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Geometry and kinematics of extensional structures in the Alpine Foreland Basin of southeastern France

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Abstract—The basin of southeastern France is developed between the Bresse Graben and the Mediterranean Sea. In this area, the Western European Oligocene rift system is locally superimposed on early Jurassic (Liassic) extensional structures of the Tethyan palaeomargin, and was later involved in Neogene compressive deformation of the Alpine foreland. The aim of this paper is to reconstruct the initial configuration of both thin-skinned and deep-seated Oligocene structures that are now locally inverted, and to separate the effects of Oligocene extension from Liassic extension. Cross-section balancing techniques have been applied to complex multiphase structures whose present geometries are clearly controlled by surface and subsurface geology. The resulting Oligocene configurations are compared with laboratory models and are discussed in terms of the regional extensional history.

INTRODUCTION

EXTENSIONAL structures related to the Western European rift system are clearly defined in the Rhine Graben and in the French Limagne basins (Fig. 1), which are two narrow troughs infilled by late Eocene–Oligocene deposits and bordered by steep basement faults (Michel 1978, Bergerat 1985, Villemin 1986, Brun *et al.* 1991). In southeastern France, however, i.e. from the Bresse Basin to the Mediterranean Sea (Baudrimond & Dubois 1977, Elmi 1983, 1984, Debrand-Passard *et al.* 1984, Curnelle & Dubois 1986, Burrus 1989), coeval Oligocene structures were subsequently overthrust or partially inverted during Neogene Alpine deformation. Oligocene structures were themselves superimposed on earlier Liassic–Mid-Jurassic extensional structures related to the Tethyan palaeo-margin (Lemoine 1982, 1984, Boillot *et al.* 1984, Dumont *et al.* 1984, Bas 1988, Faure & Megard-Galli, 1988, Lemoine & de Graciansky 1988, de Graciansky & Dardeau in press). Regional NE–SW basement-involved structures such as the Cévennes, Nîmes or Durance faults (Fig. 1) (Arthaud & Matte 1974, Bodeur 1976, Arthaud & Séguret, 1981), which form the major boundaries of the basin, thus show complex geometries that result from alternating extensional (Liassic and Oligocene) and compressional (late Cretaceous–Eocene and Neogene) episodes.

This paper deals with the geometry and kinematics of extensional structures in a complex polyphase area, and tries to quantify the respective amounts of Liassic and Oligocene extensional movements. Field studies, exploration wells and seismic lines have been used to constrain the present architecture of four selected polydeformed structures. In fact, conventional seismic reflection lines are available locally (Alès Basin, Manosque-Valensole area, Die area and the Baronnies, Rhône Valley and Ardèche area) and can sometimes be calibrated on exploration wells. These data, which provide crucial information down to the basement, have been used to draw the initial depth sections, which are all constructed along good quality seismic lines. A careful study of the décollement levels and the restoration of the geological sections at several intermediate stages since the initial Liassic rifting event helps to differentiate within the extensional structures, the proportion that is related to the Oligocene and the proportion inherited from early Jurassic extension. A comparison between the balanced sections and laboratory models is made in order to investigate the possible mechanisms of extension and inversion.

REGIONAL GEOLOGICAL AND GEOPHYSICAL BACKGROUND

The basin of southeastern France extends from the Bresse Graben in the north to the Gulf of Lions in the south (Fig. 1), and is bordered to the west by the Hercynian basement of the Massif Central. In the east, its Mesozoic sedimentary infill has been strongly affected by the Alpine compression (Ziegler 1983. Chauve *et al.* 1988, Guellec *et al.* 1990) and, locally, the Palaeozoic basement is also involved in overthrust structures ('Massifs cristallins externes', Gratier & Vialon 1980, Tricart 1984, Gillcrist *et al*, 1987, Mugnier *et al.* 1987, de Graciansky *et al.* 1988, Butler 1989, Gratier *et al.* 1989, Thouvenot & Ménard 1990). Despite extensive surface mapping and petroleum exploration, resulting in more than 60 dry wells deeper than 2000 m and thousands of kilometres of conventional seismic profiles, the deep structure remains largely unknown (Baudrimont & Dubois 1977, Debrand-Passard *et al.* 1984, Curnelle & Dubois, 1986). Nonetheless, a recent deep seismic profile (ECORS Alps 2 and Jura-Bresse; Bergerat *et al.* 1990, Guellec *et al.* 1990, Mugnier *et al.* 1990) has given a high quality image of its northern part. Additional deep seismic profiles are unfortunately only now being discussed for the future in the southern part of the basin.

Lithostratigraphy and décollement levels

Over the entire area, the Palaeozoic basement has been affected by Hercynian deformation, and only some local extension-related Carboniferous and Permian sedimentary deposits are seen to underlie the Mesozoic cover. Nonetheless, the coal measures which commonly occur in these late Palaeozoic sequences produce shallow potential décollement levels in the pre-Mesozoic section. These may have been activated either during the compression (thin-skinned basement units stacked in the external crystalline massifs; Guellec *et al.* 1990, Mugnier *et al.* 1990) or during the extension (Arène *et al.* 1978).

After a late Palaeozoic to early Triassic episode of continental environment, the area remained under marine conditions during most of the Mesozoic up to early Cretaceous–Cenomanian times. Nevertheless, the Mesozoic sequence of the basin of southeastern France thickens rapidly from 0 km in the west (Massif Central)

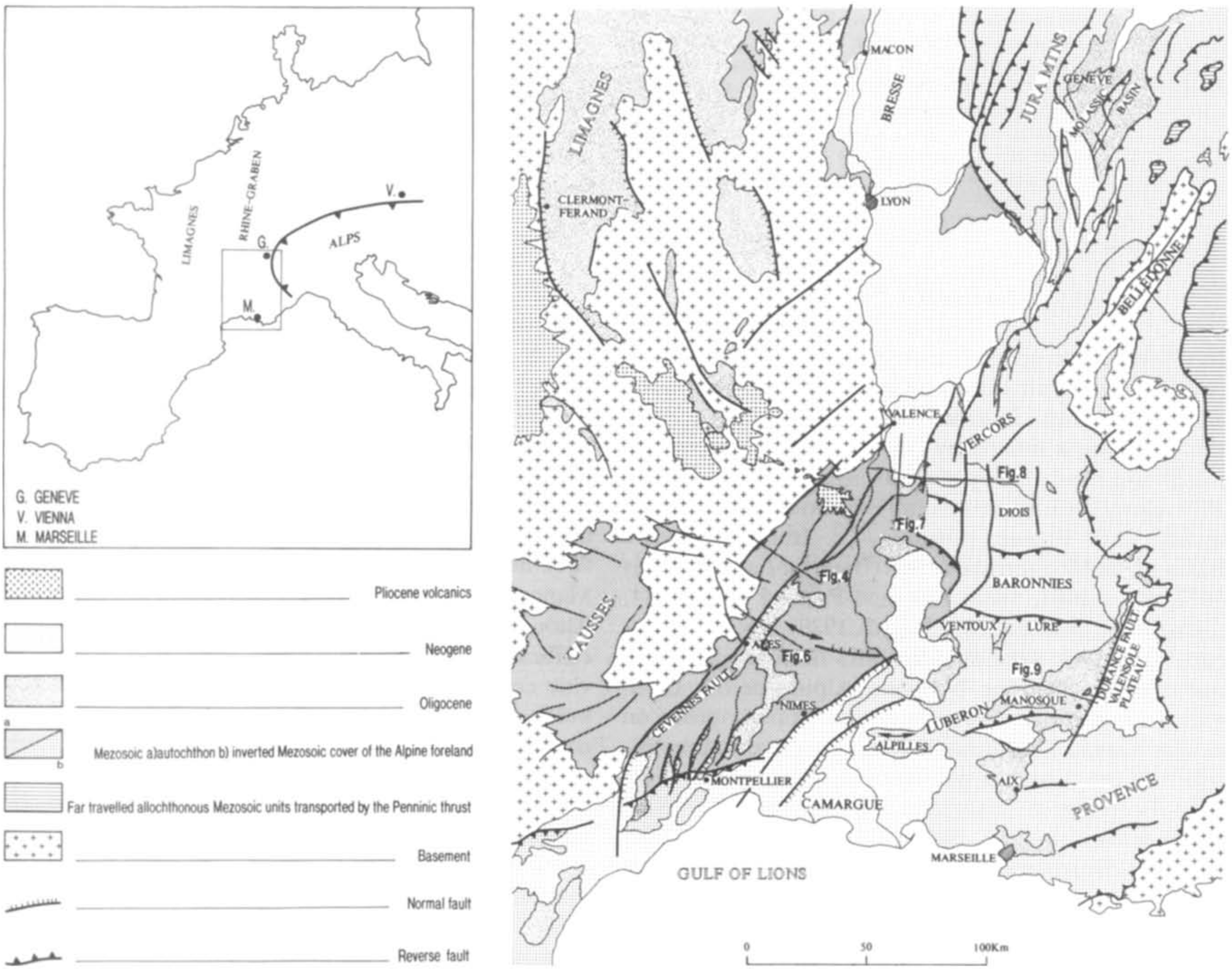

Fig. 1. Structural map of the basin of southeastern France, with location of the four sections: Ardèche border (Fig. 5), Alès Basin (Figs. 5 and 6), Drôme River (Fig. 8) and Manosque Basin (Fig. 9).

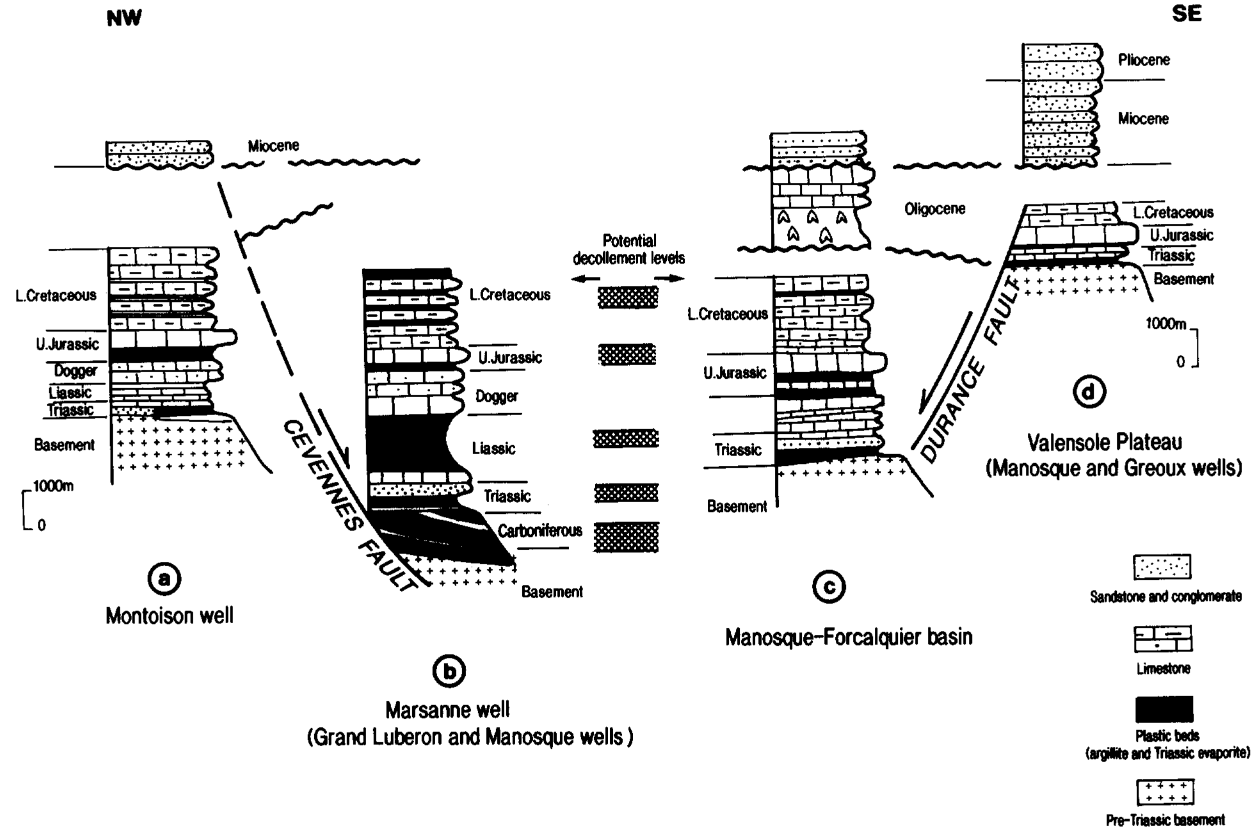

Fig. 2. Lithostratigraphic columns outlining the major potential detachment levels of the Palaeozoic basement and Mesozoic to Cenozoic sedimentary cover in the basin of southeastern France.

to more than 8 km east of the Rhône Valley in its central part (Die area and the Baronnies, Fig. 1). However, thin Mesozoic deposits are encountered east of the Durance Fault beneath the Valensole Neogene molasse (Fig. 1). On a regional scale, the lithostratigraphic column shows a succession of competent beds (basal Triassic sandstones, Middle Jurassic dolomite, Lower Liassic, late Jurassic–Tithonian and Lower Cretaceous–Urgonian limestones) which are interbedded with weaker units (Keuper evaporites, Upper Liassic, late Jurassic–Oxfordian and Valanginian marls; Fig. 2), which may act as décollement levels. However, lateral facies variations, which are produced by emergence and erosion, are common and may help to explain the local absence of décollement levels.

Palaeogene continental sediments are only locally preserved and usually fill narrow Oligocene grabens or elongated basins (Alès, Camargue, Valence, Manosque, Aix and Bresse Basins; Fig. 1). In the south, marine molasse represents foredeep deposits which are linked to the Neogene Alpine lithospheric flexure (Fig. 2).

Strain pattern and timing of deformation

The pre-Oligocene deformational events include:

(a) a poorly defined Triassic extension, only imaged locally by block-faulting and high subsidence rates (Brunet 1984, Mégard-Galli & Faure 1988);

(b) major Liassic rifting, whose stretching orientation is locally 110°N and did not differ strongly from the Oligocene trend (Faure & Mégard-Galli 1988, Grand 1988);

(c) early Cretaceous extension, characterized by E–W-trending normal faults between the Vercors and Ventoux Massifs, controlled development of the Vocontian Trough. This event was coeval with the opening of the Bay of Biscay (de Graciansky & Lemoine 1988);

(d) late Cretaceous to early Eocene Pyrenean compression, with N–S oriented shortening, is responsible for the E–W-trending folds and thrust belt to the south in Provence and Languedoc (Fig. 1), and local reactivation of the Cévennes Fault as a sinistral strike-slip fault (Arthaud & Matte, 1974, Bodeur 1976, Arthaud & Séguret 1981).

For the Oligocene extension, the principal direction of stretching remains remarkably constant (110°N) across the area studied and is slightly oblique in relation to the N040-oriented basement structures of the Liassic margin. Figure 3 summarizes the results of the microtectonic studies carried out in the Corconne–Pic St Loup area (Colletta & Roure, 1986) as well as near Manosque (along the Cévennes and Durance faults, respectively), both in Oligocene and pre-Oligocene rocks. Nonetheless, additional data from literature were also used to compile the map presented here (Meynot *et al.* 1975, Arthaud *et al.* 1977, 1981, Zadeh-Kabir 1983, Arthaud & Etchecopar 1985, Bergerat, 1985, Hippolyte 1988).

Neogene Alpine compression with a horizontal σ_1, progressively rotating from N–S to E–W, induced the tectonic inversion of earlier extensional structures, especially east of the Rhône Valley.

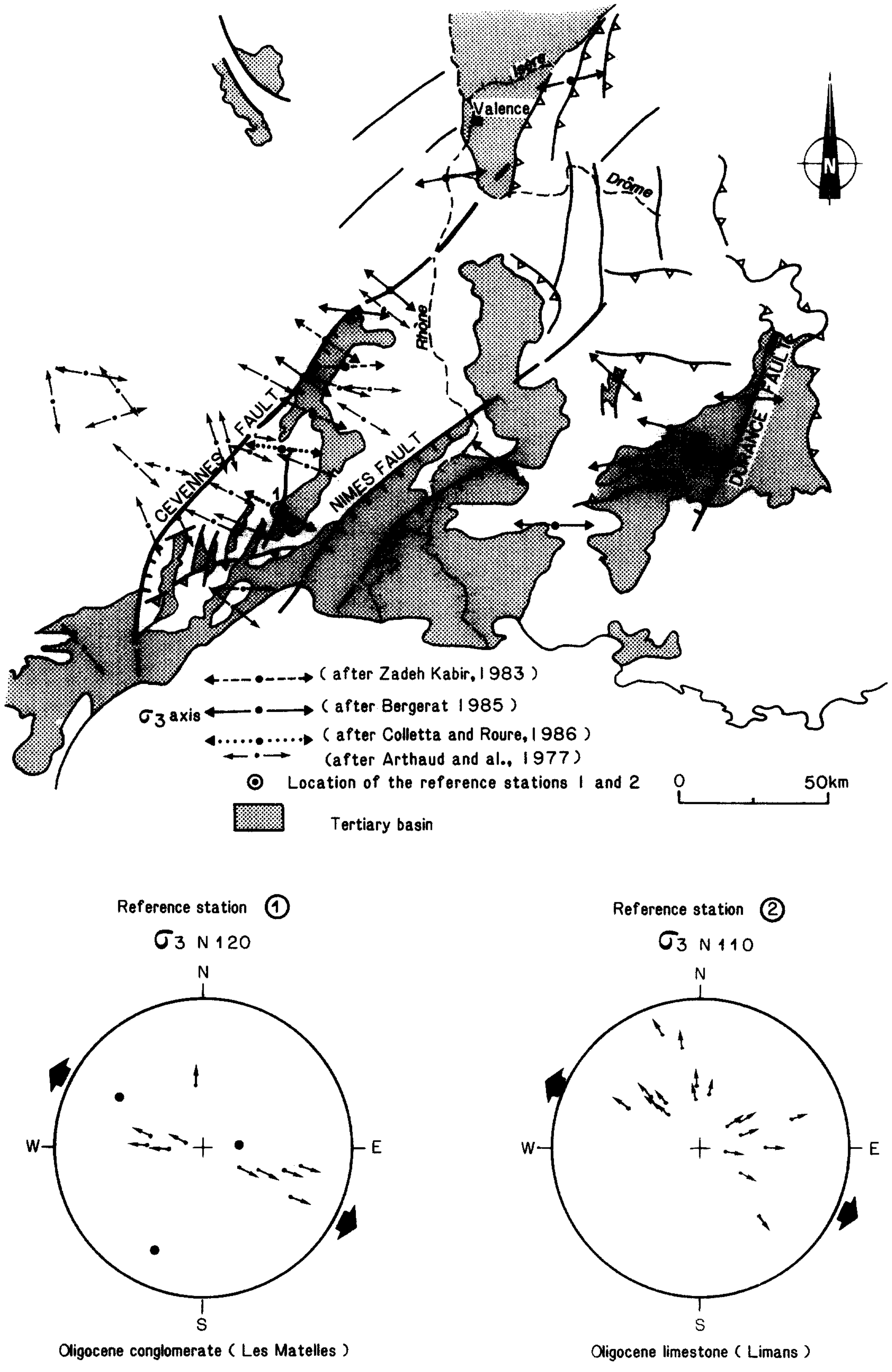

Fig. 3. Regional stress pattern and stereograms of slickenside lineations induced by the Oligocene extension.

Major structures

NE–SW-trending basement structures such as the Cévennes or the Durance faults (Fig. 1) are clearly related to the Liassic extension, and may have directly controlled thickening of the Mesozoic sedimentary sequence. Other parallel structures, for example the Nîmes or Costières faults, were probably developed later since they delineate Oligocene or even Pliocene depocenters, respectively.

Large-scale compressive structures are usually E–W-trending in the south and correspond to the late Cretaceous to Eocene Pyrenean fold- and thrust-systems of Provence (Alpilles, Luberon, Ventoux, etc.) and Languedoc (Montpellier and Pic St-Loup thrust folds). In the east, however (i.e. in the Vercors subalpine massif), N–S-trending folds and thrusts relate to a younger, late Miocene compression (Alpine orogeny).

Two areas may be distinguished as far as Oligocene structures are concerned. These are:

(1) west of the Rhône Valley, where careful analysis is necessary to decipher the principal stretching directions of the Liassic and Oligocene extensional events;

(2) east of the Rhône, where the effects of the Oligocene extension on polyphase structures of the Alpine foreland and fold-and-thrust belt can only be inferred on the basis of restored cross-sections from which the Neogene deformation has been removed.

With the exception of a N–S section across the Cévennes Fault (Fig. 7), all the sections studied here are E–W and thus do not record early Cretaceous extensive or late Cretaceous–Eocene Pyrenean compressive structures.

Geophysical background

Despite the fact that Mesozoic thinning has already affected the European crust, deep refraction data mainly provide information on a younger crustal thinning linked to the Oligocene extension. The depth contours map of the Moho show a narrow zone of thin crust which is parallel to the Rhône Valley (Giese & Prodehl 1976, Hirn *et al.* 1980, Thouvenot *et al.* 1990), branching southward into the Gulf of Lions. Eastward, however, the Moho deepens rapidly beneath the Alps, due to the loading effect of the allochthonous units, which induces a regional flexure in the European lithosphere (Sapin & Hirn 1974, Giese & Prodehl 1976, Michel 1978, Hirn *et al.* 1980, Thouvenot *et al.* 1990).

The present configuration of the Moho, although useful for understanding the late Palaeogene and Neogene crustal evolution of the area, is no help in studying the Liassic crustal stretching. Only indirect methods, such as the study of subsidence curves or Mesozoic facies distribution, can contribute to the prediction of the initial Triassic or Jurassic crustal thicknesses (Brunet 1984, Arthaud 1988, Rudkiewicz 1988).

EFFECTS OF EXTENSIONAL EPISODES WEST OF THE RHONE RIVER

A recent ECORS deep seismic profile across the Bresse Basin (Fig. 1) (Bergerat *et al.* 1990) has shown that, in addition to the late Eocene evaporitic layers, the Triassic evaporites also acted locally as a detachment level during the Oligocene extension. As a result, there is a complete decoupling of the gently folded Mesozoic cover which wraps over the underlying tilted basement blocks. According to the respective lengths of the Palaeozoic and Mesozoic beds involved in the Oligocene structures of the Bresse Graben, cross-section balancing predicts denuded areas of the basement in the east, from where the Mesozoic cover has progressively glided westward.

In the Languedoc area, however, Liassic carbonate units show numerous tilted blocks that are also detached above the Triassic décollement level (Petit *et al.* 1973, Roure *et al.* 1988). Nevertheless, the late Liassic age of deformation is well constrained by the occurrence of synrift Liassic marls and overlying unconformable Mid-Jurassic limestones.

On a regional scale, the Triassic decoupling level was thus locally active either during the Liassic or the Oligocene extensional events. Nevertheless, the following section demonstrates that, in most cases, the same decoupling level was used during both extensional episodes, and that only accurate cross-section balancing can help to distinguish the effects of the Oligocene stretching from the Liassic extension.

The two geological transects presented here across the Ardèche margin and the Alès Basin, have been chosen on the basis of available seismic profiles and exploration wells. Both profiles escaped Alpine compression, and therefore their early extensional structures are still well preserved. However, they differ in the amount of Oligocene extension (only found east of the Ardèche Fault), and in the extent of the Oligocene deposits (restricted to the Alès Basin).

The Ardèche margin section

A seismic reflection profile has recently been recorded across the Ardèche margin of the basin of southeastern France (Fig. 1) and is published elsewhere (Giot *et al.* 1989, 1991a,b). This geological profile can be extended both eastwards and westwards, thanks to mining and oil exploration wells (Fig. 4). The basement, clearly exposed west of Largentière, is affected by two steep normal faults near Uzer and Balazuc, before deepening progressively along a gentle monocline further east.

From the surface, both the Uzer and Balazuc faults appear to be sealed or masked by Mid-Jurassic marls and Upper Jurassic limestones. Along the seismic line, both faults clearly affect the Liassic sedimentation. The sedimentary cover is partially detached from its basement along the Triassic evaporites.

East of these Liassic basement faults, the Mesozoic sedimentary cover is affected by listric normal faults that crop out near the Ardèche River (Ardèche Fault) or further east (La Gorce Fault, Fig. 4). Previously interpreted as steep basement involved structures (Rampon *et al.* 1984), these two faults are in fact connected with the Triassic detachment level. Although no Oligocene deposits are known to occur along these faults, they clearly affect post-Jurassic sequences (Tithonian and early Cretaceous on the footwalls, and early Cretaceous and late Cretaceous in the down-faulted blocks). Differences in the sedimentary thicknesses on both sides of these faults suggest that they probably moved during the

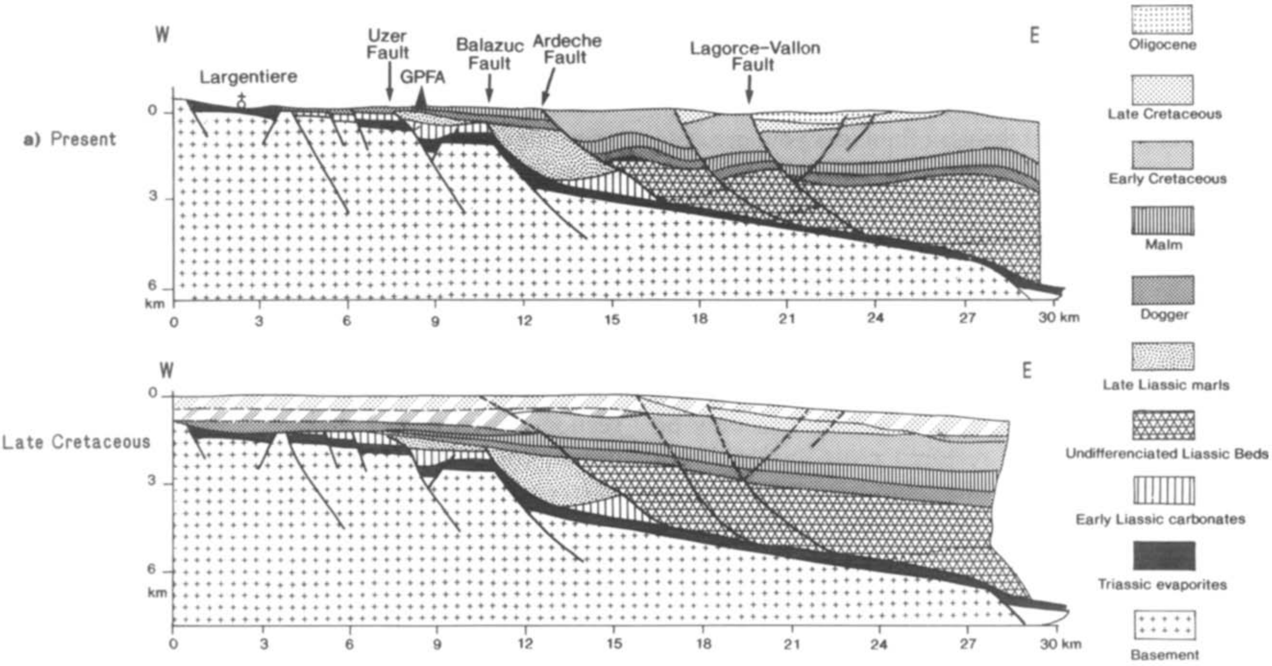

Fig. 4. Balanced cross-section along the Ardèche border. Note that Liassic structures are still undeformed west of the Ardèche Fault, whereas early faults were reactivated in Oligocene times farther east. The restored solution proposed here favors the hypothesis of quite late Jurassic–early Cretaceous subsidence, with no fault reactivation during these stages; other balanced solutions are also possible, with limited displacement along the basal detachment, even during the Cretaceous.

early Jurassic prior to their reactivation in post-Cretaceous times, most probably during the Oligocene.

The amount of Oligocene extension in the sedimentary cover (2 km, i.e. 10% between the Balazuc Fault and the eastern border of the section) is not balanced by coeval underlying basement structures, since basement structures along the profile result exclusively from the Jurassic extension. An equal amount of Oligocene extension is thus expected to occur further east in the basement (Cévennes and Nîmes faults probably).

The Alès Basin–Cévennes Fault section

The Alès Basin (Fig. 1) consists of an elongated depression filled by Oligocene deposits. In the west, it is bordered by steeply dipping normal faults that delimit early Mesozoic (mainly Triassic and Liassic) outcrops (Fig. 6). In the east, it is bounded by minor W-dipping normal faults which separate the Oligocene infill of the basin from older sequences (early and late Cretaceous beds) locally affected by W-dipping reverse faults (shown as R in Figs. 5 and 6).

On the seismic lines of the area, the whole Oligocene basin, as well as the Cretaceous and older sequences to the east, appears to be detached from an autochthonous unit along a gently dipping reflector (s in Figs. 5 and 6), that cuts through the sedimentary sequences. Above this reflector, the Mesozoic displaced cover is referred to as 'allochthon' in Fig. 6). Near the axis of the basin, numerous exploration wells have encountered either Cretaceous–Liassic or Triassic–Palaeozoic units directly underlying the Oligocene infill, from which they are tectonically separated.

This regional E-dipping reflector (s) is interpreted here as a shallow detachment fault that merges at the surface either along the western border of the basin (steeply E-dipping normal border fault), or further west (gently E-dipping basal detachment of the Liassic tilted blocks). In any case, this structure formed in Oligocene times and directly controlled the geometry of the basin through which the depocenters migrated with time (Fig. 5).

West of the emergence of this shallow Oligocene detachment fault (i.e. in the footwall block), other extensional structures can be attributed either to earlier (Liassic) or to coeval (Oligocene) extensional events. Due to the occurrence of coal beds in the Carboniferous sequences, a deeper detachment (d) was locally activated, and thin-skinned basement-involved structures are also assumed to have had some partial control on the extension.

Geological mapping (Arène *et al.* 1978) strongly suggests that the Mesozoic sedimentary cover west of the basin appears to be detached from its Palaeozoic substratum along either a Triassic or a Carboniferous horizon. It is not clear whether this basal detachment (d in Fig. 6) is Liassic or younger, since only Liassic and older beds lie between the westward emergence of the structure, and the border fault of the Alès Basin.

East of the Oligocene infill of this basin, strong reflectors above the shallow Oligocene detachment(s) are interpreted as Mesozoic carbonates, but similar W-dipping reflectors also occur beneath the basal décollement of the basin and are tentatively referred to as autochthonous Liassic remnants (Fig. 5). Therefore, a steeply dipping basement fault is assumed to separate

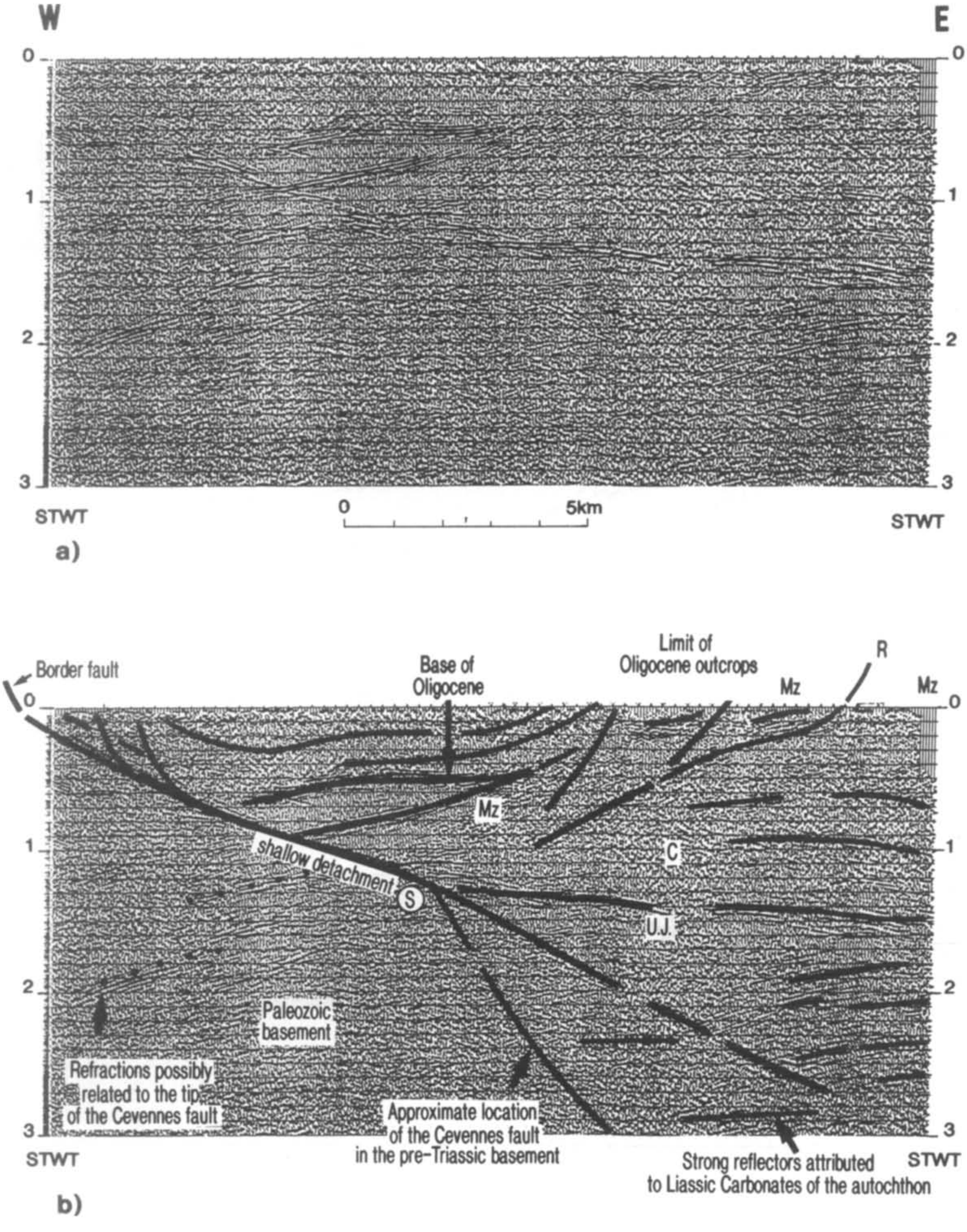

Fig. 5. Unmigrated seismic line across the Alès Basin. Note the E-dipping detachment surface that connect with the Triassic evaporites (courtesy of SNEA(P)).

these Liassic tilted blocks of the footwall (autochthon) from the Palaeozoic rocks that crop out beneath the basin axis in the west. The occurrence of such a steep structure beneath the Alès Basin is best interpreted as a remnant of the pre-Oligocene Cévennes Fault, along which major movements probably occurred in Liassic times. In fact, although this fault is also known to have acted locally as a left-lateral strike-slip during the Pyrenean compression (Arthaud & Mattauer 1969, Bodeur 1976, Arthaud & Séguret 1981), it had a strong control on Mesozoic sedimentation, as expressed along a N–S seismic section in the Rhône valley near Valence (Fig. 8).

Whereas the shallow basal detachment(s) of the Alès Basin controlled the Oligocene sedimentation, the exact amount of Oligocene stretching is also dependent on (1) the amount of displacement along the deeper (intra-Palaeozoic) decoupling horizon (d), and (2) whether the Liassic carbonates of the Mesozoic displaced cover (allochthon in Fig. 6a) belonged to the footwall or to the down-faulted block of the Cévennes Fault. Two distinct restorations are shown here, which differ with respect to

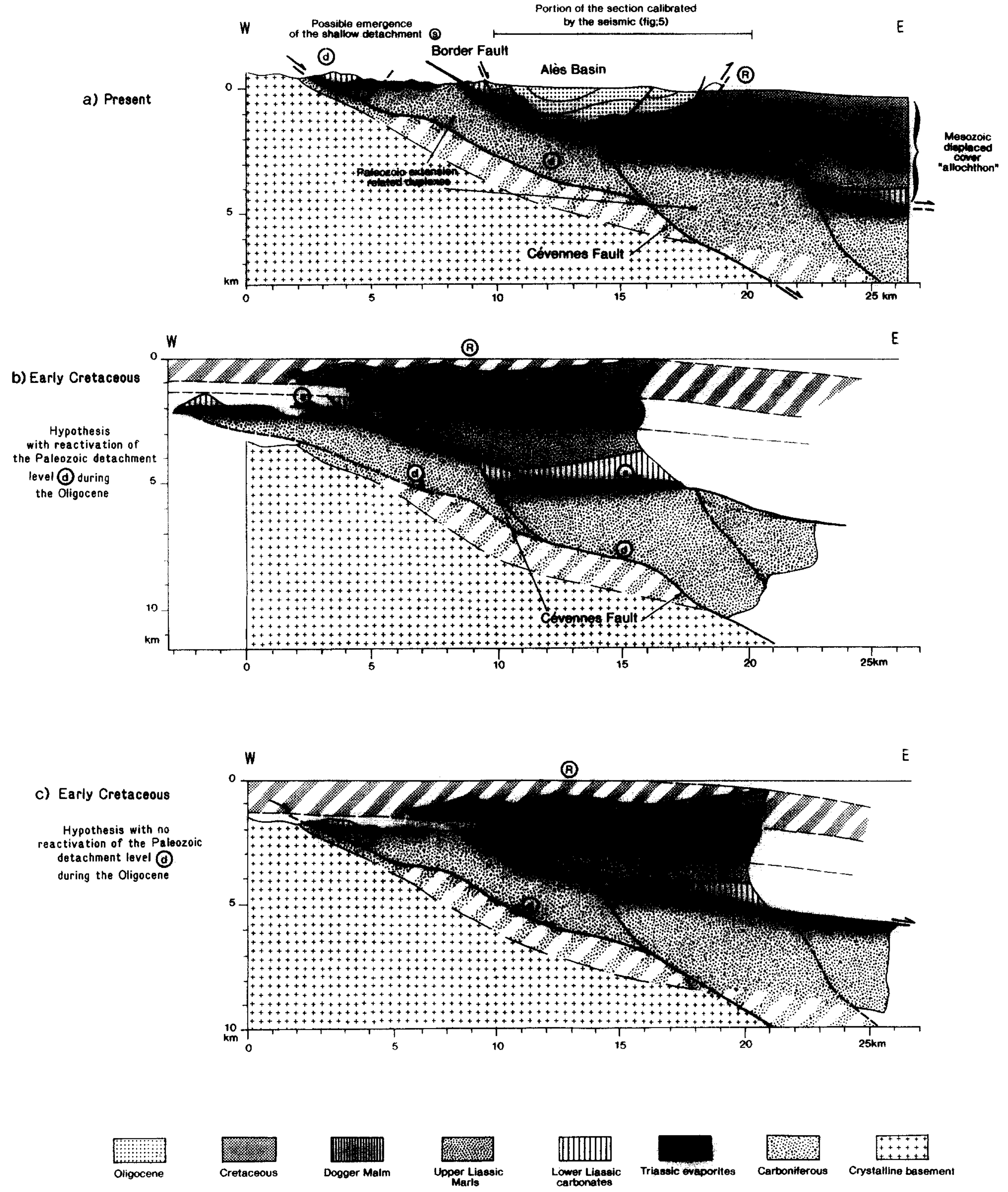

Fig. 6. Balanced cross-section in the Oligocene Alès Basin. Part of the structures beneath the Oligocene detachment are inherited from Liassic extension (a = present). Two distinct solutions are proposed (b and c), which differ in the age (either Liassic or Oligocene) of the activation of the deeper Palaeozoic detachment level.

the age of the intra-Palaeozoic detachment:—a conservative solution considers only a limited Oligocene extension (Liassic carbonates of the allochthon derived from the down-faulted block of the Cévennes Fault), with no Oligocene displacement along the Palaeozoic horizons (Fig. 6c);—another solution would imply a larger amount of Oligocene extension, with the Liassic allochthonous carbonates still derived from the Cévennes Fault hangingwall (Fig. 6b), but with additional displacement along the deeper intra-Palaeozoic detachment. In such an extreme solution, extension-related duplexes may occur due to the superposition of two distinct detachment levels (Fig. 6b).

Oligocene extension values calculated for the base-

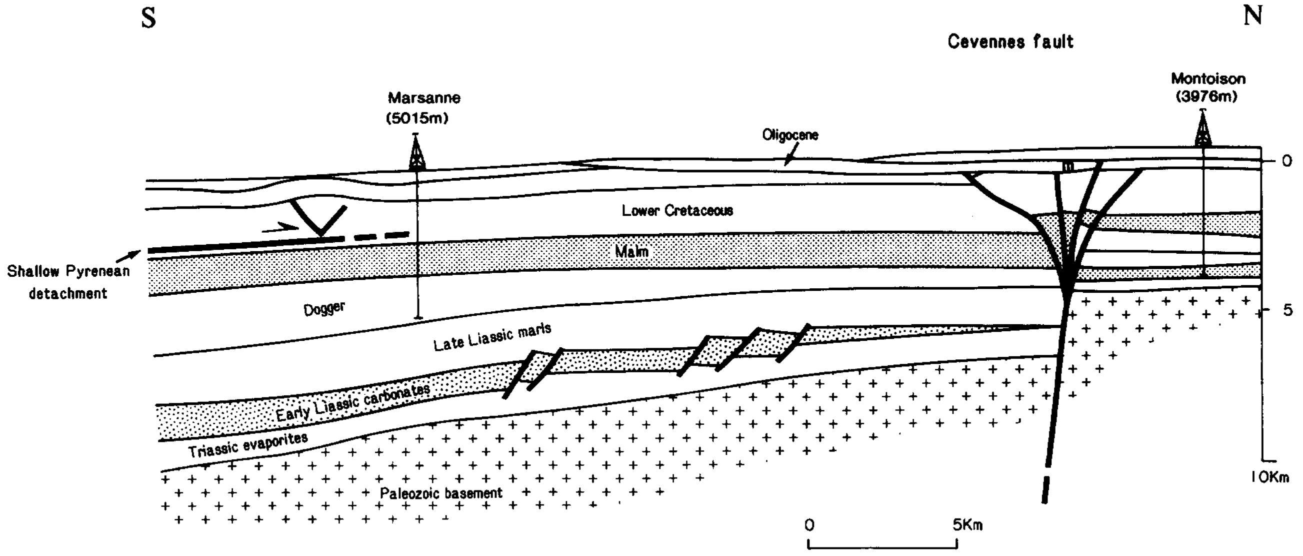

Fig. 7. N–S cross-section in the Rhône Valley near Valence, outlining the polystage history of the Cévennes Fault.

ment and the cover differ greatly in each solution. In the conservative hypothesis (Fig. 6c), it reaches a value of 16% in the sedimentary cover (i.e. 5 km), whereas the extension for the pre-Triassic basement is only 4% (i.e. 1 km). In the more allochthonist solution (Fig. 6b), the extension for the sedimentary cover is 33% (i.e. 10 km), whereas the extension in the Carboniferous beds reaches only 12% (3.5 km).

In both solutions, part of the Cretaceous sedimentary cover, which now crops out east of the Alès Basin, was originally deposited west of the surface trace of the border fault, and thus also west of the Cévennes Fault. As in the Bresse Graben, the shoulder of the basin has been denuded during the Oligocene extension, and the sedimentary cover as a whole (the allochthon) has glided eastward to the centre of the basin of southeastern France.

In addition to the basement extension imaged by this profile, 4–5 km of additional basement extension are expected to occur farther east to balance the Oligocene extension. Complementary offset of the basement surface may occur along the Nîmes or related normal faults to the east.

INVERTED STRUCTURES ON THE EAST SIDE OF THE RHONE VALLEY

Inverted Oligocene structures are exposed along the Jura 'strips' (Chauve *et al.* 1988) and have also been

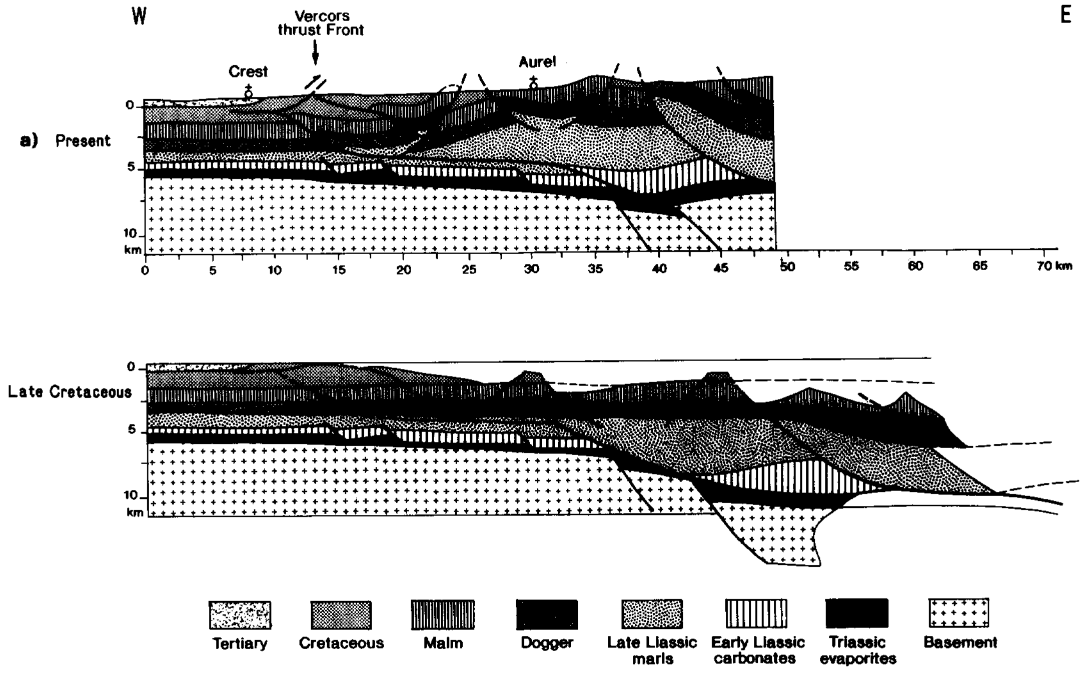

Fig. 8. Balanced cross-section along the Drôme River. Note the undeformed Liassic distensive structures of the autochthon, compared to the inverted sequences of the Vercors allochthon. As in the other sections, all the extensional structures related here to Liassic rifting were sealed by the late Jurassic. During the Cretaceous, only regular thermal subsidence occurred.

described recently along the eastern border of the Bresse Graben, underneath the frontal Jura units (Guellec *et al.* 1990).

Basement inversions are also well known further south in the external crystalline massifs (Gratier & Vialon 1980, Lemoine 1984, Gillcrist *et al.* 1987. Mugnier *et al.* 1987), but most likely these later structures refer to Alpine inversion of Liassic tilted blocks rather than to younger Oligocene structures. In fact, although the main timing of the inversion observed in the area occurred during the Neogene, the age of the original normal faults may be either Liassic or Oligocene.

Two geological cross-sections are described here. The first one, along the Drôme River, relates to a relatively simple inversion history, with the Liassic normal faults not being reactivated until the Alpine compression. The second section across the Durance Fault, however, is more complex, imaging a history of repeated extension and inversion, with additional Pyrenean (late Cretaceous–Eocene) and Oligocene episodes of fault reactivation.

The Drôme–Vercors section

An E–W seismic profile has been recorded between the Rhône Valley and Glandasse Mountain (Figs. 1 and 8) along the Drôme River. This section shows a progressive eastward deepening of the basement as well as a thickening of the Jurassic sequences.

The present geometry is mainly controlled by a succession of ramps and flats at the bottom of the Vercors allochthonous unit, which was thrust westward during the Neogene (Alpine) deformation.

Accurate cross-section balancing helps to restore the geometry of the section to its pre-Neogene configuration, which demonstrates that the architecture of the Vercors mainly results from the structural inversion of Jurassic normal faults. The amount of Neogene shortening as well as the exact amount of Liassic stretching can only be estimated, depending on the lithologies of the lowermost allochthonous sequences (either basement or Liassic carbonates). In any case, the shortening and stretching calculated here in the sedimentary cover are not balanced in the underlying basement; the amount of post-Liassic shortening is 25% (20 km) in the sedimentary cover, but only 10% in the basement. Additional basement-involved structures (either extensional or compressional) have to be expected further east.

The Manosque Basin–Durance Fault section

The Durance Fault is bordered in the west by the Oligocene Manosque Basin, and in the east by the Neogene molasses of the Valensole Plateau (Fig. 1). Like the Cévennes Fault, the Durance Fault is a structure which involves basement and that is probably related to Liassic rifting.

The Durance Fault, strongly reactivated as a normal fault during the Oligocene (Fig. 9), was also remobilized as a reverse fault during the Neogene in response to the structural inversion of the Oligocene Manosque Basin. Although the balancing technique applied here disregards the amount of possible strike-slip motion along the Durance Fault, the restored geological sections help to constrain the Oligocene geometry of the basin and the geological history of the area. If it is assumed that there was only a minor component of strike-slip motion along the Durance Fault during most of its history, the balanced cross-section indicates the following.

(a) The fault cuts through the pre-Mesozoic basement.

(b) The Mesozoic normal motion was active during Liassic and early Cretaceous times.

However, the Cretaceous history cannot be established with the same accuracy since most of the Cretaceous strata have been eroded in the footwall of the Durance Fault in the Valensole area. Nevertheless, a Pyrenean inversion of the Durance fault can be inferred from our restored sections. Effectively, by carefully restoring the erosional surface at the bottom of the Palaeogene deposits, we have tried to quantify the amount of shortening that affected the area during the late Cretaceous to Eocene Pyrenean compression. The late Cretaceous sequences are now mostly preserved away from the Durance Fault, because Pyrenean inversion and subsequent erosion have removed them from the vicinity of the fault.

(c) The amount of post-Triassic basement extension and shortening (reactivation of the Durance Fault) is very small along the section, being less than 3% (i.e. 1 km). On the contrary, 15% of additional Oligocene extension (i.e. 5 km) can be added to the Liassic extension due to the probable mobilization of the Triassic décollement level between the reactivated Durance Fault and other basement faults located further west. A similar amount of basement shortening (i.e. around 4 km) is actually required to occur elsewhere, further to the west, in order to balance the excess Mesozoic cover.

(d) The present geometry results from the tectonic inversion of the Manosque Basin, since the Oligocene sediments were thrust over the Miocene molasse of the Valensole Plateau. However, the deeper part of the section is still poorly constrained. A major question still remains regarding the amount of fault reactivation along the Durance basement fault, and the degree of remobilization of the Triassic evaporites which represent a major décollement level reactivated beneath the Manosque Basin. To answer this critical question, analogue experiments were performed and compared with the present and restored geological sections; the results are discussed below.

SAND-BOX EXTENSIONAL MODELS AND INVERSION EXPERIMENTS

The major problems arising from the restored sections of both the Alès Basin and the Durance Fault concern the large discrepancy observed between the basement and cover extension values along the profiles. In addi-

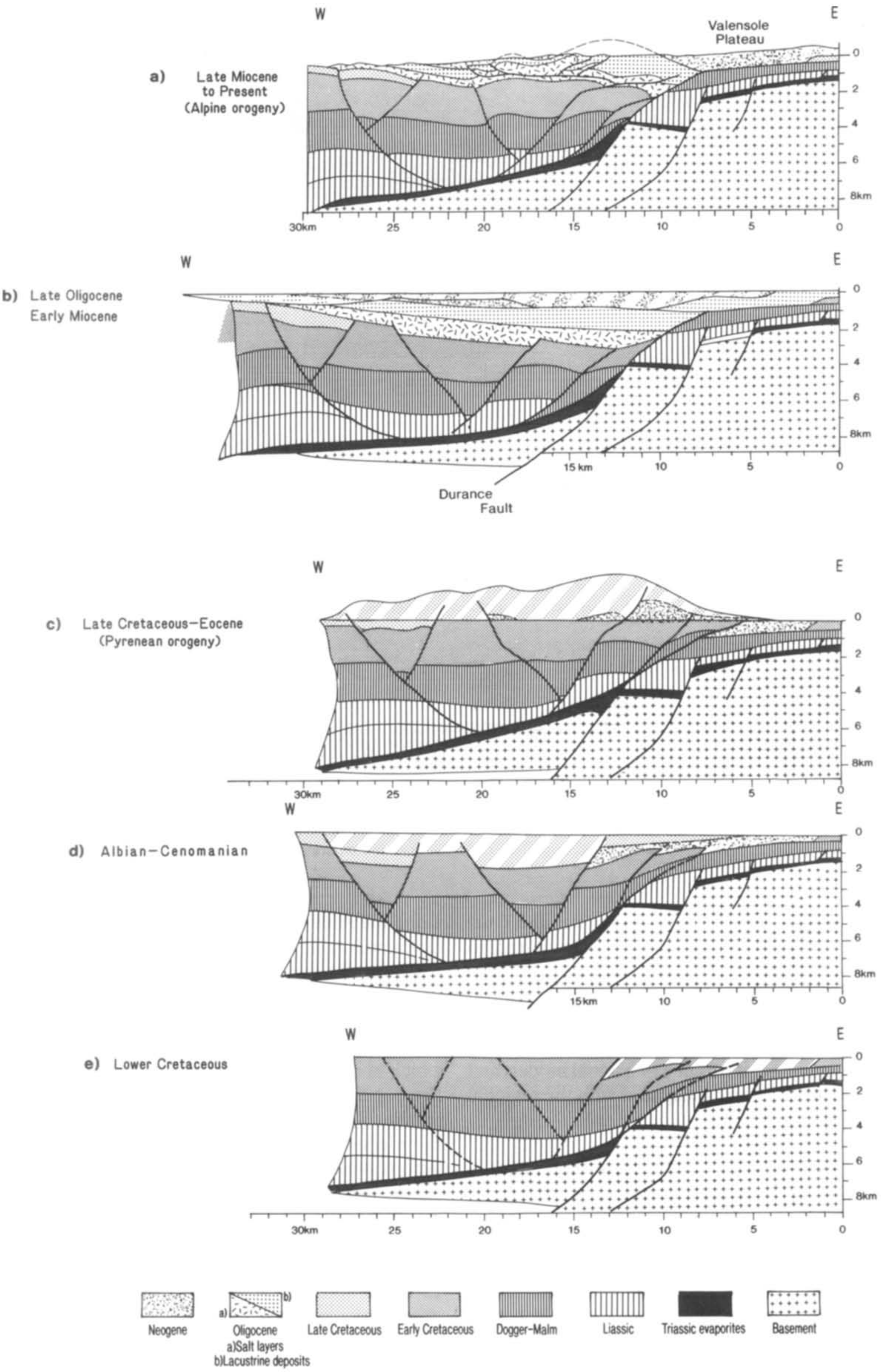

Fig. 9. Inverted Oligocene Manosque Basin. This figure shows the multiphase deformational history of the Durance Fault. The restored sections outline the effects of the Oligocene and Liassic extensions, but also of the Miocene and Pyrenean inversions.

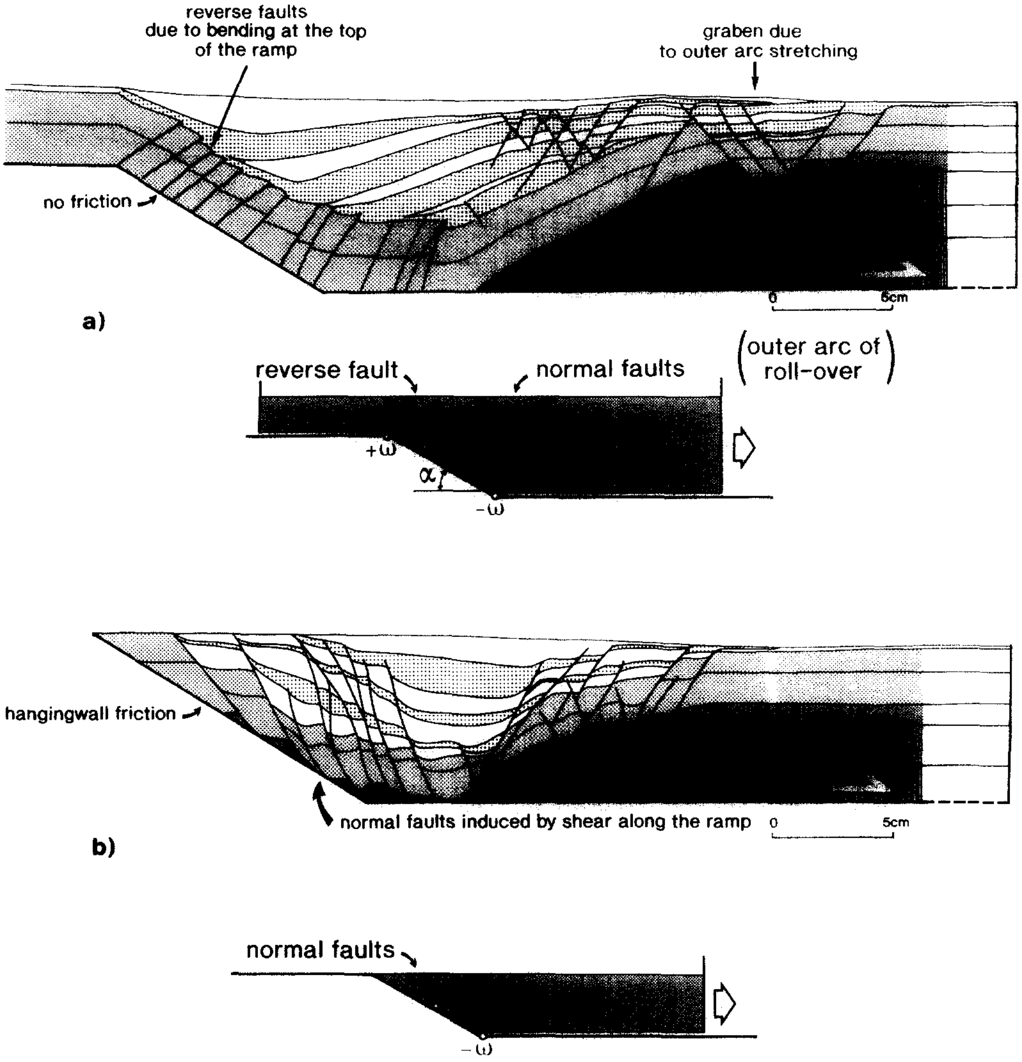

Fig. 10. Laboratory models of flat–ramp extensional systems showing the fault patterns and basin structures obtained: for (a) total decoupling along flats and ramps; and (b) total decoupling along the flat and frictional coupling along the ramp (after Ballard 1989, and Brun *et al.* in preparation).

tion to the basement border faults (Cévennes and Durance faults), an important decoupling is required to occur along the Triassic horizons, with a progressive gliding of the Mesozoic sedimentary cover (allochthon) towards the centre of the basin.

To confirm this hypothesis of a large displacement of the sedimentary cover, different extensional models and inversion experiments were compared with the regional geological data.

Hanging wall faulting and basin structure above a flat–ramp detachment surface: some inferences from sand-box experiments

The Alès section balancing suggests that two décollement layers were involved during the Oligocene extension (Fig. 6), namely coal layers within the Palaeozoic basement (d) and Triassic evaporites (s) at the base of the Mesozoic cover. The final flat–ramp geometry developed during extension due to duplex-type normal faulting of the Palaeozoic layers between the two décollements (Fig. 6). A comparison of the structures observed along the Alès section with those produced in sand-box experiments involving flat–ramp extension helps us to understand some mechanical aspects of fault development.

It is beyond the scope of this paper to give a comprehensive description of the laboratory experiments, which are described elsewhere in detail (Ballard 1989, Brun *et al.* 1991). Sand models were built in a rectangular tank whose rigid base was shaped to the desired flat–ramp geometry. Various types of basal boundary conditions were tested. For the purpose of the present paper, it is especially relevant to compare two experiments in which the hanging wall is either frictionally coupled to or totally decoupled from the footwall along the ramp (Fig. 10). In both experiments the flat is a surface of total decoupling. Decoupling was obtained by coating the ramp and/or the flat with a plastic sheet. When the sand is in direct contact with the ramp, the hanging wall–footwall coupling depends on the frictional properties of the sand (Ballard 1989). When the basal plastic sheet is pulled out, a basin forms at the surface of the model which is progressively filled with

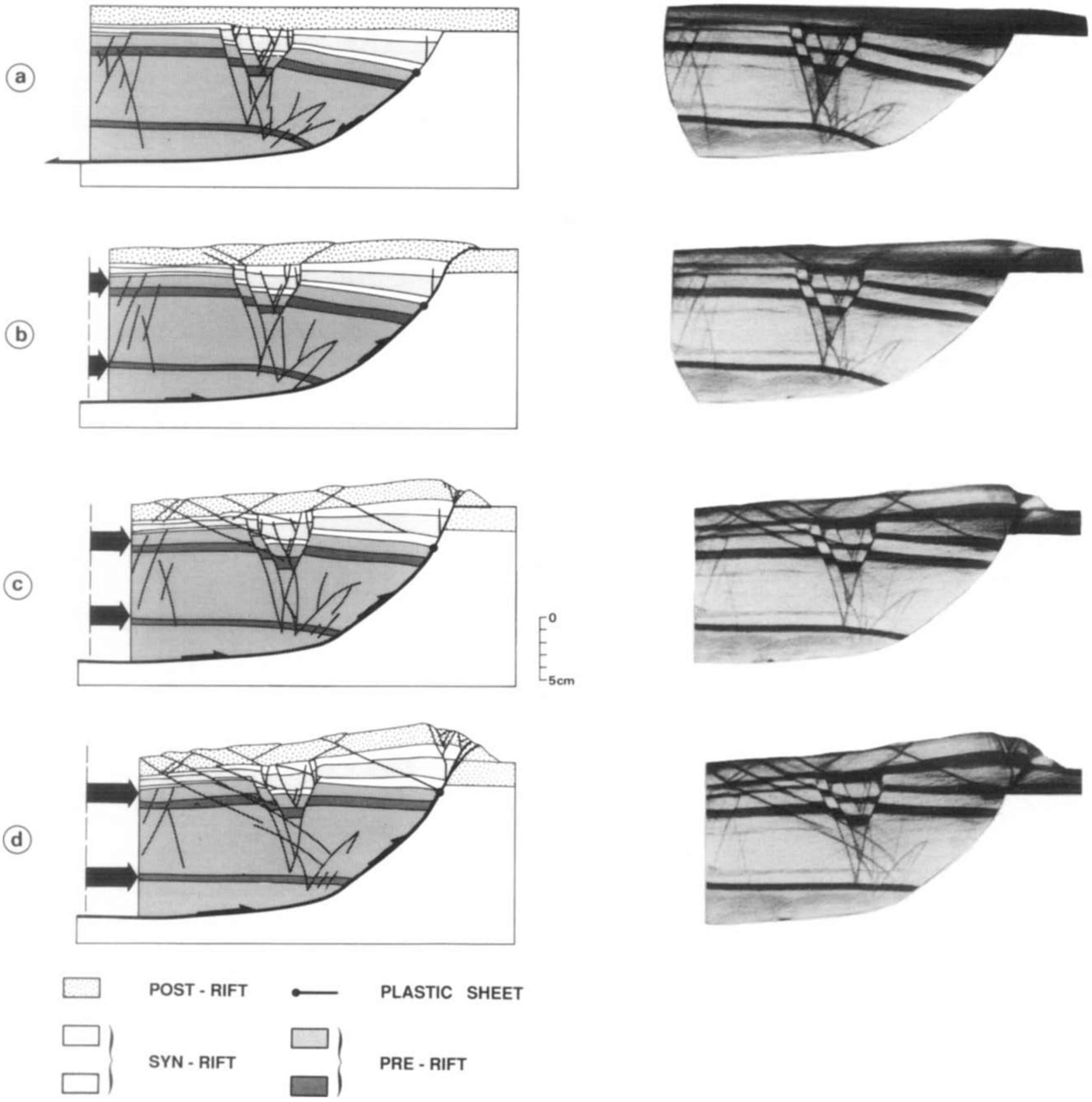

Fig. 11. Analogue models of tectonic inversion of listric shaped fault comparable with the Manosque section. The model is composed of sand and pyrex; cross-sections are X-ray tomography images. (a) Cross-section after extension; (b)–(d) successive stages of shortening.

fresh sand. For other details concerning the experimental techniques, the reader is referred to Vendeville *et al.* (1987).

In both experiments, a roll-over anticline forms opposite the ramp due to a bending moment at the lower flat–ramp junction. The deformation within the roll-over anticline is accompanied by Y-shaped conjugate normal faults, which outline a graben in the outer arc and then propagate basinward. The major normal faults dip towards the ramp as observed in the western limb of the roll-over anticline on the Alès section (Fig. 6).

Hanging-wall faulting along the ramp depends on the type of coupling. If the hanging wall is decoupled from the footwall, then steep reverse faults develop due to bending at the upper flat–ramp junction (Fig. 10a). These reverse faults show very little throw and do not affect the basin fill. The depocentre remains located near the top of the ramp, and layer thickness decreases from the ramp toward the rollover anticline. During extension, the layers are progressively tilted to a dip angle equal to dip of the ramp. Similar experiments have previously been described by McClay & Ellis (1987a,b). If the hanging wall is not decoupled from the footwall, normal faults dipping toward the basin develop along the ramp (Fig. 10b). These faults affect the basin fill and propagate basinward. Thickness variations of the basin layers indicate a migration of the depocentre away from the ramp during extension. This configuration is very similar to the one observed on the Alès section, suggesting a coupling along the ramp (Cévennes Fault or shallow detachment S), which controlled the development of the Alès Basin during the gliding of the Mesozoic allochthon toward the east.

Tectonic inversion sand-box modelling

As predicted by the mechanical theory of fault reactivation (Jaeger & Cook 1969, Sibson 1985), normal faults with a steep dip are generally not reactivated during compressional events. This feature is confirmed by sand-box experiments (McClay 1989, Buchanan & McClay 1991, Souriot *et al.* 1991), in which Mohr–Coulomb behaviour was assumed. However, although the normal faults were generally not reactivated, seismic examples of inversion tectonics in the North Sea (Badley *et al.* 1989), the English Channel (Chapman 1989), and the Eastern Sunda platform (Letouzey 1990), show that the inversion of graben structures is always controlled by the bounding normal faults. Moreover, the reverse faults caused by the inversion have their root at the tip of pre-existing normal faults. In order to analyse in detail this phenomenon of normal fault reactivation, experiments comparable to those already performed by McClay (1989) and Buchanan & McClay (1991) were attempted here. The complete kinematic evolution of these experiments was studied by X-ray tomography techniques (Colletta *et al.* 1991). The apparatus consists of a glass-sided wooden box with a rigid basal listric-shaped bottom. The maximum size of the box is 42 × 45 × 13 cm. The wall opposite the listric fault is mobile and moved by two worm screws. Part of the bottom of the model is coated by a thin flexible plastic sheet attached to the moving wall. Thus, during extension and later shortening, the plastic sheet constitutes a surface of total decoupling between the deformable hanging wall and the rigid footwall.

The preliminary extensional process produced an asymmetrical half graben basin and a conventional roll-over structure with a crestal collapse graben cut by numerous normal faults as in Fig. 9(d) (Fig. 11a).

Since the basal conditions impose a ‘constant slip’ geometry for the roll-over anticline, the throws of the normal faults bounding the crestal collapse decrease downwards and vanish at the detachment level. During deformation, the resulting half graben is periodically fed with sediment (Fig. 11a).

In a second step, progressive shortening was applied to restore the pre-extensional position of the mobile wall (Figs. 11b–d). Shortening occurs first at the top and then migrates downwards. The neutral line corresponds to the basal detachment fault. The resulting geometry shown in Fig. 11(b) indicates that normal faults are not reactivated but act as the roots of reverse faults during the first stage of inversion. This phenomenon was pointed out by Buchanan & McClay (1991). When deformation increases, the offset and the number of reverse faults increases downwards (Figs. 11c & d). In this kind of inversion, the major listric fault that accommodates all the slip-motion is a surface of total decoupling. In fact, part of the deformation of the sand pack can be compared to a folding process in which the sand cake is forced to conform to the curved shape of the listric fault. This bending of the sand cake induces a strong shortening at the top of the model as in the inner part of an isopach fold.

Such a relation can account for the Manosque–Forcalquier Basin where the steeply dipping normal faults in the Mesozoic succession are connected with the low-angle reverse faults produced by the late Miocene compressive event. This experiment also suggest that, during inversion, Triassic units act as a decoupling surface. The model helps to understand seismic lines where normal offsets are still present at depth, while reverse faulting occurs close to the surface. In this experiment, the major listric fault is reactivated because no friction occurs along the fault plane. The inversion produces an anticlinal geometry and a thrust fault of limited offset, which nucleates at the tip of the major listric fault.

CONCLUSIONS

Despite a complex tectonic history with alternating episodes of extension and compression, the structure of the basin of southeastern France can be viewed as a type example for the quantification of extension. The amounts of Oligocene and Liassic extension in the sedimentary cover can be estimated from restored cross-sections. These restored sections also show that the basement was considerably less stretched than the sedimentary cover in the studied areas.

The restorations presented here tend to restrain the Cévennes Fault to a Liassic palaeogeographic feature, which was only slightly reactivated in the Cenozoic. As a matter of fact, most of the Oligocene motion occurred along shallower detachment surfaces that truncate the Cévennes Fault as in the Alès Basin.

The important discrepancy observed between the Oligocene basement and cover extension values near the Cévennes or Durance faults attest to an important gliding of the sedimentary cover toward the centre of the basin of southeastern France, the place where deep refraction data precisely image a thinning of the crust. Denuded areas are assumed to occur west of the Alès Basin, from which parts of the Mesozoic sedimentary cover has been translated eastward across the Cévennes Fault basement trace. Nevertheless, only future deep seismic profiles could help to locate the expected extension in the basement along the Alès–Manosque transect. The normal movement along the Nîmes Fault still needs to be quantified.

The Oligocene basins thus appear to be either half-grabens bounded by basement normal faults (Manosque Basin) or extension-related piggyback basins passively transported above the flat of an underlying décollement level (Alès Basin). Long flats and localized ramps account for the extensional structures observed in the sedimentary cover of all the studied area. Two superposed detachment levels, either in the basement or in the sedimentary cover (Triassic and Carboniferous), have locally been activated during the same extension episode, thus help to generate distensive duplexes.

Analogue modelling helps to validate the deep structural interpretations, especially the amount of coupling along the basal detachments. In addition, it provides a meaningful explanation for the reverse faults observed in an extensional regime (Alès Basin) and for the shallow thrusts that occur in the vicinity of the inverted Durance Fault (Manosque Basin).

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