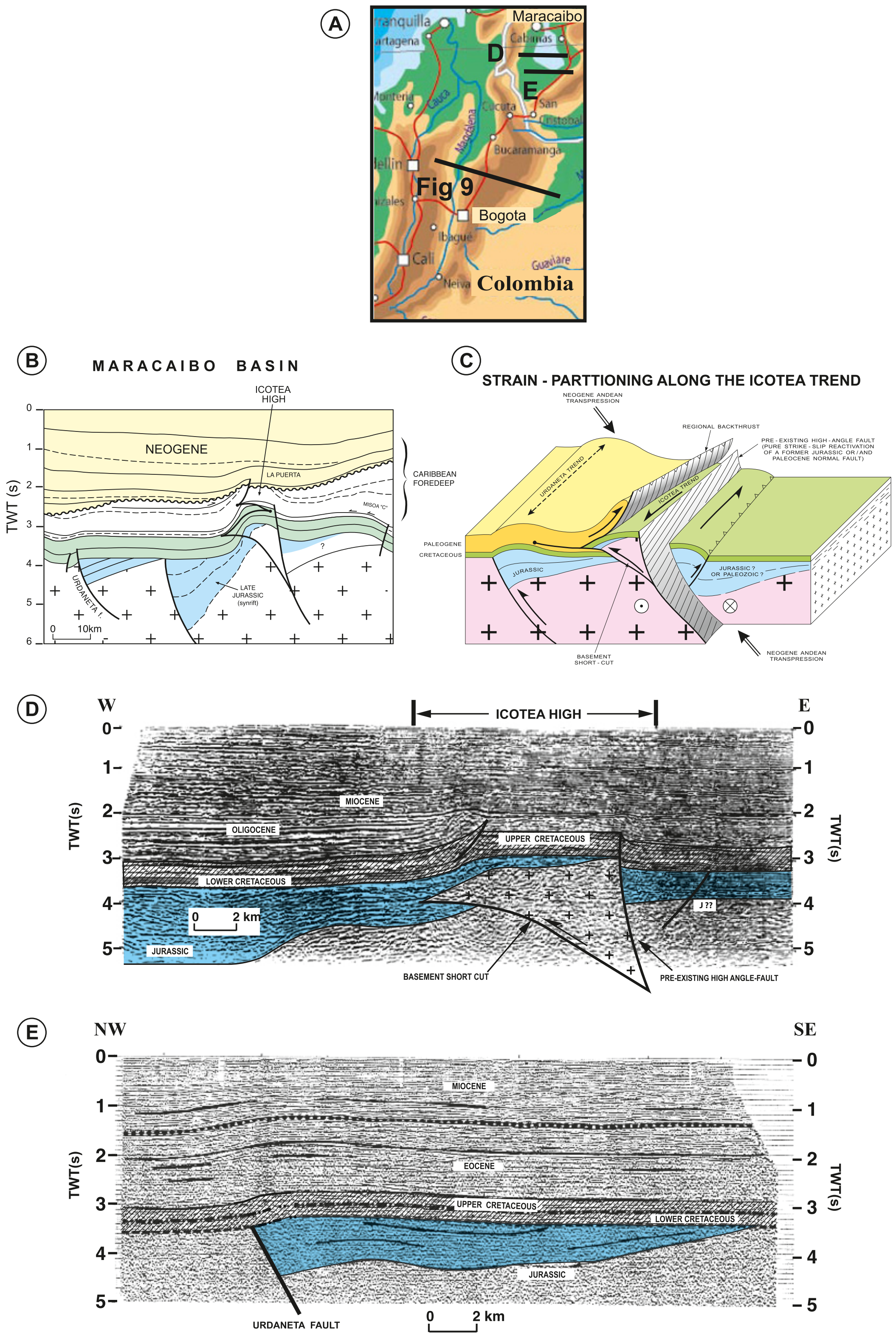

Fig. 8. Structural sections across the Maracaibo Basin (Venezuela), outlining the role of Jurassic normal faults in the localisation of Laramian and Andean inversion features (modified after Roure et al. 1997): a) Location map; b) Synthetic and contracted section across the Maracaibo Lake, outlining the distribution of the main Jurassic depocenters; c) 3D block diagram outlining the basement short-cut and fish-tails associated with the transpressional reactivation of the Icotea trend; d) Seismic profile across the Icotea trend, outlining a basement short-cut and passive transport of the pre-existing Jurassic normal fault. e) Profile across the Urdaneta Jurassic half-graben, outlining a slighter inversion.

the Jurassic series are now exposed at more than 2 or 3 km of elevation (Fig. 9).

Because paleostress directions changed with time (Freymüller & Kellogg 1993; Freymüller et al. 1993), from a dominantly north-south maximum principal stress during the Caribbean/Laramian deformation episodes (Late Cretaceous to Eocene), to a rather northwest-southeast attitude of the main horizontal stress during the Late Miocene-Pliocene Andean deformation, Jurassic normal faults of the Maracaibo Lake have been reactivated successively as right-lateral or left-lateral transpressional features, with also a few episodes of transtension.

Limited inversion occurred along the Urdaneta trend in the south of the Lake, where Jurassic grabens are still overlain by flat Albian and younger post-rift and synflexural series.

Farther north, incipient inversion accounts for the folding of the Albian unconformity, with zero displacement at the tip of the underlying Jurassic border fault (Fig. 8c).

In contrast, oblique inversion becomes the dominant structural style along the Icotea trend, in the north-central part of the Lake, where it accounts for localized basement highs. Careful analysis of seismic profiles shows that the main Jurassic normal fault has been passively uplifted but still preserves its normal offset along the eastern border of the Icotea High, whereas the western border of this anomalous topography is related to a west-verging late-stage reverse fault accounting for a basement short-cut (Fig. 8d).

East-west horizontal shortening is very limited in the area of Maracaibo Lake. Most thin-skinned tectonic structures are localized in the vicinity of the basement-involving inversion features and are related to transpression, with the occurrence of numerous fish tails and other local accommodation features induced by a mechanical decoupling between the rigid basement and more plastic sedimentary cover (Roure et al. 1997). Larger shortening accounts for the major foreland uplifts of the Merida Andes and Eastern Cordillera, which will be further discussed in Chapter 4.

3 Thrust-top basins as a mirror of sub-thrust tectonic accretion

Piggyback or thrust-top basins developing on top of the mobile allochthonous edifice have been identified first in the Apennines a long time ago (Ori & Friend 1984; Casero et al. 1991). They are also well documented in Sicily (Caltanissetta Basin; Roure et al. 1990b), as well as in Eastern Venezuela (Morichito Basin; Roure et al. 1994b) and in many other thrust belts where depocenters have developed at the rear of frontal anticlines, being either isolated or still in direct connection with coeval sediments infilling the adjacent foreland basin.

Although they commonly display contrasting lithofacies, usually shallow marine or continental, making direct chronostratigraphic correlations with the deeper-water foredeep sediments a bit challenging, their basal and successive internal unconformities usually provide unique constraints to document the timing of tectonic accretion. Progressive tilting of these imbricated unconformities and coeval lateral shifts of piggyback depocenters can be used also as additional templates to guide the geologist when addressing forward kinematic modelling and editing intermediate geometries between the present and pre-orogenic configurations:

- In the southern Apennines, subthrust accretion of deeply buried Mesozoic platformal duplexes beneath the basinal Lago-Negro nappes and Neogene clastics of the Bradano Trough accounts for the development of nappe anticlines, tectonic windows and klippen, which result from the refolding of former thrusts and coeval erosion (Fig. 10; Roure et al. 1990a, 1991). Piggyback basins can also develop above flat segments of the sole thrust, in the core of overlying nappe synclines, and help to decipher whether tectonic accretion operates farther east at the thrust front, or farther west, by underplating of deeply buried duplexes (Fig. 10, bottom; Hippolyte et al. 1991, 1994; Roure et al. 1991).
- Pleistocene piggyback depocenters observed along a famous seismic transect published by Pieri and Bally in the Northern Apennines (Pieri 1983; Fig. 11a) provide also evidence for post-Pliocene and still ongoing deformation along the basal décollement, which is located at more than 10 km depth in this portion of the Apennines (Scrocca et al. 2007). Along this transect, Pliocene and older outcrops are located in wide regional antiforms that developed above the ramps of the deeper, still active décollement, whereas Pleistocene depocenters are found above its flat segments (Fig. 11b). In this case, the lithospheric flexure also had a direct control on the subsidence pattern of the foothills, as evidenced by forward kinematic simulations (Zoetemeijer et al. 1992, 1993):

Tectonic accretion above a flat décollement surface would rather generate uplift and erosion in the hinterland, in an area where the main Pleistocene depocenter is located, thus implying that thrusting operated synchronously with ongoing flexural subsidence of the underthrust foreland lithosphere.

4 The development of hinterland basins: a combination of strain partitioning, strike-slip faulting and thrust reactivation

Collisional orogens like the Alps and the Pyrenees and American cordilleras like the Andes and Rocky Mountains do share a number of surficial similarities, although their driving mechanisms are quite distinct at a deeper level, with the juxtaposition of two continental lithospheres in the Alps and the Pyrenees, vs. complex interplays between the American continents and the subduction of the Pacific Ocean in the Andes and the North American Cordillera:

- In these two contrasting types of orogens, oblique convergence accounts for strain partitioning, most of the oblique component being frequently absorbed along active strike-slip faults which run parallel to the plate boundary (Chemenda et al. 2000; Martinez et al. 2002; Lingrey 2007). This is the case for instance with the Periadriactic Line in the Alps

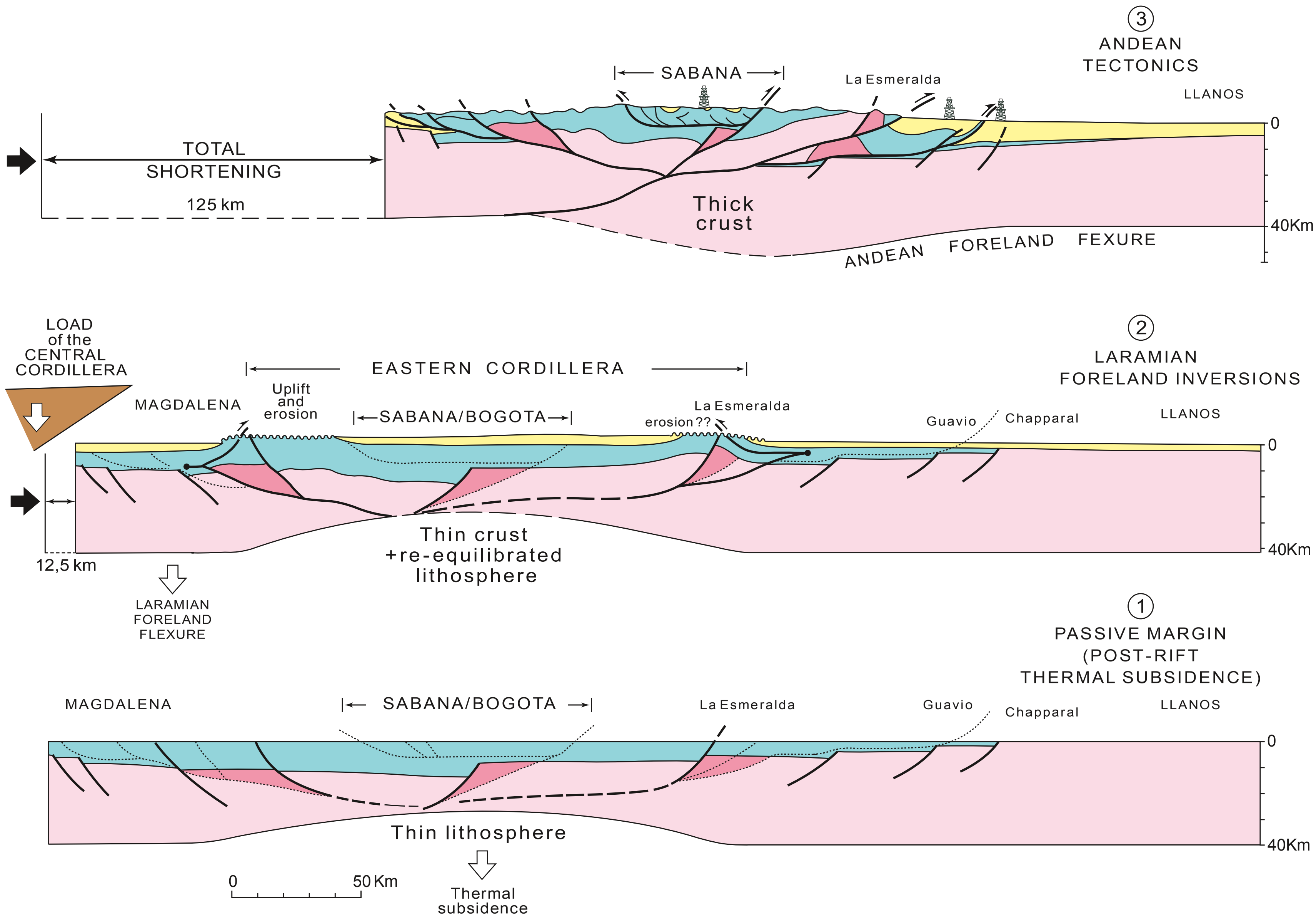

Fig. 9. Structural section across the Eastern Cordillera of Colombia, outlining the control of Jurassic normal faults and basement short-cuts in large Andean foreland basement uplifts (see location in Figure 8a): Top section: Present stage accounting for the overall inversion of the former Jurassic depocenter of the Sabana de Bogota. Notice also the geometry of the Esmeralda Fault, a former Jurassic fault which has been passively transported piggy-back of the main east-verging basement up-thrust of the Cordillera; Central section: reconstruction at the end of the Laramian orogeny (Eocene). Notice localized erosions in the Laramian foreland, due to incipient inversion features similar to the present-day Icotea trend of Western Venezuela (compare with Figure 8); Bottom: Pre-orogenic architecture of the transect.

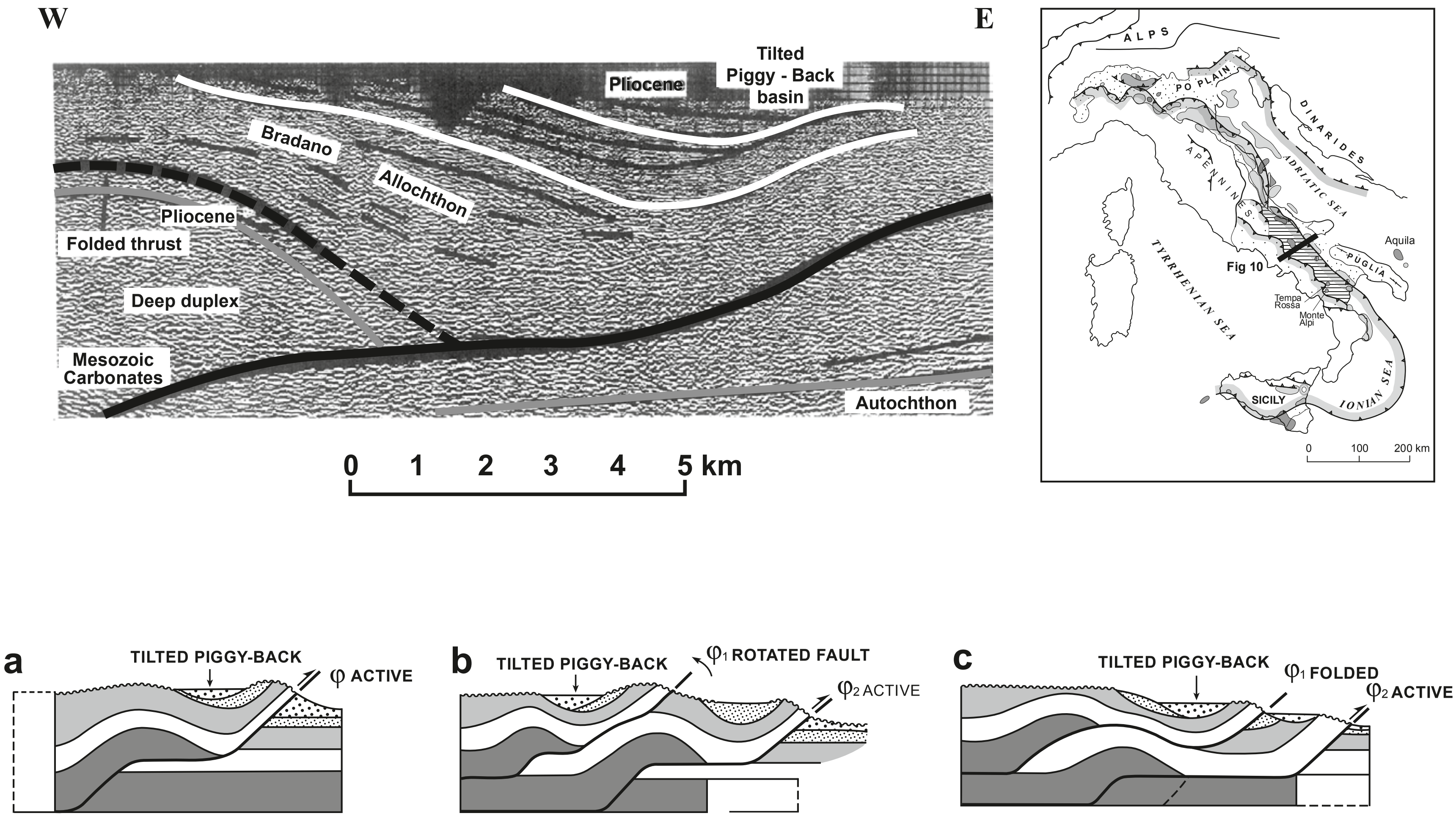

Fig. 10. Structural sections across the Southern Apennines, outlining the role of deep buried duplexes in the overall architecture and tilting of thrust top basins (modified after Roure et al. 1991).

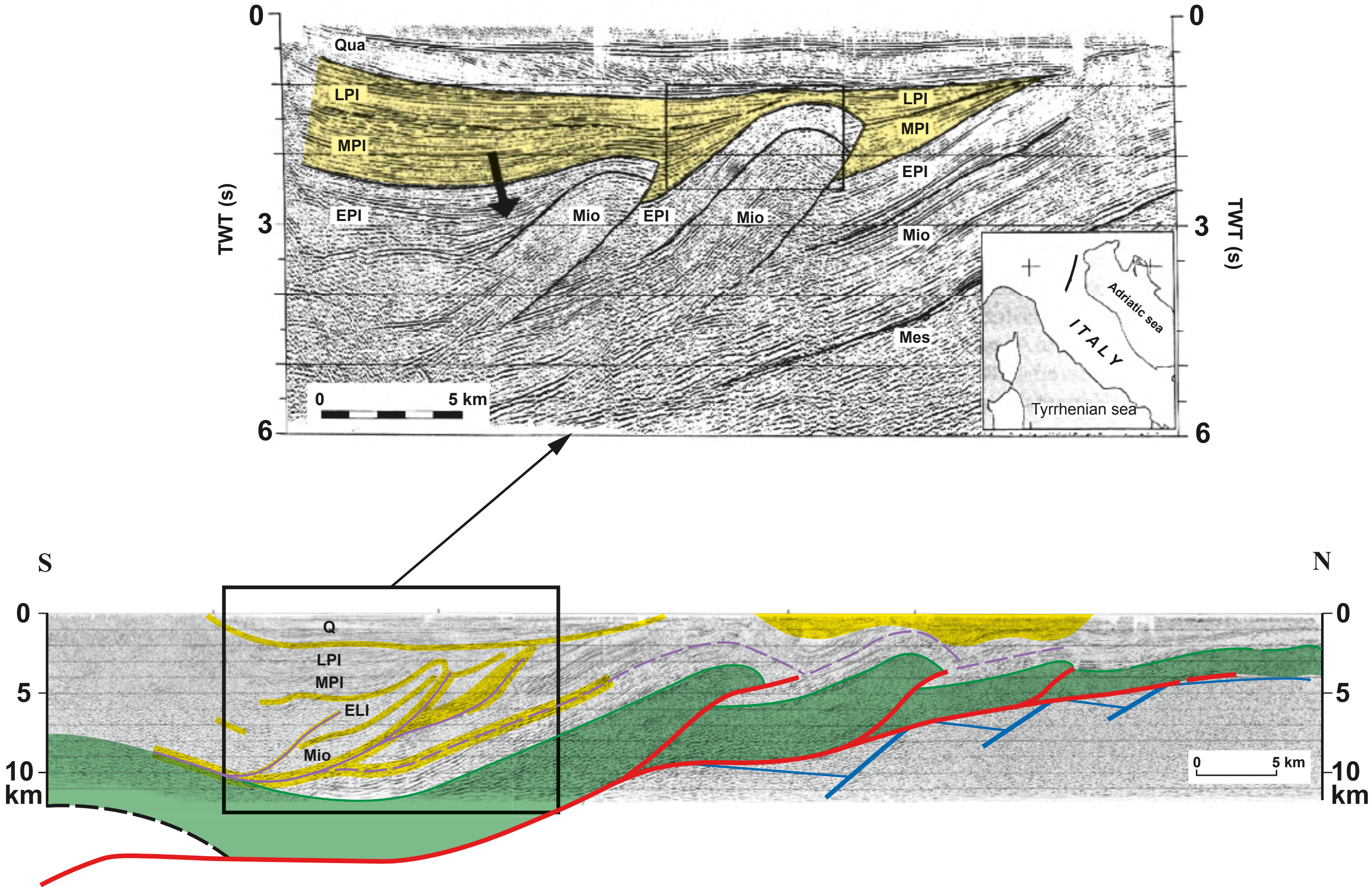

Fig. 11. Structural section across the Northern Apennines, outlining synkinematic Pliocene and Quaternary deposits, and ongoing displacement along the basal décollement (seismic profile from Pieri 1983): Top: Stratigraphic calibration of shallow horizons made by Pieri and Bally (in Pieri 1983). Black arrow and frame show progressive onlaps of growth stata on Pliocene anticlines. Bottom: Deep interpretation outlining the diachronous activation of an early intra-Miocene decollement level (pink, mainly active during the Lower and Middle Pliocene), and a deeper, younger intra-Triassic basal detachment (red, mainly Upper Pliocene but still active during the Quaternary).

(Schmid et al. 2004) and the North Pyrenean Fault in the Pyrenees. The indentation and eastward escape of the intra-Carpathian blocks account also for the post-collisional Miocene strike-slip dismembering of the former Pieniny Klippen Belt (Sauer et al. 1992). Strain-partitioning in areas of oblique convergence accounts also for the northward escape of the Salinian block west of the San Andreas Fault in California, for the southward motion of the Maracaibo indenter west of the Bocono Fault in the Merida (Venezuelan) Andes, and the eastward escape of the Carribean plate north of the El Pilar fault in Eastern Venezuela (Freymüller & Kellogg 1993; Freymüller et al. 1993). Due to partitioning, transport direction remains dominantly perpendicular to the thrust anticlines in the foothills.

– Overthickened crust of the Alps, other Tethyan/Mediterranean orogens and the American Cordilleras was affected by a ductile flow of the lower crust, associated with well-documented post-orogenic collapse and orogen parallel extension in the Basin and Range (Wernicke 1981), as well as in the Betic and Rif orogens and the intervening Alboran Sea (Dewey 1988). Although aternative hypotheses involving a roll-back of the subduction and coeval back-arc opening have been proposed for the Pannonian Basin, the Aegean and Tyrrhenian domains, where no former high mountain plateau could account for a post-orogenic gravitational collapse, these areas display also evidence of reactivation of former thrust faults as low-angle normal faults. Negative inversion is effectively obvious at various scales within these three intra-arc systems, i.e. in Hungary (Horvath 1993; Peresson & Decker 1997; Tari et al. 1999; Horvath et al. 2006), in the Cycladic Islands and the Apennines (Bally et al. 1988; Ghisetti et al. 1993; Brun et al. 1994; Jolivet et al. 1994, 1998; Ghisetti & Vezzani 2002).

Paleomagnetic and microtectonic studies performed in the Southern Apennines and adjacent Bradadano and Puglia foreland (Hippolyte et al. 1991, 1994) could identify periods of strong coupling between the allochthon and the foreland, i.e., paleostress directions being then similar on both sides of the thrust front, separated by time intervals when a complete decoupling between the thrust belt and the autochthon prevailed, with very distinct paleostress directions.

Various parameters such as pore-fluid pressure in potential décollement levels and thermomechanical behaviour of the lower crust and sub-continental mantle probably control the coupling or decoupling between the orogen and its foreland, foreland inversions developing when all the tectonic stress propagates forelandward from the plate boundary during periods of strong coupling (Ziegler et al. 1998, 2002).

These successive changes in coupling and decoupling between the hinterland and the foreland, associated with deeper controls exerted by the structural grain of the crust (i.e., occurrence of pre-existing weakness and inherited structures in the crust), or with the negative inversion of former thrusts, are the main processes accounting for the localisation and development of hinterland basins:

4.1 Post-orogenic collapse and negative inversion of former thrusts

The negative, extensional inversion of former reverse faults is a common phenomenon in the hinterland of most orogens, where it accounts for the development of syn-extensional depocenters, i.e. in the Basin and Range province of the USA (Wernicke 1981), in the hinterland of the Canadian Rocky Mountains (Price 1986), in the Betic Cordillera and Alboran Sea (Dewey 1988), and the Tyrrhenian side of the Apennines (Jolivet et al. 1994, 1998). Additionally, localisation of the deformation along former orogenic structures has been envisioned or even demonstrated in many rift systems and passive margins, i.e. for the Jurassic basins of northern Colombia and western Venezuela, for various segments of the East African Rift, but also for the northwestern margins of the Atlantic Ocean and Gulf of Mexico, which were prone to reactivate former thrusts of the Appalachians and Ouachita Paleozoic orogens (Ando et al. 1983; Hatcher et al. 1989), as well as for the Caledonides in Scandinavia and off England (Séguret et al. 1989; Séranne et al. 1989, 1995; Séguret & Benedicto 1999; Séranne 1999).

In France, negative hinterland inversion associated with syn-extensional basin development has been well documented locally:

- In the Aquitaine Basin, the North Pyrenean deep seismic Ecors profile has evidenced the development of Permian grabens above reactivated Hercynian thrusts (Choukroune et al. 1990; Roure et al. 1996). Although there is no seismic profile yet available, the same process could probably account for many other post-Hercynian European basins, such as the Permian Lodève Basin in the vicinity of the Montagne Noire, where post-orogenic collapse has been well documented on the basis of microtectonic and petrofabric data (Faure & Becq-Giraudon 1993; Becq-Giraudon & van den Driessche 1994; Burg et al. 1994).
- In Languedoc, Oligocene extension associated with the opening of the Gulf of Lion and Western Mediterranean is known to have locally reactivated Pyrenean thrusts in the St-Chinian Arc and Montpellier fold (Benedicto 1996; Benedicto et al. 1996; Séguret & Benedicto 1999), thus accounting for the development of the Quarante Basin and adjacent roll-over regionally know as the La-Clappe anticline (Roure et al. 1988; Fig. 12).

4.2 Thrust-top pull-apart basins

The Vienna Basin is probably the most famous and archetype of thrust-top pull-apart basins, developing above the Alpine allochthon after its thrust emplacement, in connection with lateral eastward block escape along the Carpathian arc (Royden 1985; Sauer et al. 1992; Seifert 1996; Decker & Peresson 1996).

Other pull-apart basins have developed in the hinterland of Circum-Mediterranean thrust belts, i.e. in the Apennines and in North Algeria, as a result of local and temporal changes in the paleostress regimes, and in relation to strain partitioning.

The physiography and lozenge shape of the Chelif Basin in North Algeria is well identified on geological maps and landsat imagery (Fig. 13). This basin is located north of the Tellian thrust front, which reached its current position during the Langhian (Frizon de Lamotte et al. 2000; Roca et al. 2004; Benaouali et al. 2006). It is adjacent to a major east-trending lineament, known as the "Dorsale Calcaire", which separates the Kabylides crystalline basement in the north from the Tellian nappes in the south, and most likely behaved as a major strike-slip fault during the development of the Chelif Basin.

The Neogene sedimentary infill of the Chelif Basin comprises Burdigalian to Langhian synkinematic series, which were deposited in a piggyback position at the same time as the main southward thrust emplacement of the Tellian nappes, at a time when oblique convergence, transpression and strain-partitioning affected the plate boundary. These basal deposits were overlain by post-nappe Tortonian to Pliocene depocenters, which are spatially limited and controlled by active normal faults. These normal faults, locally exposed at the surface, can be also traced down to the deepest part of the basin on seismic profiles and are indicative of an Upper Miocene-Pliocene episode of transtension along the North African plate boundary. These faults are oblique (en échelon) with respect to the Dorsale Calcaire lineament. In a similar way as the El Pilar Fault in northern South America, the Dorsale Calcaire lineament accommodated the lateral shift of the Kabylides with respect to the Tell allochthon and underlying underthrust African foreland during a Tortonian to Pliocene post-nappes episode of transtension.

Plio-Quaternary inversion of these depocenters accounts for renewed transpression along the plate boundary, with folding and erosion of Pliocene series in the vicinity of the major border faults of the Chélif Basin.

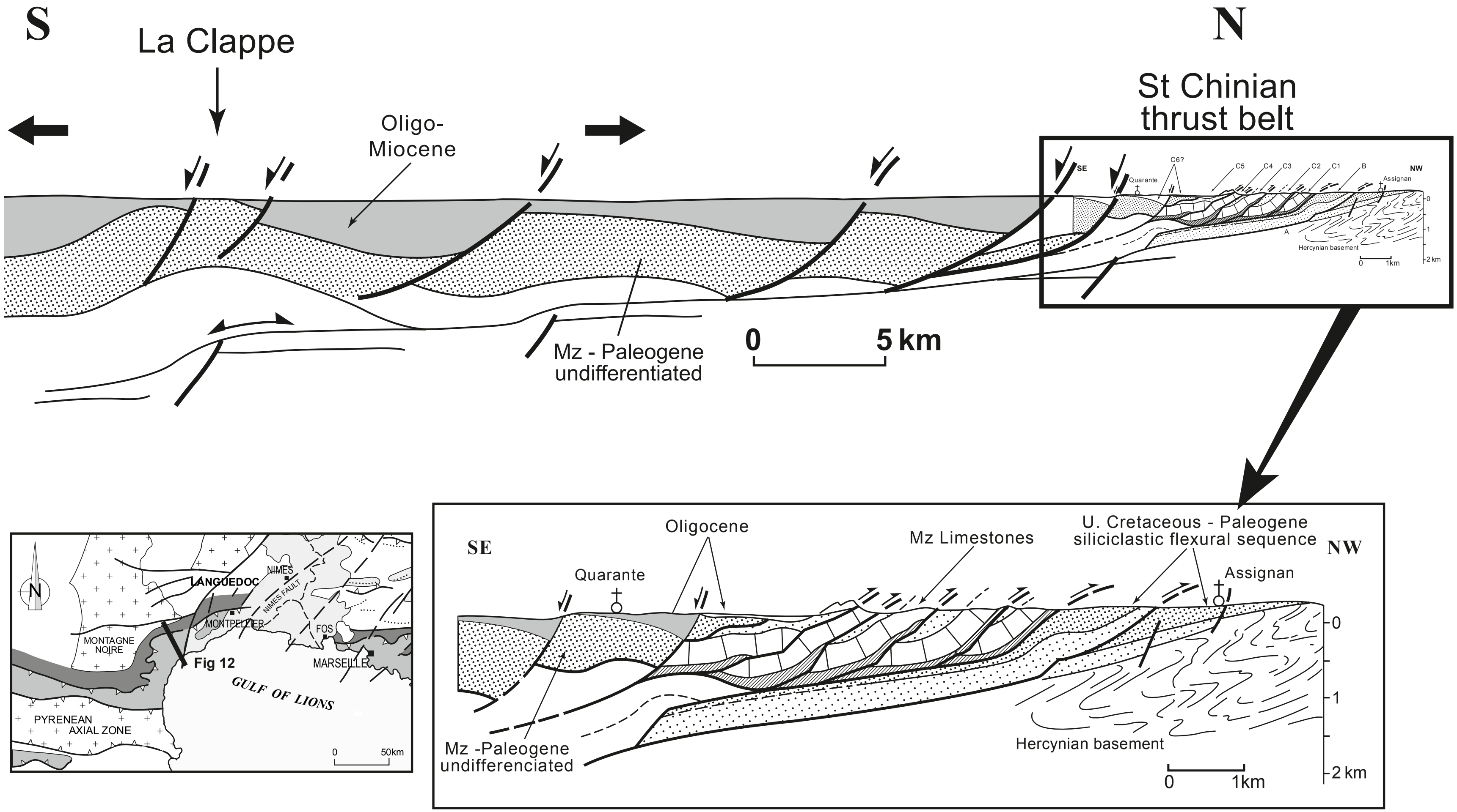

Fig. 12. Structural section across the Quarante Fault and La Clappe anticline in Languedoc (northern Pyrenean foreland), showing the Oligocene negative inversion of the former Late Cretaceous to Eocene north-verging thrust system.

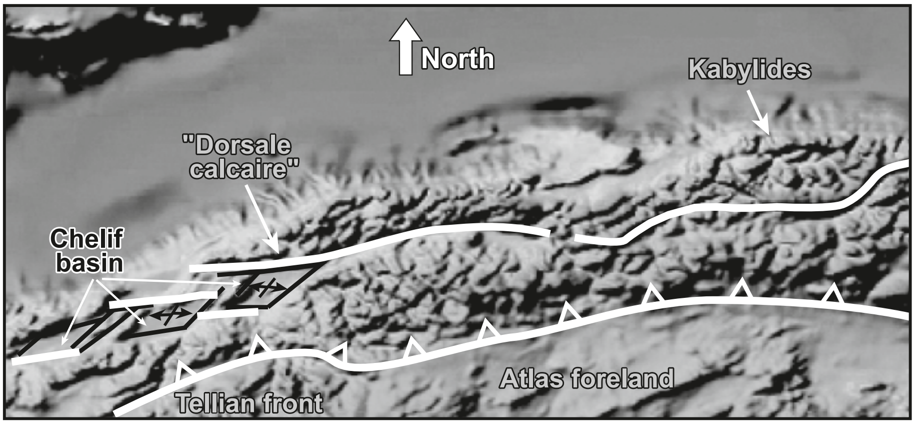

Fig. 13. Landsat image of Northern Algeria, outlining the distribution of thrust-top pull-apart depocenters of the Chelif Basin associated with a major east-trending lineament (Dorsale Calcaire), between the Tellian thrust front in the south and the Kabylides-Western Mediterranean plate in the north.

4.3 Intra-crustal backthrusts and development of intramontane basins

Analogue models accounting for the flow of the ductile lower part of an overthickened continental crust have been proposed to account for the development of pop-down intramontane basins such as the Magdalena Basin in Colombia (Davy & Cobbold 1991), where thick and dominantly continental Neogene deposits have been trapped between the growing topographies of the Central and Eastern Cordilleras.

Industry seismic profiles across the Llanos foothills, Garzon Massif and Middle Magdalena Basin help to constrain regional balanced cross-sections and to propose new interpretations for the crustal structure of this transect, whereby the regional west-verging backthrust of the Garzon Massif connects at depth with former Paleozoic east-verging thrusts (Fig. 14; Roure et al. 2003, 2005a; Toro et al. 2004; Sassi et al. 2007).

Occurrence of Paleozoic thrusts in the Llanos foreland has also been recognized farther north in the Barinas Basin in Venezuela (Fig. 14b). It is likely that this inherited structural grain of the South American foreland accounted for both the localisation of the Jurassic rifting (Fig. 9), and subsequent Andean foreland basement uplifts.

As such, the present day location of the Maracaibo Basin is very similar to the one of the Magdalena Basin. Although the Maracaibo area is mostly interpreted as a distinct microplate, it could also be adequately considered as an intramontane basin, which became isolated from the main Llanos foreland basin in the east due to the intervening Neogene basement uplift of the Merida Andes.

5 Mantle dynamics and post-orogenic uplift of foreland basins

5.1 Post-orogenic uplift and erosion of foreland basins

Many foreland basins are no longer close to the sea level, but have experienced uplift and erosion since the end of the main compressional/tectonic loading episodes (Fig. 15):

- In North Algeria, Langhian deep-water turbidites deposited near Tiaret in the foreland autochthon, immediately south of the Tellian thrust front, are presently located at an elevation of 1 km above sea level (Roca et al. 2004).
- In the Alberta Basin in Canada, up to 3 km of synflexural sediments were removed by erosion since the end of the Laramian/Cordilleran deformation, i.e. from Eocene onward (Faure et al. 2004; Hardebol et al. 2007). Worth to mention, the city of Calgary itself, which is located in the foreland autochthon, about 100 km east of the thrust front, currently displays an average elevation of 1 km above sea level, which is quite surprising for an ancient foredeep basin (Price & Fermor 1985; Price 1994; Fig. 15a).
- The same type of post-orogenic uplift and erosion of former flexural sequences occurred also along the western margin of the Gulf of Mexico, i.e. in the foothills of the Sierra Madre Oriental and adjacent coastal plain, which is actually superimposed on the former Cordilleran foreland basin. Up to 4 km of post-Laramian erosion is thus recorded in the Burgos Basin in the north, and about 2 to 3 km farther south in the Chicontepec Basin and in the Cordoba Platform in the Veracruz State (Fig. 15b) (Gray et al. 2001; Roure et al. 2008).

In Mexico, these post-orogenic uplift and unroofing processes have completely changed the former attitude of the basement, which is currently dipping toward the east beneath and in front of the Cordoba Platform, whereas it was dipping westward at the time of foreland basin development. Late Cretaceous to Paleocene turbidites and gravity slides infilling the former Chicontepec flexural basin currently display apparent downlaps toward the Faja de Oro or Golden Lane, whereas they were initially deposited as onlapping sequences, prior to post-orogenic tilting and unflexing of the foreland basement (Alzaga et al. 2007a, b).

Erosional products derived from the Sierra Madre itself, but also from post-Laramian uplift and unroofing of the adjacent foreland, account for a huge Oligocene to Neogene siliciclas-

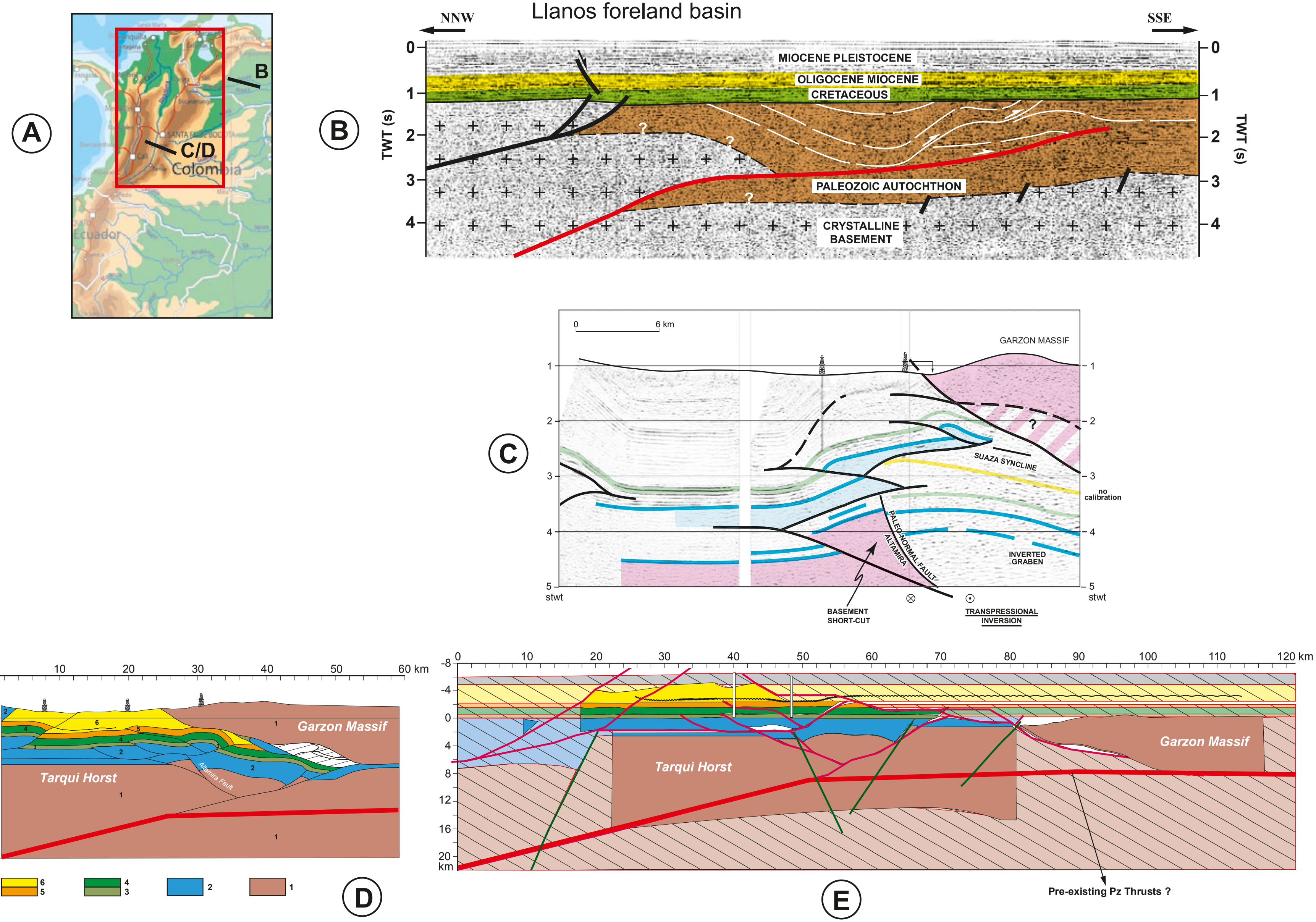

Fig. 14. Crustal section across the Eastern Cordillera and Middle Magdalena Basin (Colombia), outlining the likely tectonic control of Paleozoic thrusts in localising Jurassic extension and subsequent thrust development west of the Llanos foreland basin (after Roure et al. 2005): a) Location map; b) Seismic profile across the Barinas Basin, outlining the occurrence of east-verging Paleozoic thrust sealed by the Albian unconformity (modified after Colletta et al. 1997); c) Seismic profile across the Altamira High, outlining inversion features similar to the Icotea trend of western Venezuela (compare with figure 8). d and e) Balanced cross-section across the Middle Magdalena Basin and Garzon Massif, showing crustal wedging, development of a foreland-dipping monocline associated with the forelandward propagation of a blind thrust (thick red line) beneath the Llanos Basin and antithetic west-verging backthrust of the Garzon Massif. We assume that this east-verging blind thrust is directly controlled by the pre-existing Paleozoic structural grain, Paleozoic thrusts being successively inverted as normal detachments during the Jurassic rifting, and as thrust faults during both Laramian and Andean foreland inversions.

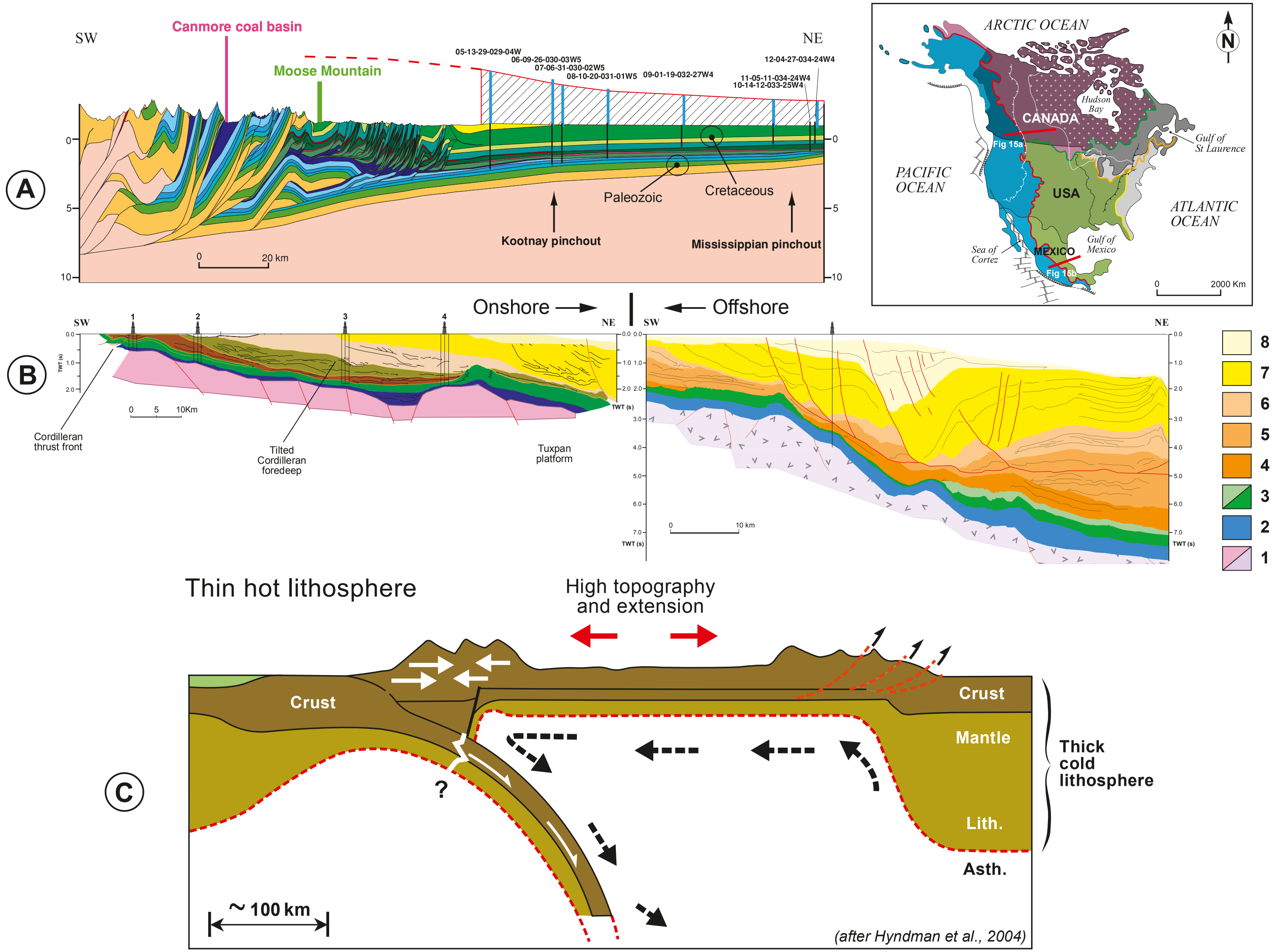

Fig. 15. Lithospheric sections in North America, outlining the role of asthenospheric rise in post-orogenic uplift and erosion of former flexural basins. Location of the sections a and b is shown on the map (blue, green, violet and grey patterns relate to the Pacific, Mississippi-Gulf of Mexico, Arctic and Arctic drainage areas, respectively). a) Structural section across the Canadian Rocky Mountains, outlining the amount of post-Laramian uplift and erosion (modified after Faure et al. 2004). Amounts of erosion have been derived from 1D thermal modelling on wells (foreland) and outcrop data (foothills). Thick Paleozoic (i.e. Cambrian, Devonian and Mississippian passive margin carbonates) and Cretaceous synflexural series are indicated by circles. Intervening Permian to Jurassic series are very thin along this section. b) Structural section across the Sierra Madre Occidental and Gulf of Mexico, outlining the post-orogenic tilting of the former Laramian foredeep basin and foreland basement, coeval with more than 4 km of erosion and denudation in the Sierra Madre and Cordoba Platform (modified after Alzaga et al. 2008). Colour code: (1) basement; (2) Jurassic; (3) Cretaceous; (4, 5 & 6) Paleogene; (7) Miocene); (8) Plio-Quaternary. c) Lithospheric section across the East-Pacific subduction and North American Cordillera, outlining the asthenospheric rise above the retreating subducted slab (modified after Hyndman et al. 2005). Deep mantle processes are advocated here to account for high elevations, rapid denudation and extension in the Basin and Range province, from Canada to Mexico.

tic sedimentary influx into the Gulf of Mexico, resulting in the building of overpressures in underlying Eocene shales and to the gravitational collapse of the margin (Alzaga et al. 2007a, b). Post-orogenic erosional products derived from the uplift of the Alberta foreland basin, which is devoid of any post-Cretaceous series, have also been certainly transferred either to the north into the Arctic, or to the south into the Gulf of Mexico, depending on the actual position of the continental divide between the Mississippi and Arctic basins during the Eocene and younger periods.

Apart from this Cordilleran example, where vertical motion is controlled by an astenospheric rise, post-orogenic uplift and erosion are also common processes in other orogens such as the Alps, the Carpathians, the Apennines-Maghrebides-Betics system, as well as in the Brooks Ranges, among others. Unlike in the Cordillera, where the subduction of the Pacific Ocean lithosphere beneath the orogen never stopped, alternative hypotheses involving a slab detachment, as described below, have been proposed to account for the recent vertical motion recorded in most Circum-Mediterranean and Alpine orogens (Wortel & Spakman 1992, 2000; van der Meulen et al. 1998; Frizon de Lamotte et al. 2000; Roca et al. 2004)

5.2 Mantle dynamics and coupling with surface processes

Mantle dynamics constitute the engine accounting for the post-Laramian uplift and erosion of the Canadian and Mexican forelands. Due to a corner effect of the Pacific subduction, hot mantle is progressively thinning and uplifting the North American lithosphere over an extremely wide surface, accounting for the post-Laramian collapse of the Cordilleran orogen coeval with the development of metamorphic core complexes and basin and range-type extension, for recent volcanic activity, but also for the wide doming and unroofing observed in the foreland, from Canada to southern Mexico (Price 1986; Hyndman et al. 2005; Fig. 15c).

In the Central Apennines, rapid changes observed during the Upper Pliocene and Pleistocene in the subsidence history of the Adriatic foredeep and coeval increase in the uplift rates of adjacent foothills have been interpreted as an evidence for slab detachment, the slab pull no longer contributing to the down-flexing of the Adriatic foreland lithosphere (van der Meulen et al. 1998; Wortel & Spakman 1992, 2000; Spakman & Wortel 2004). Although such process is still debated, it could actually be proposed also to account for the flexural rebound observed in the North Algerian foreland, south of the Tellian front.

Alternatively, asthenospheric rise and advection of hot mantle in the Western Mediterranean and Tyrrhenian back arc basins could easily explain such late stage vertical motion of the foreland lithosphere (Wortel & Spakman 1992, 2000; Spakman & Wortel 2004).

Conclusions

Strong coupling between the thrust belt and its foreland can occur at different times in both subduction-related (i.e. Cordilleran-type) or collision-related (i.e. Alpine-type) orogens, thus accounting for both early and late foreland inversion processes (Ziegler et al. 1998, 2002).

Since the mid 80's, deep crustal seismic imaging across many orogens such as the Alps, the Pyrenees and the North American Cordillera has provided direct controls on the deep architecture of the thrust systems, and a better understanding of the coupling between thin-skinned and thick-skinned tectonics, whereas since the 90's, mantle tomography is progressively documenting the occurrence or absence of lithospheric slabs beneath recent orogens. In many thrust belts where neither deep seismics nor mantle tomography is yet available, the pending question is to know whether slab detachment may account for rapid uplift and post-orogenic erosion of former foreland basins, as described in the Central Apennines by van der Meulen et al. (1998), or if mantle convection and asthenospheric rise alone can account for post-orogenic uplift, as evidenced in the Alberta and Veracruz basins.

Source to sink studies are also necessary to define the spatial and temporal coupling between erosion, sedimentary transfer and deposition. Until recently, most efforts were devoted to high resolution seismostratigraphic studies coupled with core and outcrop descriptions of the synflexural/synkinematic sedimentary infill of the foreland basins. Today, however, GPS measurements and thermo-chronometers such as Apatite Fission Tracks and U-Th, can provide direct control on the uplift and unroofing history of the hinterland. Ultimately, new techniques must still be developed to provide information on paleo-elevations, which are essential for discriminating between different tectonic models, e.g. orogenic collapse and rollback, and which are also likely to control the boundary conditions (hydraulic heads) required for computing the pore-fluid pressure evolution in adjacent low lands (Schneider 2003; Schneider et al. 2004; Roure et al. 2005b).

Further understanding of the coupling between deep (mantle) and surface (climate) processes in orogens and adjacent foreland basins constitutes one of the main current challenges for Earth scientists, which will require access to well documented data bases to feed numerical models, involving a lot of integration and multi-disciplinary team work. International networks such as the Transmed (Cavazza et al. 2004a, b) and ILP task forces and related workshops may help to initiate these new collaborations. Pioneer work is currently done in Europe (Topo-Europe programme), where continental topography has been indeed widely impacted by the Alpine orogen and recent mantle upwelling in the Western Mediterranean and West European rift system.

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