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Crustal architecture, thermal evolution and energy resources of compressional basins

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ABSTRACT. Our understanding of sedimentary basins, orogens and links between deep and surface processes has greatly benefited from recent improvement of imagery techniques, including crustal scale reflection seismic and mantle tomography. ECORS profiles across the Pyrenees, the Alps and the Paris Basin for instance provide a unique control on the crustal architecture of both Cenozoic and Paleozoic orogens in western Europe. Alternatively, mantle tomography and deep focal mechanisms in the southeastern Carpathians and the western and central Mediterranean outline the progressive delamination at the Moho level of the continental lithosphere of Moesia and Adria, only its mantle part being actually recycled into the asthenosphere during the roll-back of the subduction associated with the southeastward shift of the Carpathians and Apenninic-Maghrebian arcs. This paper describes also, using various case studies from the Apennines, Albania and Venezuela, the integrated workflow developed at IFP-EN to reconstruct the kinematic and thermal evolution of fold-and-thrust belts (foothills) and adjacent forelands, and the way numerical modelling and analytical work can improve our predictions in terms of energy resources, hydrocarbon potential and reservoir risk assessment.
Ultimately, key examples from the North American Cordillera, from the Arctic to the Gulf of Mexico, are used to document the controls of mantle dynamics on lithosphere thickness and thermicity, continental topography, post-orogenic unroofing and foreland unflexing, and the related changes observed in drainage areas and petroleum systems. Lateral changes observed in the lithosphere thickness between the Canadian Rockies and their foreland are also compared further with similar changes observed across the Tornquist-Teisseyre Line in the architecture, thermicity, rheology and deformation pattern of the European lithosphere.

KEYWORDS: Crustal architecture, continental mantle lithosphere delamination, foothills, basin modelling, reservoir appraisal, petroleum systems

1. Introduction

For decades, Alpine geologists and petroleum industry had only a limited access to the subsurface architecture of sedimentary basins and foothills, relying either on outcrops, horizontal tunnels or vertical wells to extrapolate 1D or 2D stratigraphic and structural information into a 3D volume, the depth to which such extrapolation was permitted being ultimately very limited. Fortunately, continuous innovation on geophysical techniques provides now increasingly accurate images of the Earth interior, not only at the scale of the sedimentary infill of the basins, but also at the scale of the entire lithosphere. These new data provide accurate information on the overall architecture of the continental crust and lithospheric mantle, i.e. the depth to the Moho, which constitutes locally a major decoupling horizon, and the depth to the 1300°C isotherm, which constitutes the asthenosphere-lithosphere boundary (Artemieva, 2009; Roure et al., 2010b; Cloetingh et al., 2013; and references therein).

Seemingly, early explorationists were relying extensively on surface seeps and outcrops of potential source rocks to evaluate the petroleum potential and identify the most promising areas for drilling (Lafargue et al., 1994; Bessereau et al., 1997; Koltun et al., 1998). However, coupled analytical and numerical techniques have been progressively developed to decrease the risk of drilling dry wells.

This paper will first summarize, using a number of real case studies in France, Europe and the Mediterranean, what we have learned within the last 3 decades from crustal and mantle imagery on the architecture of orogens and sedimentary basins. It will then describe the integrated workflow developed at IFP-EN during the same period for the prediction of the petroleum potential and reservoir risk assessment in foothill domains and adjacent forelands, using numerous case studies from the Apennines, Albania and Venezuela. Finally, the impact of mantle dynamics on lithosphere thickness, thermicity, topography and the overall coupling between deep and surface processes and its impact on the petroleum systems in foreland fold-and-thrust belts (FFTB) will be further illustrated by recent studies in Canada and Mexico, and compared with the current architecture, thermicity and rheology of the European lithosphere on both sides of the Tornquist-Teisseyre Line.

2. ECORS data and crustal architecture of the Pyrenees, Alps and Hercynian orogens

The French ECORS programme was initiated in the eighties, with a first profile dedicated to the recording of a regional profile across the Paris Basin, outlining a flat Moho and layered lower crust below the former Hercynian orogen, and a dominantly transparent crust north and below the Midi Fault, which constitutes the limit between the former Carboniferous tectonic wedge and its foreland (Cazes et al., 1986).

Thanks to bilateral collaboration with Spain and Italy, ECORS was also able to record continuous deep seismic profiles across two younger, Cenozoic orogens, i.e. the Pyrenees and the Alps, both being still characterized by important crustal roots associated with a high topography (ECORS Pyrenees Team, 1988; Choukroune and ECORS Pyrenees Team, 1989; Roure et al., 1989 a, b; Nicolas et al., 1990; Roure et al., 1990a).

More recently, mantle tomography images could bring additional data to better constrain the current architecture of the Pyrenees and the Alps, as well as of the Paris Basin, which indeed constitutes an epi-sutural, post-orogenic basin that developed on top of the former Hercynian orogen (Souriau et al., 2008; Averbuch and Piromalo, 2012).
Alltogether, as discussed below, these 3 ECORS profiles now provide end-member references for our understanding of intra-cratonic and collisional orogens.

2.1. A comparison between the ECORS Pyrenees and the ECORS-CROP Alps profiles

Figures 1a and 1b evidence the overall crustal architectures of the Pyrenees and the Western Alps, as imaged by the French-Spanish ECORS Pyrenees and French-Italian ECORS-CROP Alps profiles, respectively. Surprisingly, these two crustal cross-sections of the Pyrenees and the Alps look quite similar, despite the fact that these orogens result from very distinct geodynamic scenarios (Roure et al., 1996). Actually, only about 150 km of shortening occurred in the Pyrenees, accounting for the Late Cretaceous to Oligocene trans-pressional inversion of a former intra-cratonic system of Albian trans-tensional pull-apart basins, the other, out-of-the-plane component of the deformation being accommodated by trans-current motion of Iberia relative to Europe along their common plate boundary, which is more or less superimposed to

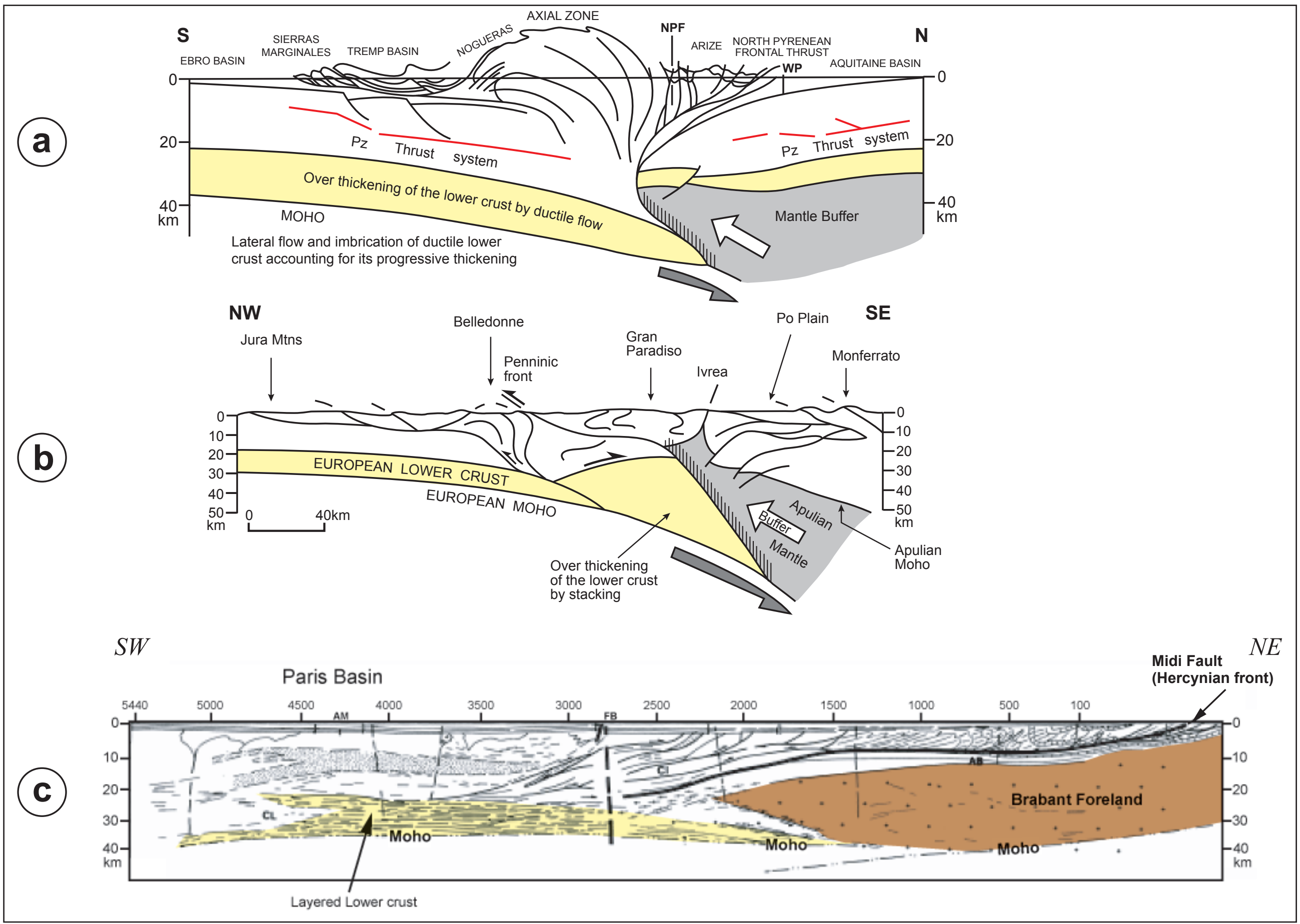


Figure 1: Crustal architecture along reference ECORS profiles:
a. Crustal section of the Pyrenees along the ECORS profile. Notice the progressive wedging of the Iberian lithosphere along the Moho surface, and the thickenning of its lower crust as due do a lateral flow of ductile material. Instead, the brittle European upper mantle behaves as an indenter, whereas the mantle lithosphere of Iberia is progressively subducted into the asthenosphere (after Choukroune et al., 1989, and Roure et al., 1989a, modified).
b. Crustal section along the ECORS-CROP Alpine profile. Notice the progressive wedging of the European lithosphere along the Moho surface, the local stacking and thickening of the European lower crustal material beneath the Internal zones, and the rapid uplift of the brittle Apulian upper mantle which behaves as a buffer (after Roure et al., 1989b and 1996, modified).
c. Crustal section of the Paris Basin along the ECORS profile, outlining a flat layered lowered crust beneath the former Hercynian thrust belt, and an overall transparent crust in the Brabant foreland which extends below and north of the Midi Fault (after Cazes et al., 1986, modified).

the current surface trace of the North Pyrenean Fault (Roure et al., 1989 a, b). In contrast, the Western Alps result from the closure of the Ligurian Tethys which once separated Apulia (also referred to Adria or African Promontory in the literature) and Europe, a few hundred of km of oceanic lithosphere having been subducted during the Late Cretaceous and Paleogene before reaching the current stage of continent-continent collision since the Neogene.

In the case of the Pyrenees (ECORS Pyrenees Team, 1988; Choukroune and ECORS Pyrenees Team, 1989; Roure et al., 1989 a, b; Fig. 1a), the shallow part of the structural section is relatively cylindrical and displays two well developed flexural basins, i.e. the Ebro Basin in the south and the Aquitaine Basin in the north, with an overall fan shape of the intervening Pyrenean thrust belt which is characterized by south-verging thrusts in the south and north-verging thrusts in the north. In contrast, the crustal architecture becomes totally asymetric at depth, with a progressive deepening of the Iberian Moho from the Ebro River in the south towards the Axial Zone of the Pyrenees in the north, whereas the European Moho remains relatively flat or is even becoming shallower between the North Pyrenean thrust front and the Axial Zone. In the mean time, both Iberian and Aquitaine forelands are still characterized by well imaged south-verging Hercynian thrusts in the middle crust, and by a highly reflective layered lower crust, the later being significantly thicker on the Spanish side as compared to the French side, despite the fact that both the Ebro and Aquitaine crustal domains recorded a similar Hercynian and Alpine evolution.

The broad picture of this orogenic system relates to a progressive decoupling of the Iberian crust from its underlying infra-continental mantle at or near the Moho surface, the brittle European upper mantle acting as the main indenter forcing the Iberian mantle lithosphere to subduct. During wedging, part of the Iberian upper crust is thrust towards the south whereas the other part is progressively back-thrust towards the north on top of the European upper mantle indenter. In the mean time, a ductile flow of the Iberian lower crust is propagating towards the south, thus accounting for its progressive thickening as far south as the Ebro basin.

New tomographic data also document the fate of the Iberian mantle lithosphere down to about 200 km, i.e. to a depth which could not be investigated by the ECORS survey, but which is still consistent with the 150 km of shortening estimated earlier on the basis of seismic interpretation and cross-section balancing (Souriau et al., 2008).

In the case of the Western Alps (Nicolas et al., 1990; Roure et al., 1990a; Fig. 1b), the shallow part of the section is currently asymetric because of the post-Messinian reconfiguration of the Po Basin and activation of the Montferrato and Northern Apennines thrust systems, most shallow deformation being accounted for by a northwest-verging thrust system extending from the Outer Crystalline Massifs (e.g. Mont Blanc) as far west as the Bresse Graben. Seismic profiles from the industry help however to document east-verging thrust systems in the eastern, Italian side of the Alps, which are currently inactive, all these Alpine thrusts being sealed by the Messinian unconformity (Roure et al., 1989b).

Unlike in the Pyrenees, it is the infra-continental mantle lithosphere of Europe which is progressively subducted beneath a back-stop or buffer made up of the brittle Apulian upper mantle.

Also, rather than flowing laterally and becoming thickened forelandward as observed beneath the Ebro Basin, the ductile European lower crust is progressively thickened and stacked near the plate boundary, i.e. just beneath the internal units of the Alps.

New tomographic surveys around the Alps and the Apennines can still detect velocity anomalies at about 600 km beneath the Western Mediterranean, which are best interpreted as remnants of the oceanic lithosphere of the former Ligurian Tethys which once separated Europe from Apulia, but has now been detached from the Earth surface and is entirely recycled into the asthenosphere (Spakman and Wortel, 2004).

Obviously, only the continent-continent collisional stage of the Alps can still be identified by means of deep reflection seismic, the amount of Neogene intra-continental shortening in the Alps being in the same order of magnitude as the overall amount of shortening in the Pyrenees. This is probably the reason why crustal sections across these two orogens, but also crustal sections crossing other intra-continental thrust belts such as the Merida Andes in Venezuela and the Eastern Cordillera in Colombia (Colletta et al., 1997), look so similar.

2.2. New insights of mantle tomography on the long term subsidence mechanisms of the Paris Basin

The main result of the ECORS profile beneath the Paris Basin (Fig. 1c) was the identification of a layered lower crust and flat Moho beneath its main Mesozoic and Cenozoic depocenters, which rest unconformably on top of the eroded remnants of the former Hercynian orogen (Cazes et al., 1986). The same type of layering is actually observed also beneath the forelands of the Pyrenees and the Alps, i.e. beneath the Ebro and Aquitaine basins, as well as below the Molasse Basin and the Jura Mountains, but it is instead lacking in the foreland of the Hercynian orogen north of the Midi Fault, making likely that such reflectivity and layering developed during the Permian post-orogenic extensional collapse of the orogen, or during younger episodes of intra-continental rifting and extension.

However, this ECORS profile was unable to document any major Triassic or Jurassic normal fault and rift structures that would have contributed to the long lasting Mesozoic and Cenozoic subsidence of the basin. Fortunately, more recent studies have elucidated this puzzling question of how to account for subsidence without active rifting and/or post-rift thermal cooling of the lithosphere:

(i) As documented by the erosional pattern of the Vosges and Black-Forest on the one hand, and the dominantly northeast-trending attitude of the Cenozoic depocenters of the Paris Basin on the other hand, most if not all its post-Cretaceous subsidence can be interpreted as long wave-length buckling of the European foreland lithosphere during Alpine collision (Bourgeois et al., 2007).

(ii) New tomographic surveys account also for a velocity anomaly in the upper mantle beneath the central part of the Paris Basin, which can be interpreted as a metamorphic, eclogitized high density remnant of the former Hercynian slab which has not been entirely detached (Averbuch and Piromalo, 2012). This sub-crustal load is assumed to have controlled the overall subsidence of the basin during the entire Mesozoic times, without the need for any thermal rejuvenation or rifting.

3. Mediterranean basins and mantle delamination

Despite the fact that the Western and Eastern Mediterranean basins probably share a similar deep water environment since the onset of the Neogene, both having been impacted during the Messinian by a similar salinity crisis, they result from two totally different geodynamic evolutions: on the one hand, the Western Mediterranean is underlain by a thin and hot oceanic lithosphere and can be described as a neo-formed Neogene ocean, resulting from back-arc opening at the rear of the Apennines-Maghrebian orogen (Cavazza et al., 2004 a, b; and references therein). Its initial rifting phase has been dated as Oligo-Aquitanian in the Gulf of Lion, Gulf of Valencia and Algerian Basin, but is even younger in the Tyrrhenian basins, the later being indeed characterized by Pliocene or even Quaternary oceanic crust. On the other hand, the Eastern Mediterranean is characterized by a thick and cold

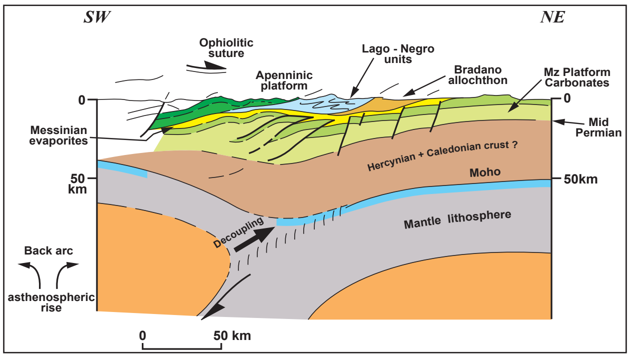


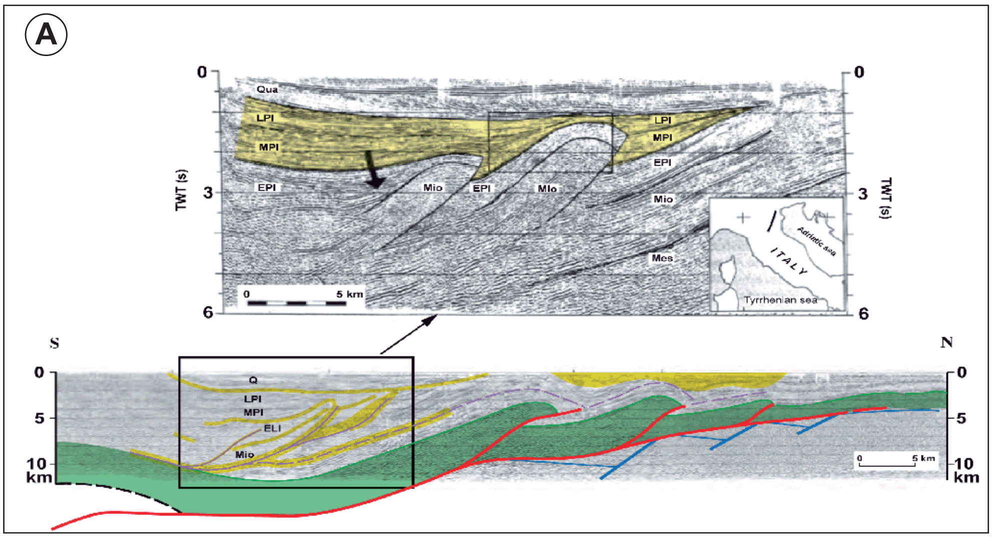
Figure 2: Tentative lithospheric section of the Southern Apennines, outlining the progressive delamination of the Apulian mantle lithosphere induced by the roll-back of the subduction and rise of the Tyrrhenian asthenospheric mantle. Notice the continuous Apulian Moho extending from the Adriatic foreland in the east to the foothills in the west, and the ophiolitic suture which is still locally preserved in the innermost, shallowest units of the allochthon (after Roure et al., 2012, modified).

lithosphere, the nature of which, either continental or oceanic, being still debated.

For instance, many paleogeographic maps (Dercourt et al., 2000; Stampfli and Borel, 2004; and references therein) have proposed to separate the Apulian Promontory from Africa by an intervening Permian, Jurassic or even Cretaceous oceanic domain. However, a more or less continuous belt of paleo-oceanic ophiolitic remnants occurs onshore on the northern side of the Apulian-Eastern Mediterranean domain, making it likely that any more external domain relative to this Tethyan suture should be considered as part of the former African margin that was actually made up of highly contrasted segments, either of platformal (thick Kruja, Gavrovo, Puglia, Apenninic and Panormide carbonate platforms) or basinal (thin Ionian, Umbrian-Marchesian, Lago-Negro and Imerese basinal series made up of pelagic limestones and radiolarian cherts) affinities (Roure et al., 1991, 2012). For instance, the oceanic suture is outlined by the Mirdita ophiolite which rests on top of the Kruja platform carbonates in Albania, whereas another Tethyan ophiolite rests on top of Gavrovo-equivalent platform carbonates in Crete.

Worth to mention, the deep Ionian Basin and Libyan Sea constitute two reference segments of the Central and Eastern Mediterranean which are involved in a roll-back of active subduction planes associated with the Calabrian and Aegean arcs. They provide good analogues for the former evolutionary stages of other, currently inactive segments of the Apennines-Maghrebides and Hellenides-Albanides-Dinarides where the lithospheric slab has been entirely detached. Mantle tomography, crustal imagery and distribution of focal mechanisms have also documented recently the architecture of the Moho and subducted lithospheric slab in the southeastern Carpathians, which constitutes another well documented case of roll-back subduction. There, it can be demonstrated that only the infra-continental lithospheric mantle of Moesia is currently subducted beneath the Carpathians, whereas the shallow Moho observed beneath the foothills is continuous with the deeper foreland Moho, thus evidencing a progressive delamination of the Moesian lithosphere at the Moho level (Bocin, 2010).

The same overall model of crustal delamination of the foreland continental crust is likely to operate beneath the Calabrian and Aegean arcs, and to have operated also during the Pliocene contraction of the Apennines, making likely that the Tyrrhenian Moho beneath the foothills of the Southern Apennines is indeed continuous with the Adriatic foreland (Fig. 2; Roure et al., 2012). The implication of such delamination process for the perspective of energy resources is that the deep portions of the Ionian Basin and Libyan Sea are probably still underlain by thinned continental crust of distal portion of the North African-Apulian margin, and not by oceanic lithosphere, making their petroleum potential much more attractive and worth to explore.



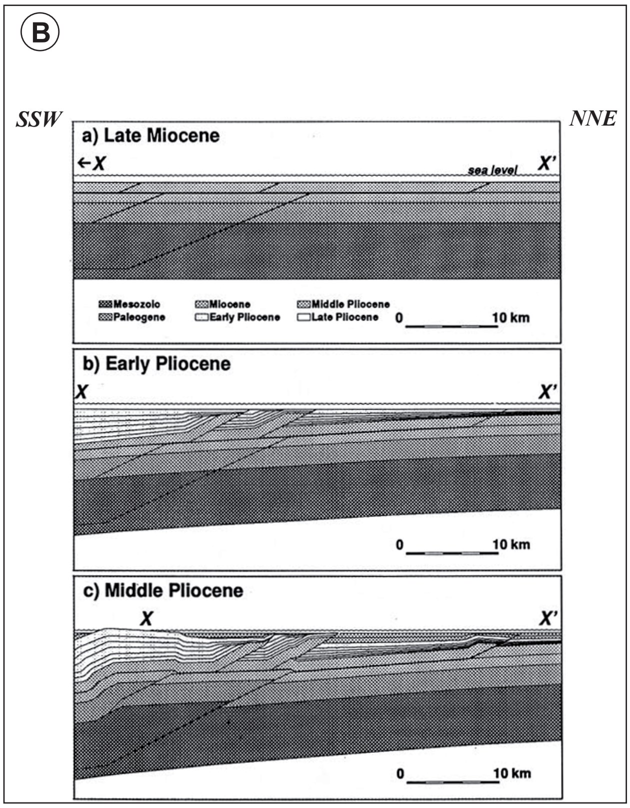


Figure 3: Thin skinned tectonics and foreland flexure in the Northern Apennines:
a. Structural interpretation along a regional seismic profile, outlining an early decollement level located in the Cenozoic clastics, which was active during the Lower Pliocene but has been refolded during the Upper Pliocene and Quaternary, as due to the activation of a deeper decollement level located within the Triassic evaporite. Notice the development of a wide Quaternary piggyback basin on top of the allochthon, recording the long lasting flexural subsidence of the foreland lithosphere (after Roure, 2008, modified).
b. Forward kinematic and stratigraphic modelling of the same section (after Zoetemeijer et al., 1992 and 1993, modified).

4. Thin-skinned tectonics and petroleum systems in the Apennines and Albanides

Since the nineties, IFP-EN has developed the Thrustpack and Ceres numerical codes for the prediction of the petroleum potential in compressional systems, the first prototypes having been dedicated to 2D kinematic reconstructions (Zoetemeijer et al., 1992; 1993; Roure et al., 1991, 1993; Roure and Sassi, 1995), whereas further coupling with thermal modules, kinetics of the transformation of kerogen into hydrocarbons, HC (hydrocarbon) explusion and migration as well as pore fluid pressure reconstruction were then progressively implemented for a qualitative evaluation of the exploration risks (Schneider, 2003).

More focus is however currently dedicated to the development of kinematic reconstructions in 3D, with the objective to couple them with classic basin modelling codes able to handle thermal evolution and HC generation and migration, 3D modelling being actually a pre-requisite for proper quantitative evaluations of HC trapped in individual structures (Roure et al., 2010b).

4.1. Forward kinematic modelling of thrust systems

We have first used various case studies in the Neogene foothills of the Carpathians, Apennines and Albania to test new numerical codes allowing to simulate the forward kinematic evolution of thin-skinned thrust systems (Casero et al., 1991; Zoetemeijer et al., 1992; 1993; Roure et al., 1993, 2004; Lafargue et al., 1994; Roure and Sassi, 1995; Koltun et al., 1998; Swennen et al., 2000; Van Geet et al., 2002).

As illustrated in Fig. 3 which relates to the Northern Apennines, the first requisite step is to properly interpret the 2D seismic data, in order to propose a coherent geometric connection between the various thrusts observed in the structural section, even in areas where they are not properly imaged on the seismic data. Growth strata and local unconformities are also used to date individual deformation events.

In the case of the Northern Apennines and adjacent Po Valley, seismic data recorded down to 5 stwt (seconds two-way time) only allow to identify the shallower decollement level, located within the Cenozoic clastics, and geometric constructions are instead required to extrapolate the attitude of the basal, intra-Triassic decollement in the inner part of the transect where the seismic does not allow to image the deepest part of the sedimentary section (Fig. 3; Zoetemeijer et al., 1992, 1993; Roure, 2008). The distribution of surface anticlines and the location of the wide Quaternary piggyback basin located on top of the allochthon provide a good validation of the trajectory of the still active basal decollement, the Quaternary piggyback basin extending over a flat of the basal decollement, whereas most of the surface anticlines are directly controlled by kinks between flat and ramp segments of the active underlying thrust. Conversely, the unconformity at the base of the Upper Pliocene and growth strata in the lower Pliocene demonstrate that the shallower, intra-Cenozoic decollement was active at an earlier deformation stage, during the Lower Pliocene, at a time when the underlying Mesozoic carbonates were not yet involved in the thrust system.

As evidenced by early modelling results, it is very important to control the evolution of the foreland flexure through time, as it will allow or not the development of vertical subsidence and thus the preservation of piggyback basins in the inner part of the tectonic wedge, or instead a rapid uplift and unroofing of the allochthon.

Once the structural interpretations made on time sections have been converted into depth sections, restoration to their pre-orogenic stage can be performed in order to document the future trajectory of the thrusts, their initial spacing, and the initial thickness variations of the pre-orogenic, i.e. synrift or passive margin sequences. Various kinematic scenarios can then be tested, confronting various thrust sequences and various increment/partition of the deformation along individual thrusts during the successive evolutionary stages of the system (Roure and Sassi, 1995; Sassi and Rudkiewicz, 2000).

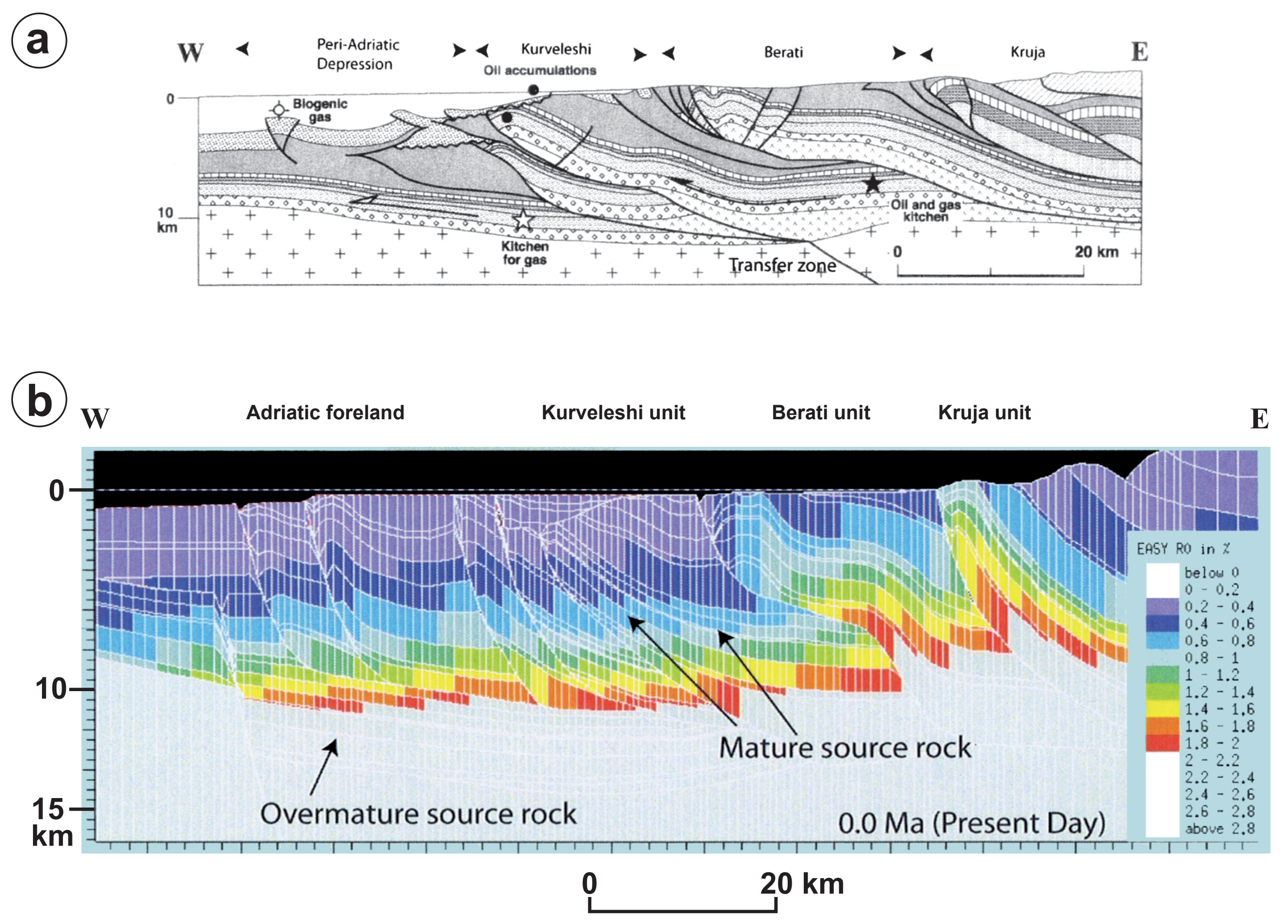


Figure 4: Thin-skinned tectonics and petroleum systems in Albania.
a) Regional structural transect across the Periadriatic depression and adjacent Ionian inverted basin in Albania (after Roure et al., 2004, modified).
b) Results of a coupled 2D kinematic and petroleum modelling along the same transect, accounting for two independant HC kitchens. Oil generated early in the Mesozoic source rocks from the autochthonous foreland have migrated westward across the Adriatic Sea, such long distance migration accounting for HC accumulations along the Italian side of the basin. Instead, Triassic and Liassic source rocks cropping out in the core of the growth anticlines of the Albanian foothills are still immature, implying that HC stored in underlying reservoirs from the allochthon originated in adjacent synclines where tectonic burial forced the source rocks to enter the oil window (after Vilasi et al., 2009, modified).

4.2. Coupled thermal and petroleum modelling of thrust systems

Once the geologist is satisfied by the consistency of his forward kinematic model with respect to the seismic data, (s)he can enter a second phase of the modelling that will handle the thermal reconstruction and computation of the maturity rank of the organic matter.

In this purpose, (s)he needs to provide conductivity values for the various lithologies, define the surface temperature through times, and to calibrate the basal heat flow and geothermal gradient against the present-day temperature data (Bottom Hole Temperatures), using also the current distribution of paleo-thermometers such as Tmax (temperature measured by Rock-Eval pyrolysis, at which the maximum amount of hydrocarbon is released by kerogen; Espitalié et al., 1977), Ro (% of vitrinite reflectance measured in oil) and kinetics of the organic matter of lacustrine (type I), marine (type II) or continental (type III) origin, and any other analytical data such as Apatite Fission Tracks, Th (homogenization temperature) of fluid inclusions or calcite twins, likely to constrain the paleo-temperatures as well as the paleo-burial (former thicknesses of the eroded sequences; Roure et al., 2003 and 2004; Mosca et al., 2004; Sciamanna et al., 2004; Toro et al., 2004; Deville and Sassi, 2006; Sassi et al., 2007; Lacombe et al., 2009; Tarapoanca et al., 2010; and references therein).

The first 2D modelling tool developed by IFP-EN for petroleum prediction in thrust systems, Thrustpack, did not account for the flow of fluid-phases and buil-up of overpressures due for example to compaction-related dewatering of the sedimentary succession during burial, and the generation and migration of hydrocarbons (Roure and Sassi, 1995; Sassi et al., 2007). All these fluid transfer processes have been instead implemented in the Ceres code, which uses the same thermal, kinetics and compaction laws as Temisflow software (Schneider, 2003; Vilasi et al., 2009; Callot et al., 2010). As Temisflow however, Ceres is a backward tool that focuses on the progressive backstripping of the structural section, which is actually relatively easy to handle in passive margins where there is no lateral transport operating in the rock mass through time but only vertical compaction, but becomes much more difficult to address in thrust systems. To overpass this problem, the best workflow is to first built forward kinematic scenarios with Thrustpack or other forward modelling tools, and then use the template of the intermediate stages as helpfull targets to control/build the coeval stages in the backward Ceres tools. Fig. 4 illustrates the result of such backward Ceres modelling performed along a regional transect in the Albanian foothills, using intermediate targets constructed with the Thrustpack software (Vilasi et al., 2009).

5. SUBTRAP (SUBThrust Reservoir APpraisal in Foreland Fold-and-Thrust Belts (FFTB)

Dewatering processes with channelization of compaction, commonly overpressured fluids along horizontal conduits below efficient seals, or vertical escape of mud diapirs have been well studied by numerous ODP legs in the modern Oregon, Nankai and Barbados accretionary wedges (Vrolijk, 1990; Vrolijk et al., 1990; Cochrane et al., 1994; Morgan et al., 1994). Despite the fact that meteoric water is also likely to invade tectonic wedges onshore, the fluid circulations and deformation pattern in synflexural and synkinematic siliciclastic deposits of foreland

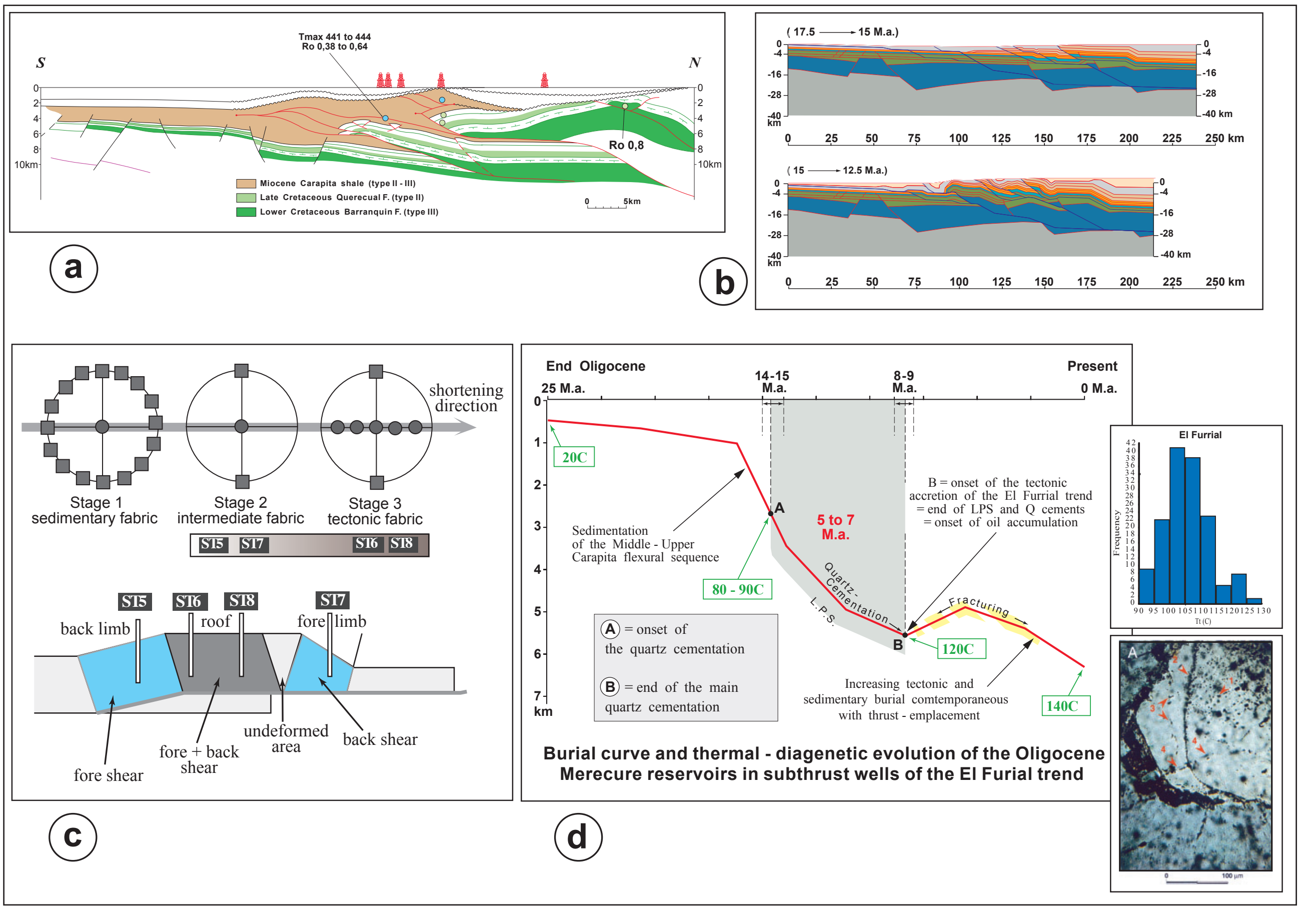


Figure 5: Main results of the SUBTRAP Venezuelan case study: (I) Dating of the diagenetic events: a. Structural section of the Eastern Venezuelan transect across the Serraña Foothills in the north and the Maturin Basin and Orinoco foreland in the south (after Roure et al. 2003, modified). The Naricual sandstone reservoir is located between the light green Upper Cretaceous Querecual source rock and the brown Miocene Carapita seal.
b. 2D forward kinematic and stratigraphic modelling of the same section (after Roure et al. 2003, modified). The Upper Jurassic synrift sequence is in blue. The Cretaceous passive margin sequence is in green. The Naricual Oligocene sandstone reservoir is in Orange, whereas the Miocene flexural sequence (Carapita seal) is in grey.
c. AMS (Anisotropy of Magnetic Susceptibility) diagrams recorded in Oligocene sandstone reservoirs of the Naricual Formation in the forelimb, crestal culmination and backlimb of the El Furrial anticline (after Roure et al. 2003, modified). Notice that none of the plugs studied has preserved the signature of burial compaction, that would account for a vertical axis of symmetry (stage 1). Instead, most samples document an intermediate fabric (stage 2), which records the effect of Layar Parallel Shortening (tectonic compaction) operating in the footwall of active thrusts, when the El Furrial reservoir unit was still attached to the foreland autochthon. Only a few sites near the kink axes of the El Furrial anticline actually record more evolved fabrics (stage 3), accounting for very localized deformation of the reservoir matrix after the onset of thrusting.
d. Left: Burial and temperature versus time curve representative of the same Oligocene sandstone reservoir. Bottom right: Thin-section outlining the habitat of fluid inclusions in the quartz overgrowths and at the interface between the overgrowth and detrital grains. Top right: Histogram of Th measurements in the fluid inclusions of the quartz overgrowths (after Bordas-Le Floch, 1999 and Roure et al., 2003, 2010, modified).

basins and adjacent foothills are quite similar to the processes operating in active offshore wedges (Guilhaumou et al., 1994 and 1996; Larroque et al., 1996). As these processes can impact either positively or negatively the overall sandstone reservoir-rock properties, they have been a major target for the SUBTRAP (SUBThrust Reservoir APpraisal) Joint Industry Project operated by IFP-EN from 1996 till 2002, with the support of numerous national and international companies, and the involvement of many university teams and national research institutes (Roure et al., 2005 and 2010a).

One of the main focus of SUBTRAP was the study of the Oligocene sandstone reservoirs of the Naricual Formation along a regional transect in eastern Venezuela, from the Serraña del Interior in the north, as far south as the Faja Petrolifera near the Orinoco River in the south, thus crossing the entire foothills domain, giant subthrust plays of El Furrial and adjacent fields in the Maturin basin, as well as the entire flexural basin (Figs 5 & 6). Quartz overgrowths and pressure-solution between detrital grains constitute the two damaging processes likely to impact the overall porosity and permeability of these sandstones, and the SUBTRAP study aimed at better understand and predict their impact on reservoir quality (Bordas-Le Floch, 1999; Roure et al., 2003; Toro et al., 2004).

The workflow applied to this case study involved numerous steps, the first one aiming at the construction of a regional structural section using available seismic profiles and wells, and its restoration to its pre-orogenic configuration. We then performed a forward kinematic and thermal modelling of this regional transect using the 2D Thrustpack software. Bottom hole temperatures and maturity ranks of the organic matter (Tmax and Ro) were also used in order to calibrate the basal heat flow and eroded thicknesses, the main result of the thermal modelling being a temperature-burial versus time curve for the main reservoir interval of the El Furrial and other available wells (Roure et al., 2003). In the mean time, Bordas-Le Floch (1999) was studying the aqueous fluid inclusions of the crystal quartz overgrowths, for which a mean Th value of 110°C was measured, that is quite colder than the current 130 to 160°C temperature of the reservoirs. When plotting these temperature values measured on fluid inclusions on the temperature-burial versus time curve derived from the Thrustpack modelling, it became obvious that the main cementation event impacting the reservoir quality was a fossil one, dating back to the period when the reservoir was less buried than today, and still attached to the foreland autochthon (Roure et al., 2005). Ultimately, colleagues from the university of Cergy-Pontoise studied also the Anisotropy of Magnetic Susceptibility (AMS) in numerous oriented plug samples from deep cores of the El-Furrial field (Fig. 5c), demonstrating that the Oligocene sandstone reservoirs currently uplifted in the tectonic wedge were still recording the signature of Layer Parallel

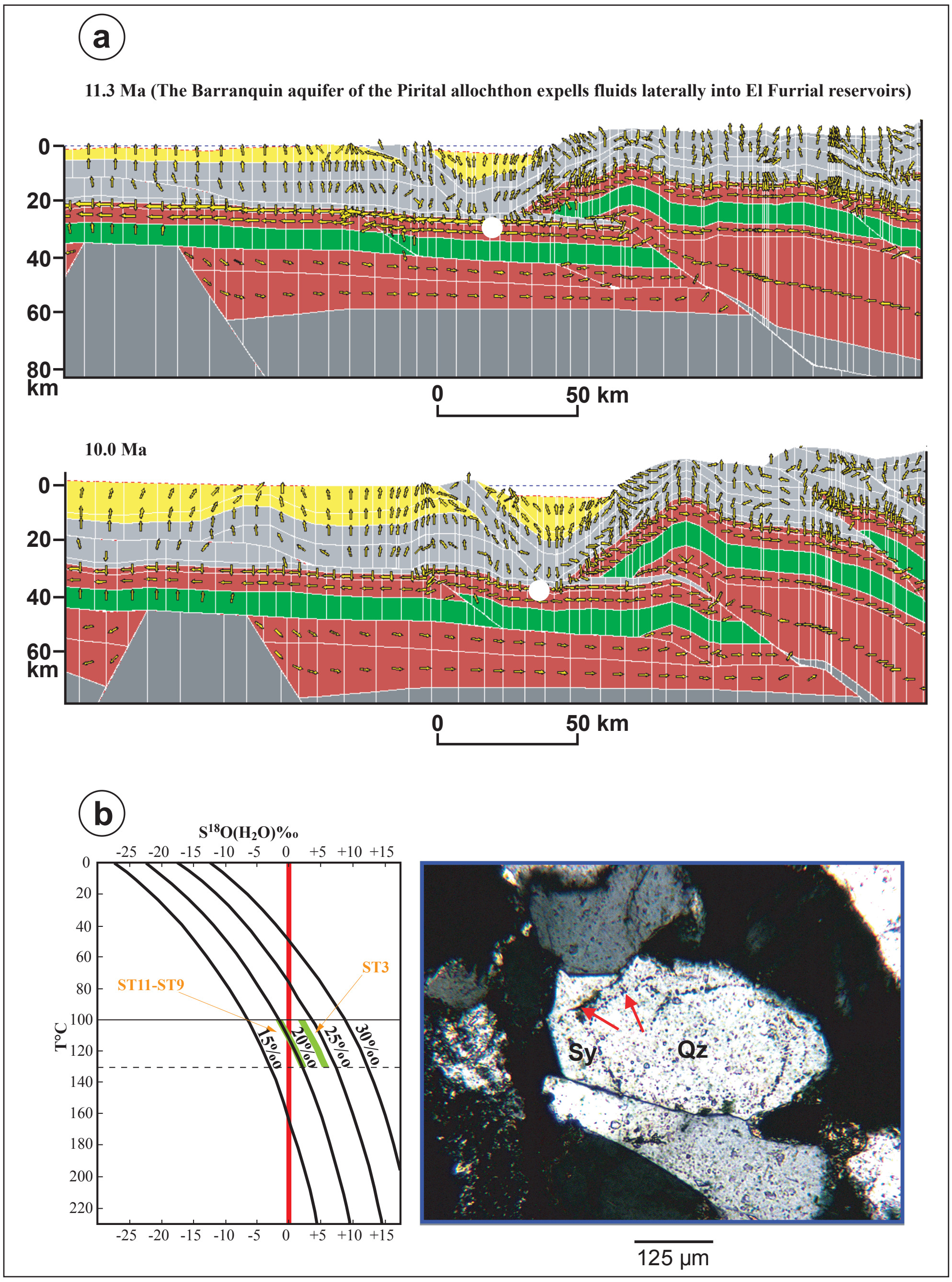


Figure 6: Main results of the SUBTRAP Venezuelan case study: (II) Fluid transfers and pore fluid pressure regimes during compression:
a. Results of coupled 2D fluid flow and pore fluid pressure modelling along the same Eastern Venezuelan transect (after Schneider, 2003 and Roure et al., 2010a, modified). The two deformation stages illustrated here document the early motion of the Pirital thrust (top), and onset of motion along the Furial thrust (bottom), at a time when the Pirital thrust was still active. Notice the overall lateral forelandward escape of fluids in the Oligocene sandstone reservoirs (upper orange layer) below and south of the Pirital Thrust, but also the local transfer of fluids between older, Cretaceous sandstone aquifers of the Barranquin Formation (lower orange layers) and the Oligocene Naricual sandstone reservoirs across the Pirital Thrust. The green layer between the Oligocene Naricual sandstone and the Lower Cretaceous Barranquin sandstone is made up of Upper Cretaceous series and includes the main source rock horizon (Querecual Formation, Cenomanian-Turonian in age).
b. Right: Thin-section outlining multiple generations of syntaxial quartz overgrowths around the same detital grain. Left: Plot of $\delta^{18}0$ values measured in the successive syntaxial quartz overgrowths (Sy), accounting for major changes in the composition of paleo-fluids between the main cementing event and younger episodes of silicification (after Schneider et al., 2004 and Roure et al., 2010a, modified).

Shortening (LPS), that resulted in tectonic-induced pressure-solution when the reservoir was still attached to the autochthon, without any obvious signature of younger compaction.

The main conclusion from this first Venezuelan study was that it is now possible to date diagenetic events by coupling fluid inclusion data with petroleum modelling. It demonstrated also that the main process damaging sandstone reservoirs in FFTB is the pressure-solution associated with LPS, that operates when the reservoir unit is getting close to the deformation front. A companion study made on the Eocene sandstone reservoirs of the Mirador Formation of the Cusiana oil field and other key wells from the foothills of the Eastern Cordillera in Colombia helped to confirm the over-regional significance of our Venezuelan observations (Roure et al., 2003; Toro et al., 2004).

During the second leg of the SUBTRAP project, we came back to this Venezuelan case study, this time with the objective to reconstruct the pore-fluid pressure evolution in the same Oligocene sandstone reservoirs of the Naricual Formation, and to get estimates on the velocity of the fluids in the reservoir through times (Schneider et al., 2004; Roure et al., 2010a). We had actually in mind that part of the silica could be exotic and brought to the Oligocene sandstone by the aquifers, because the volume of quartz overgrowths is sometimes larger than what can be reasonably generated by in situ pressure-solution. We also assumed that overpressures could prevent the reservoirs from further compaction, and it was therefore mandatory to know at what time these Oligocene reservoirs became overpressured.

Our team successfully attempted the measurement of Al traces in the quartz overgrowths in sandstone plugs collected at various distances from the contact between individual sandstone beds and clay intervals, the Al content decreasing significantly from the top to the core of the sandstone layers (Schneider et al., 2004; Roure et al., 2010). As the Naricual sandstones are made up of pure quartz grains, without any feldspar nor clay, the Al signature found in the quartz overgrowths in the close vicinity of the clay interbeds was a clear evidence that exotic materials, in addition to the in situ pressure-solution among quartz grains, were also contributing to the cementation, the later being thus operating in a partially open system.

Further evidence of fluid transfers from one aquifer to the other during thrusting was also provided by the study of the stable isotope content of quartz overgrowths. Actually, we identified a second and sometimes a third generation of quartz overgrowths around a few detrital grains. Even if more than 90% of the quartz overgrowths in the Naricual sandstone relate to the first generation, we attempted to measure by laser the $\delta^{18}O$ values in the different generations of quartz overgrowths (Schneider et al., 2004; Roure et al., 2010a, b). Surprisingly enough, even if Th measured in the three successive generations of quartz overgrowths showed the same trapping temperature, their $\delta^{18}O$ values appeared significantly distinct, suggesting that the main cementation event was buffered/equilibrated with the initial formation water of the Oligocene, but that a different fluid circulated in the Oligocene sandstone during the second and third episodes of cementation.

Looking at the results of the fluid flow and pore-fluid pressure modelling performed with the Ceres software along this transect (Schneider, 2003), it is clear that the Pirital Fault could operate as a conduit for the transfer of fluids from the Lower Cretaceous sandstone aquifer of the Barranquin Formation of the hangingwall, towards the Oligocene sandstone aquifer of the footwall, when these two aquifers were put at the same depth due to the reverse motion of the fault (Fig. 6). Further results of the Ceres modelling strongly suggest that the Oligocene sandstone reservoir of the El Furrial field has been overpressured at least since the time of its structural closure. Fluids were stationary in the reservoir until the foreland basin became tilted towards the south, when compaction fluids from the Oligocene started to escape laterally towards the foreland, parallel to the bedding, during a squeegee episode of water flushing.

6. Dynamic topography and its control on post-orogenic changes in HC drainage areas

Diachronous slab detachment operating along discrete segments of the Apennines-Maghrebides arc is known to induce a major unflexing, uplift and unroofing of the entire foothills domain and even adjacent portions of the autochthonous foreland. This is well evidenced by the occurrence of Langhian deep water turbidites of the former Mahgrebian foredeep, which are currently located at 1 km of elevation in Tiaret, a few km south of the Tellian front (Roure et al., 2012; Roure, 2013). Seemingly, the entire Pliocene accretionary wedge has been uplifted above the sea level in Sicily. Marine Pliocene series are indeed cropping out at more than one km of elevation in the Peloritan Mountains in the north, and have been already uplifted at a few hundred of meters above sea level along the southernmost thrust front near Gela.

As described below, post-orogenic uplift and unroofing operate also since the Oligocene along the entire North American Cordillera, from the Arctic to the Gulf of Mexico (GOM), mantle dynamics at the rear of the Pacific subduction having a major impact there on the post-Laramian evolution of drainage areas for the HC, with a rapid transfer of clastics sediments away from the thrust belt that contributed to the development of gravitational

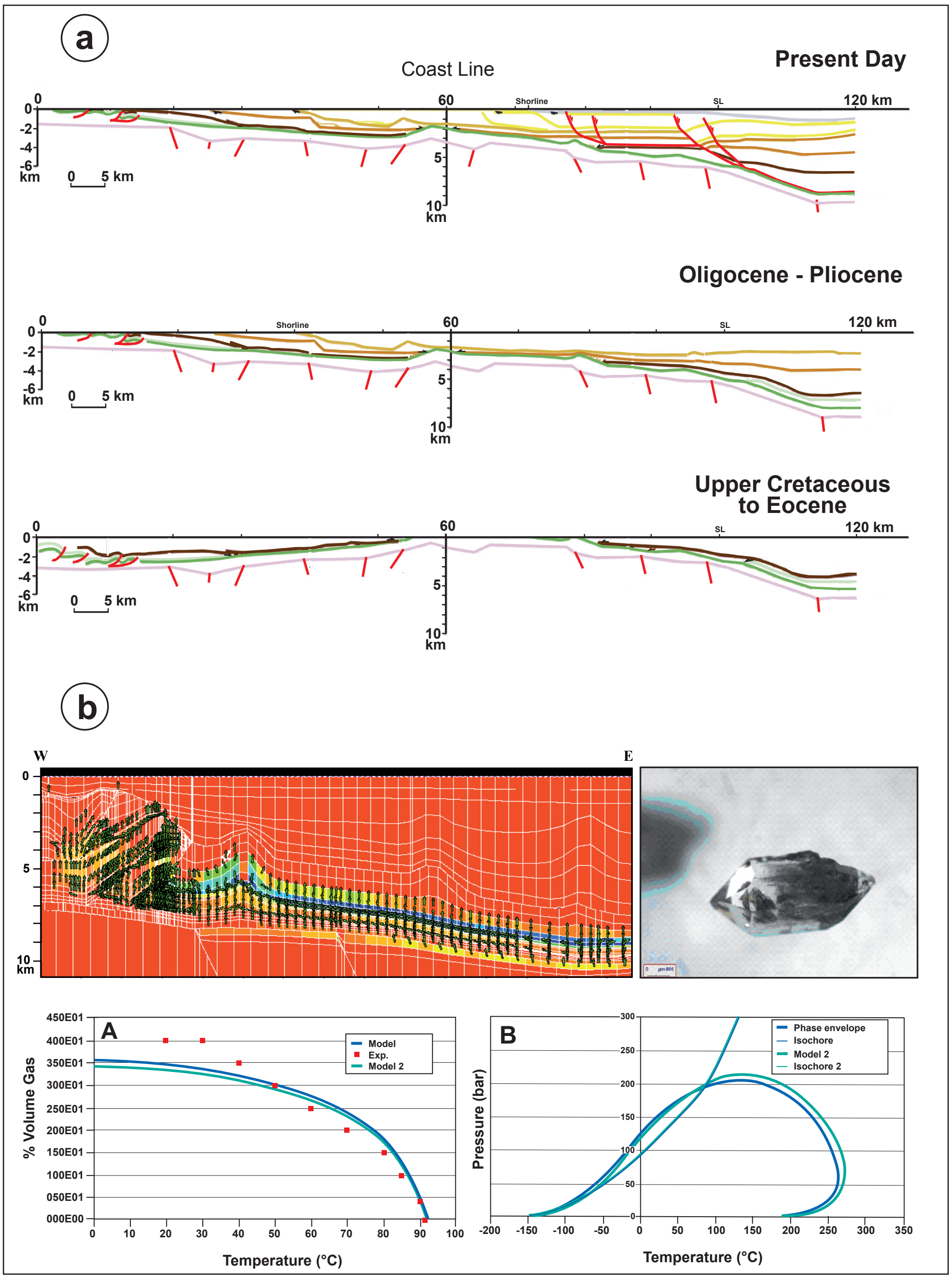


Figure 7: Post-Laramian unflexing of the foreland of the Sierra Madre Oriental and Cordoba Platform in Mexico:
a. Regional transect between the Sierra Madre and the Golden Lane, outling the post-Laramian tilting of the basement beneath the Chicontepec foredeep, post-Cretaceous subsidence of the Golden Lane atoll, and Neogene gravitational collapse of the western margin of the Gulf of Mexico (after Alzaga et al., 2008, a, b, and Roure et al., 2009, modified).
b. Top left: 2D coupled kinematic and petroleum modelling along a regional transect crossing the Veracruz Basin in the east and the Cordoba Platform in the west, outlining the recent HC charge of the frontal part of the foothills allochthon by oil generated in the Jurassic source rocks of the Veracruz foreland. Top right: Authigenic quartz crystal collected in cemented veins of Cretaceous carbonate reservoir analogues from the Cordoba foothills, containing both aqueous and HC-bearing fluid inclusions. Bottom right: Isochores of the aqueous and HC-bearing fluid inclusions (after Ferket et al., 2006, and Gonzalez-Mercado et al., 2012, modified).

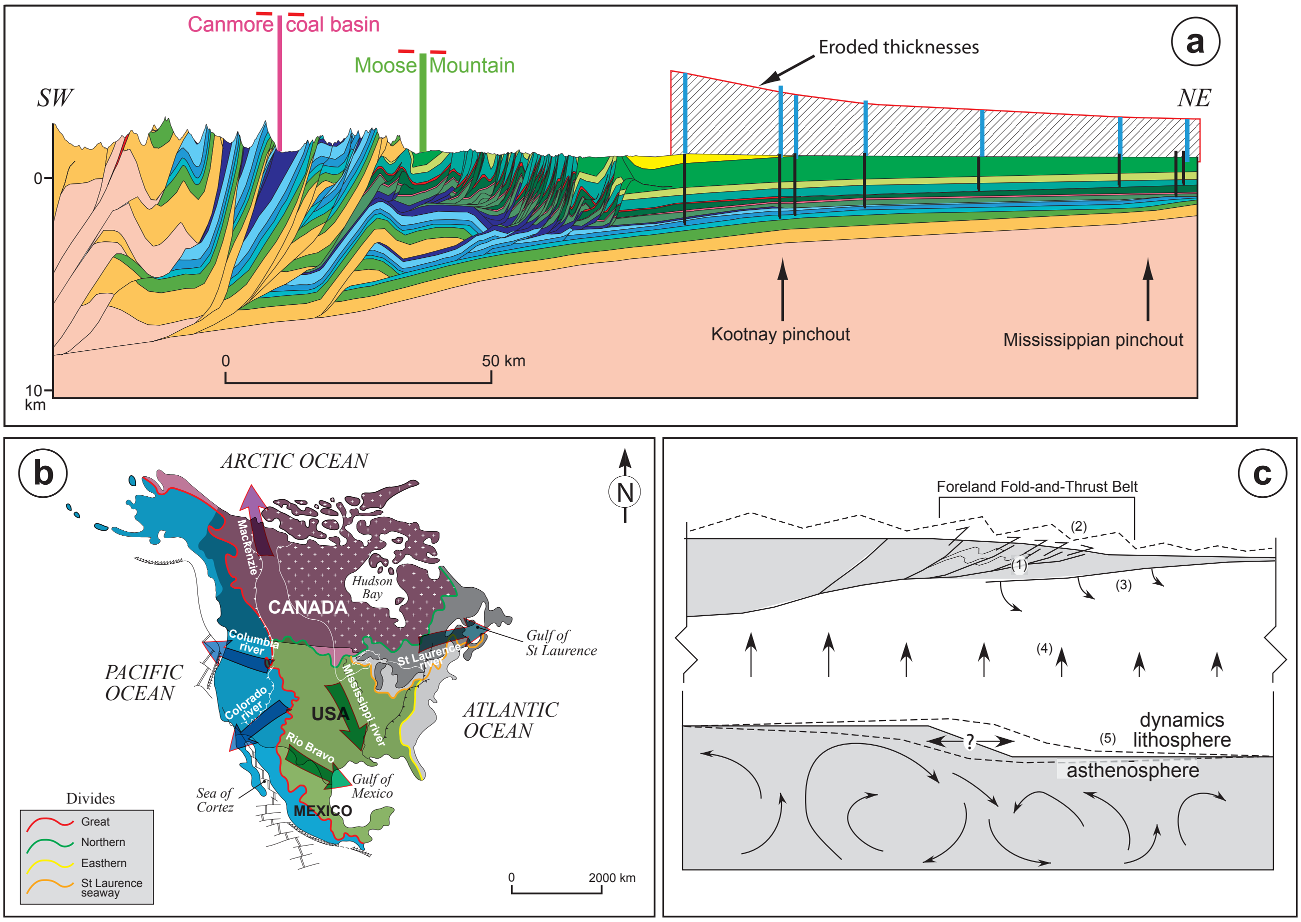


Figure 8: Dynamic topography and its controls on post-orogenic changes in HC drainage areas:
a. Structural section across the Alberta fooreland and adjacent foothills of the Canadian Rockies, outlining the huge amount of post-Laramian erosion accounted for by paleo-thermometers and 1D thermal modelling (after Faure et al., 2004, modified).
b. Simplified geological map of the North American continent, outlining the main source-sink pattern for the post-Laramian clastics sourced by the uplifted Cordilleran and adjacent foreland domains, and further transferred towards the Gulf of Mexico and Mackenzie Delta in the Arctic, where they account for gravitational collapse and destablization of the continental margins (after Roure et al., 2009, modified).
c. 2D coupled thermo-mechanical modelling of the interactions between the asthenosphere and the lithosphere at the rear of the Pacific subduction. Notice the stabilized, long lasting thickness shift observed between the thin, hot lithosphere beneath the Cordillera in the west, and the thick, cold lithosphere below the craton in the east, and the resulting uplift and unroofing of the overlying basement, both in the easternmost foothills and westernmost foreland (after Hardebol et al., 2007, 2012, modified).

deformation along both the US and Mexican margins of the GOM (Alzaga et al., 2008 a, b; Roure et al., 2009).

We shall use here the results of two other SUBTRAP case studies on carbonate reservoirs in Mexico and Canada, which indeed proved to be extremely useful to better understand the role of mantle dynamics on surface processes as well as on the overall evolution of the petroleum systems.

6.1. Post-Laramian tilting of the basement of the Veracruz Basin and Golden Lane area (Mexico)

During a project aiming at the prediction of clastics reservoirs in the Mexican offshore of the GOM using a coupled Thrustpack-Dionisos modelling approach accounting for both tectonic and sedimentary processes, we studied a regional transect across the western margin of the Gulf of Mexico, running from the Sierra Madre Oriental and Chicontepec foredeep in the west, as far to the GOM in the east, thus crossing the Golden Lane, a famous Upper Cretaceous atoll comprising excellent reefal reservoirs that contibuted to major oil production early during the nineteen century (Alzaga et al., 2008 a, b). The current tilt of this former reef and its important Neogene burial cannot be understood without considering its initial position during the development of the Sierra Madre thrust belt, when it was located at the approximate position of the forebulge that separated the Chicontepec flexural basin from the already deeper water domain of the GOM (Fig. 7). At that time, the Golden Lane operated as a natural barrier which prevented the clastics sourced by the erosional products resulting from the unroofing of the Cordillera to reach the GOM. Since the Oligocene onward, this intervening barrier being subsiding rapidly, all the erosional products of the Sierra Madre are instead transferred directly to the GOM, where they have induced a rapid burial and development of overpressures in undercompacted Eocene shales, resulting in the development of listric faults and gravitational collapse of the margin.

Farther south, the basement is also tilted towards the east beneath the Cordoba Platform and the Veracruz Basin, still in the vicinity of the former Laramian thrust front (Ferket et al., 2000, 2003, 2004; Ortuño et al., 2003). There, the Upper Cretaceous platform carbonates of the allochthon are currently devoided of any younger siliciclastic turbidites that would account for an episode of flexural subsidence prior to their tectonic accretion into the Laramian edifice. However, after an accurate search for paleo-thermometers, we could find an authigenic quartz crystal in a cemented fracture within these Cretaceous shallow water carbonates, containing two synchronous sets of fluid inclusions, i.e. the first one aqueous, and the second one oil-bearing. Knowing the water and oil composition, it was then possible to cross the isochores of the two fluids, which provided an unique opportunity to derive both the paleo-temperature and paleo-burial of the reservoir at the time of trapping, assuming a dominantly hydrostatic pressure regime (Ferket et al., 2006 and 2011). Surprisingly enough, these results forced us to admit that the Upper Cretaceous carbonates of the Cordoba Platform were initially buried beneath at least 3 km of overburden, likely to be made up of siliciclastics of the former Laramian foredeep.

When integrating this new constraint of paleo-burial in the restored geometries and further Ceres modelling, it becomes evident that the current eastward tilt of the basement initiated after the Laramian orogeny only, its initial configuration at the time of the deposition of the Laramian flexural sequence being the opposite, i.e., tilted towards the west (Gonzalez-Mercado et al., 2012).

This change in the tilt of the basement had actually a tremendous impact on the petroleum systems, the Cordoba foothills being one of a few examples around the World where the HC charge of the foothills results from a post-orogenic HC migration from the foreland towards the foothills.

6.2. Post-Laramian unroofing of the Canadian Rockies and Alberta foreland

The same type of post-orogenic uplift and erosion in the foothills and adjacent foreland has been also well documented during another SUBTRAP case study in the Canadian Rockies and Alberta foreland (Faure et al., 2004; Vandeginste et al., 2005, 2007 and 2009), where paleo-thermometers (Ro) and 1D thermal modelling evidence the erosion of more than 3 km of sediments in the foothills, decreasing progressively towards the east, with still 1 km of erosion recorded 100 km east of the former Laramian thrust front in the vicinity of Calgary, which is located at about one km above the sea level (Fig. 8).

Actually, it is the entire North American Cordillera and its adjacent foreland which have been impacted by post-Eocene uplift and erosional unroofing, most of the foothills being currently devoided of any Late Cretaceous to Eocene synflexural or synkinematic deposits, as it would be expected for such geodynamic environment. Looking at a simplified map of North America, it is obvious that all the Laramian clastics have been removed by erosion, and transferred towards the Arctic and MacKenzie Delta on the one hand, and towards the GOM on the other hand, resulting in a rapid sedimentation, loading and destabilization of the continental margin by means of gravitational collapse (Roure et al., 2009).

Unlike in Mexico, accurate data are available in Canada to constrain crustal and lithospheric scale cross-sections at the scale of the continent, outlining a crustal thinning beneath the inner part of the Cordillera, which is consistent with the development of Cenozoic normal faults and core complexes where the lower crust has been locally exhumed (Price, 1981; Price and Monger, 2000; Hardebol et al., 2007, 2012). Worth to mention, there is also an important vertical offset impacting the overall lithosphere thickness beneath the foothills, with a thin, hot and weak lithosphere in the west beneath the Cordillera, and instead a thick, cold and rigid lithosphere beneath the foreland (Fig. 8). Thermo-mechanical modelling accounting for mantle convection at the rear of the Pacific subduction has demonstrated that such bent of the lithosphere-asthenosphere boundary, i.e. bent of the 1300°C isotherm, could remain stable for long periods of time (here since at least 40 My; Hardebol et al., 2012). In addition to mantle convection, hydration of the upper mantle by fluids escaping vertically from the subduction zone could have also progressively modified its overall chemical and physical properties. No matter of the details of the process, it is now obvious that it is the mantle dynamics at the rear of the Pacific subduction which are controlling the current dynamic topography of the North American Cordillera and its adjacent foreland.

6.3. A Cordilleran view on the European lithosphere

A similar step is also observed in Europe along the Tornquist-Teisseyre Line (TTL), with a thin, hot and weak lithosphere in the west and instead a thick, cold and rigid lithosphere in the east, beneath the Russian platform (Fig. 9; Artemieva, 2009; Tesauro et al., 2008, 2009; Roure et al., 2010b; and references therein).

When looking in detail to the geodynamic evolution of Europe, it is clear that the TTL is more or less parallel to the former Hercynian thrust front, and that the mantle lithosphere of this domain may have been impacted in the past by subduction related convections, like today in the North American Cordillera. Significantly also, the crust of the former Hercynian orogen has been extended and thinned during the Permian collapse of the former Carboniferous edifice, as it is currently the case in the metamorphic core complexes and Basin and Range Province in the North American Cordillera, resulting in the well layered reflective lower crust imaged by the ECORS profiles. The thermo-mechanical weakness of the West European crust and mantle lithosphere allowed also its regular deformation during Mesozoic and Oligocene extensional episodes, as well during Late Cretaceous-Eocene (Pyrenean) and Neogene (Alpine) compressional episodes (Ziegler, 1989; Roure et al., 1990a, b, 1994; Ziegler et al., 1995, 1998, 1999, 2006; Roure and Colletta, 1996; Cloetingh et al., 2005; Tesauro et al., 2008, 2009), whereas the thick lithospheric domains of the Russian platform and Western Mediterranean/Arabian plate were little impacted by recent deformations as compared to the intervening Tethyan FFTB.

7. Conclusions

Crustal and mantle imagery is considerably enhancing our vision on the coupling between deep and shallow processes operating in compressional orogens. In addition to the well known controls of tectonic loading and slab pull on the flexural behaviour of the foreland lithosphere, mantle convection and dynamic topography

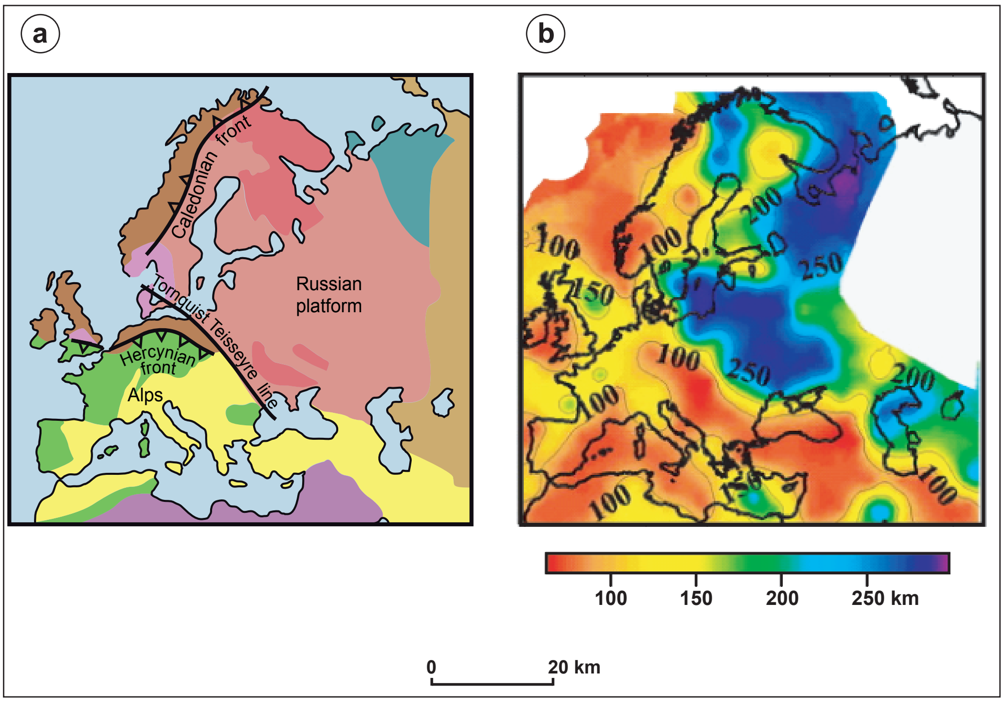


Figure 9: Simplified geological map of Europe (a) and overall lithospheric thickness (b) (after Artemieva, 2009, modified). Notice the huge step observed in the lithospheric thickness in the vicinity of the Tornquist-Tesseyre lineament, which separates a thin, hot and mobile lithosphere in the west, beneath the former Hercynian and Caledonian orogens, and a conversely cold, thick and rigid lithosphere in the east beneath the Russian Platform.

appear as other important processes controlling the post-orogenic evolution of foothills domains, being likely to impact considerably their petroleum systems. One of the main objectives of the International Lithosphere Programme (ILP) Task Force 6 on Sedimentary basins and of the Topo-Europe project is actually focused on the study of these couplings (Cloetingh et al., 2007; Lacombe et al., 2007; Al Hosani et al., 2012)

Robust 2D numerical modelling tools coupling kinematic, thermal and kinetics approaches are already able to predict properly the distribution of oil kitchens, drainage areas, timing and style of HC migration, which can be either short range and dominantly vertical or instead long range and dominantly horizontal (Ziegler and Roure, 1996; 1999; Roure, 2007). Additional work remains however required to move towards fully quantitative evaluation of the HC charge of prospects, that would require the use of 3D models which are still difficult to operate in tectonically complex environments such as FFTB (Roure et al., 2010b).

Ultimately, a major step forward has been achieved in the understanding of natural processes by means of analytical works and modelling during the SUBTRAP project and later follow-up studies. However, any new developments in the study of paleo-thermometers, paleo-barometers and radiometric dating of diagenetic cements or HC fluids are likely to improve a lot our predictions for the energy resources of sedimentary basins and foothills (Lacombe et al., 2009; Roure et al., 2010a).

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