THE NEGATIVE TECTONIC INVERSION OF THRUST FAULTS: INSIGHTS FROM SEISMIC SECTIONS ALONG THE NORTHERN FRANCE VARISCAN THRUST FRONT AND ANALOGUE MODELLING EXPERIMENTS

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Introduction

The extensional reactivation of buried thrusts has often been suggested as a major deformational mechanism in post-orogenic sedimentary basins (e.g., Roure, 2008). Its recognition is generally based on combined structural features including the collapse of the backlimb of thrust-related fold structures, the development of post-orogenic syn-rift deposits upon the crest of anticlines and the general parallelism of extensional and compressional structures in map view. The direct relationships between normal faults and the underlying thrust faults are however rarely exposed due to the general burial of these structures below a sedimentary cover controlled by the tectonic subsidence. Seismic profiles across post-orogenic basins generally does not allow neither to provide, at depth, a precise image of such relationships due to the overall structural complexity. Based on geomechanical criterion (e.g., Ivins et al, 1990; Faccenna et al, 1995) and the rare direct observations in collapsed fold-thust belts (D'Agostino et al, 1998), the amplitude of the dip of the initial thrust faults has been suggested as a major controlling parameter for a possible extensional reactivation. As the thrust surfaces flattens or steepens across the crustal layers depending on their relative weakness (the classical staircase geometries of thrusts), only part of the thrust surfaces is mechanically relevant for a reactivation in superficial domains. The footwall ramps, that exhibit the strongest dips along the thrust fault, have thus largely been considered to localize some post-compressional normal displacement. Such partial reactivation of the thust (reactivation of the ramp and the basal décollement) and the dissection of the forelimb of the thrust-related anticline by a newly formed steep fault generate an overall listric normal fault that can localize subsidence of the crest of the anticline, tilting of the hangingwall block and deposition of fan shaped syn-rift layers. Such a mechanism, that accounts for both geometric and mechanical constraints of thrusts reactivation has been generally considered as the typical model for the negative tectonic inversion process (Fig. 1)(Williams et al, 1989 ; Tavarnelli, 1999).

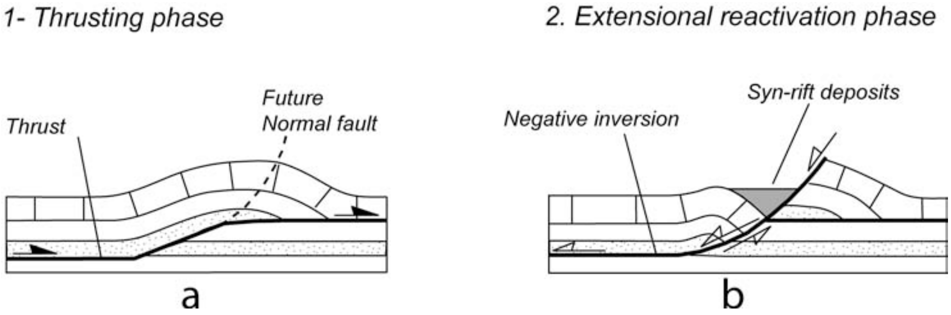

Figure 1. Sketch diagram showing the basic geometric characters of extensionally reactivated thrust structures and of the related syn-rift sedimentation (modified from Tavarnelli, 1999).

To provide further insight into this mechanism, we present here a new example of the extensional reactivation of a thrust structure based on seismic profiles imaging the buried N France Variscan thrust front. This structural approach is complemented by analogue modelling experiments that allows constraining the geometries and kinematics of the negative tectonic inversion process and discussing the possible parameters that control the reactivation of basement thrusts during a subsequent extension.

The negative tectonic inversion of the Variscan thrust front: structural evidence

The Variscan (ca. 300 Ma) thrust front in Northern France extends, below the thin Mesozoic sedimentary cover of the Paris Basin, from the English Channel to the west (Calais-Boulogne area in Fig. 2), to the Ardennes massif to the east (Valenciennes-Maubeuge area in Fig. 2). Outcrops located at both extremities (Boulonnais and Ardennes Paleozoic massifs), as well as seismic profiles and numerous boreholes show that the frontal thrust system is characterized by a major crustal-scale thrust zone, dipping gently Southward (the main frontal Variscan thrust), whose emergence corresponds to a large out-of-sequence thrust, knwown as the Midi thrust (e.g., Averbuch et al., 2004). Analysis of recent seismic data suggests that the total amount of slip along this thrust zone could be as much as 70 km in the Western Ardennes area (Lacquement et al., 1999), thereby strongly dissecting the Southern border of the coal-bearing molassic foreland basin of Namurian-Westphalian age. This foreland basin (up to 3-4 km thick) formed at the top of a reduced Devonian-Carboniferous sedimentary sequence resting unconformably on a Lower Paleozoic basement, which crops out a few tens of km North of the Variscan thrust front, in the Belgian Brabant Massif.

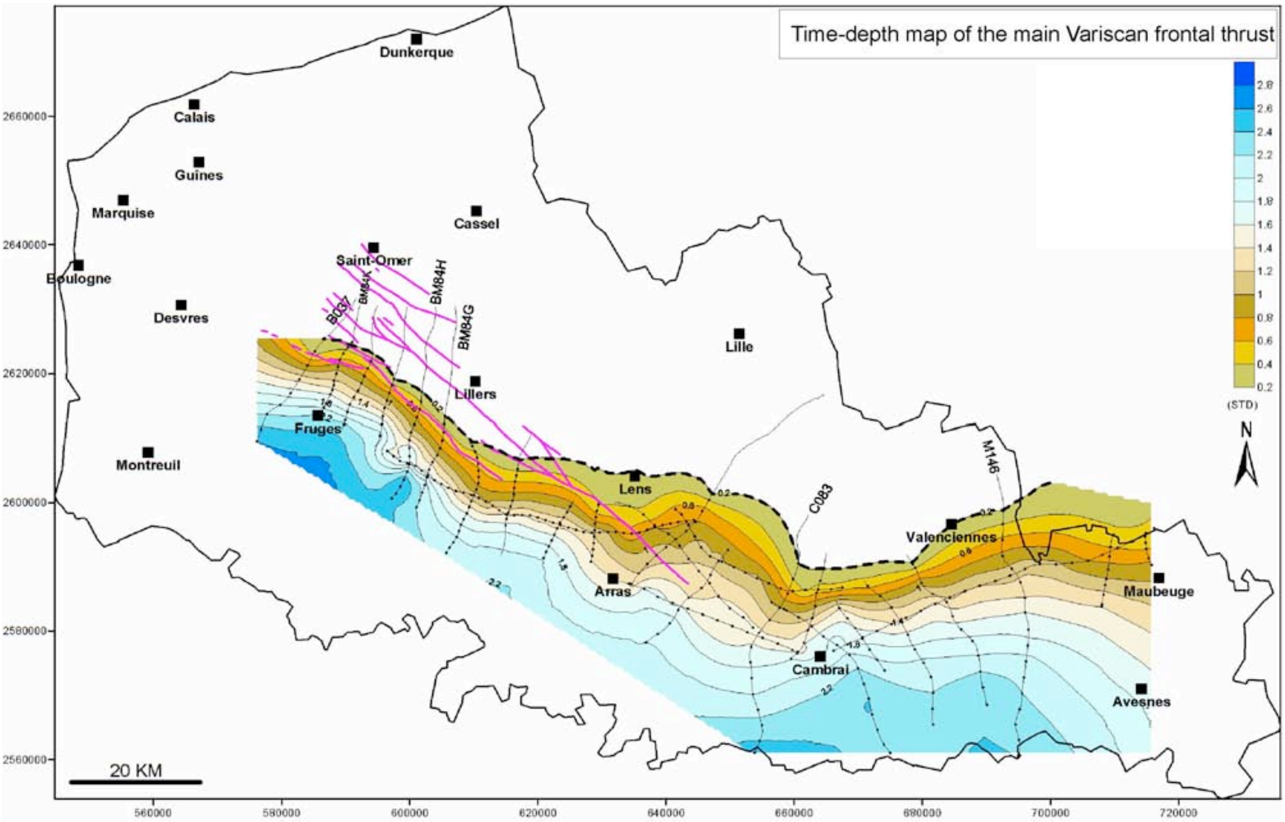

Figure 2. Subcrop trace (dashed thick line: Midi thrust) and time-depth isochrons of the main Variscan frontal thrust in Northern France (modified from Minguely et al, 2010). Colours brown to blue refer to increasing time-depth values from 0 to 2.8 seconds (two-way time travel). The black sections report the trace of the analysed seismic profiles. Profile 84K presented in Fig. 3 is located between Fruges and St Omer in the Artois region. The pink lines report the trace of the surface faults mapped in the Paris basin sedimentary cover and supposed to be controlled by basement thrusts connected to the Variscan thrust front.

Such general structural pattern of the thrust front is however slightly complicated along its western part (the Boulonnais-Artois domain, between Boulogne and Arras in Fig. 2) as it is affected by a network of steep S-dipping faults cutting through both the post-orogenic cover and the Paleozoic layers of the substratum (Fig. 2). As shown by the interpreted seismic section of Fig. 3, some of the steep S-dipping faults limits to the North some very narrow post-orogenic intramontane basins filled up with Stephanian-Permian conglomeratic deposits. These post-orogenic levels are characterized by prominent N-dipping reflectors, lying on top of the S-dipping reflectors of the Variscan deformed layers and displaying a fan geometry characteristic for the infill of progressively tilted half-graben associated with a listric normal fault. The latter apparently branch at depth upon the main Variscan frontal thrust as suggested by the continuity of the reflectors associated with this major thrust zone. Along its footwall, the Paleozoic sequences (i.e. the base Carboniferous reflector in Fig. 3) are clearly truncated whereas they are parallel to the thrust along the hangingwall (the base Lower Devonian reflector in fig. 3) illustrating the ramp geometry of the deeply eroded frontal thrust zone below the Middle Cretaceous sedimentary cover of the Paris basin. These data clearly document the negative structural inversion of the Variscan thrust front and argue for the buried ramp of the Variscan frontal thrust to have controlled subsequent Stephanian-Permian extensional deformation by localizing normal displacement, thereby inducing the reactivation of deeper parts of the thrust as an extensional detachment. The development in superficial areas of steep faults, linked downward to the thrust ramp, is suggested to induce the individualization of listric normal faults along which stepwise subsidence and block tilting induced the deposition of fan-shaped continental sequences.

Moreover, as shown by the reverse finite displacement of the unconformable Cretaceous cover, these faults were subsequently positively inverted during the Alpine s.l. Tertiary compressional stage.

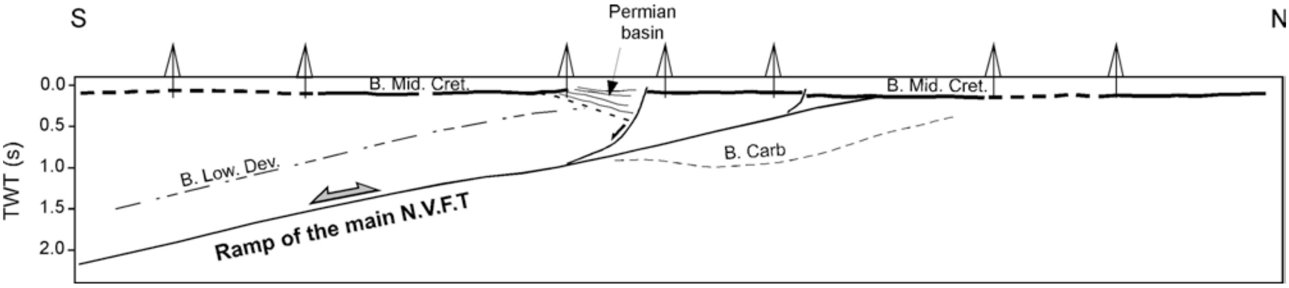

Figure 3. Interpreted seismic sections BM84K across the Variscan thrust front in the Artois area (onshore N France) constrained by borehole data and gravity modelling (modified from Minguely et al, 2010). N.V.F.T.: Northern Variscan frontal thrust; B. Mid. Cret.: Base of the mid-Cretaceous cover of the Paris basin; B. Carb.: Base of the Carboniferous rocks in the foreland of the N.V.F.T.; B. Low. Dev.: Prominent reflector at the hangingwall of the N.V.F.T. supposed to be the base of the siliciclastic Lower Devonian "red sandstone" sequence.

As exemplified in Fig. 2, the eastern part of the thrust front (the Ardennes domain), does not exhibit such post-Variscan steep faults resulting from the negative inversion of the thrust front. Time-depth map of the main Variscan frontal thrust zone based on the compilation of a large set of seismic profiles across the thrust front (Fig. 2) document a significantly lower dip of the thrust in the Ardennes domain compared to the Boulonnais-Artois area thereby suggesting a possible control of the thrust dip on the occurence of post-orogenic negative inversion.

Analogue modelling: preliminary results

We designed a set of analogue experiments in order to investigate the geometry and kinematics of the extensional reactivation of pre-existing thrusts and test some basic parameters controlling its possible development (i.e. the dip of the basal slope of the thrust wedge and the degree of truncation of thrust structures by erosion). We conducted these experiments at the tectonic modelling laboratory of the University of Lille 1. In the following, we will present only one experiment with a basal slope of 2.5° during the extensional phase and without any erosion of the first-phase compressional structures. The general set up was as follows. All models were constructed using a brittle, cohesionless, dry, porous 3 cm-thick sand unit overlying a basal silicone 1 cm-thick layer. All models, initially 111,5-cm long and 49 cm large, were built above a flat, horizontal, rigid base.The entire model was subjected to a first phase of shortening by moving progressively at a constant speed (0.5 cm/hour) the left-hand wall until a value of about 39% bulk shortening was reached (87 hours of shortening). An orogenic wedge formed against the moving wall, then propagated progressively rightward by formation of new forethrusts and by bulk thickening of the wedge itself. Four main foreland-directed thrust structures with associated minor backthrusts formed during that stage as well as major back-thusting and internal deformation along the left-hand moving wall (Figure 4). Shortening stopped, and a post-tectonic sand layer was deposited on the topographic relief of the fold-and-thrust structures to form an horizontal top surface. In the first experiment, the right border of the model was uplifted to simulate a basal slope of the thrust wedge of 2.5° and the model was then subjected to a phase of extension by moving backwards the mobile left-hand wall (speed: 1 cm/hour). As extension proceeded, the initially horizontal top surface of the model subsided locally along fault-bounded grabens that were incrementally filled-up with sand layers of different colours to simulate the progressive syn-rift deposits. The extensional stage was stopped until about 23.5% of extension was reached (16 hours of extension).
Results of this experiment are illustrated on the Fig. 4 showing on a representative section, cut near the center of the model, the final geometry of the rifted basin and the relationships of the basin-controlling normal faults with the underlying thrusts. The section was incrementally restaured at the different main steps of the basin development using 2D-Move (courtesy of Midland Valley Ltd) but this procedure won't be discussed here.
This first experiment emphasizes the characteristic geometric and kinematic features of post-orogenic basin development, and especially, it argues for the ramps of fore- and backthrusts to localize at depth respectively the master normal faults controlling depocenters and some antithetic secondary faults possibly accommodating the adjustement of the hangingwall over the basal thrust surface (Roure et al, 1992; D'Agostino et al, 1998). In the first stages of extension, normal displacement is greatly partitioned into the different underlying thrusts and no sequence of normal fault propagation can be pointed out in the model. Against the mowing wall, however, initial major back-thrusting localizes a significant antithetic normal fault zone whose displacement incrases with time compared to the other master normal faults thereby inducing a late major roll-over structure. The increased flow with time of the silicone due to the basal slope (2.5°) is likely to have had a major role on this possible experimental artefact.

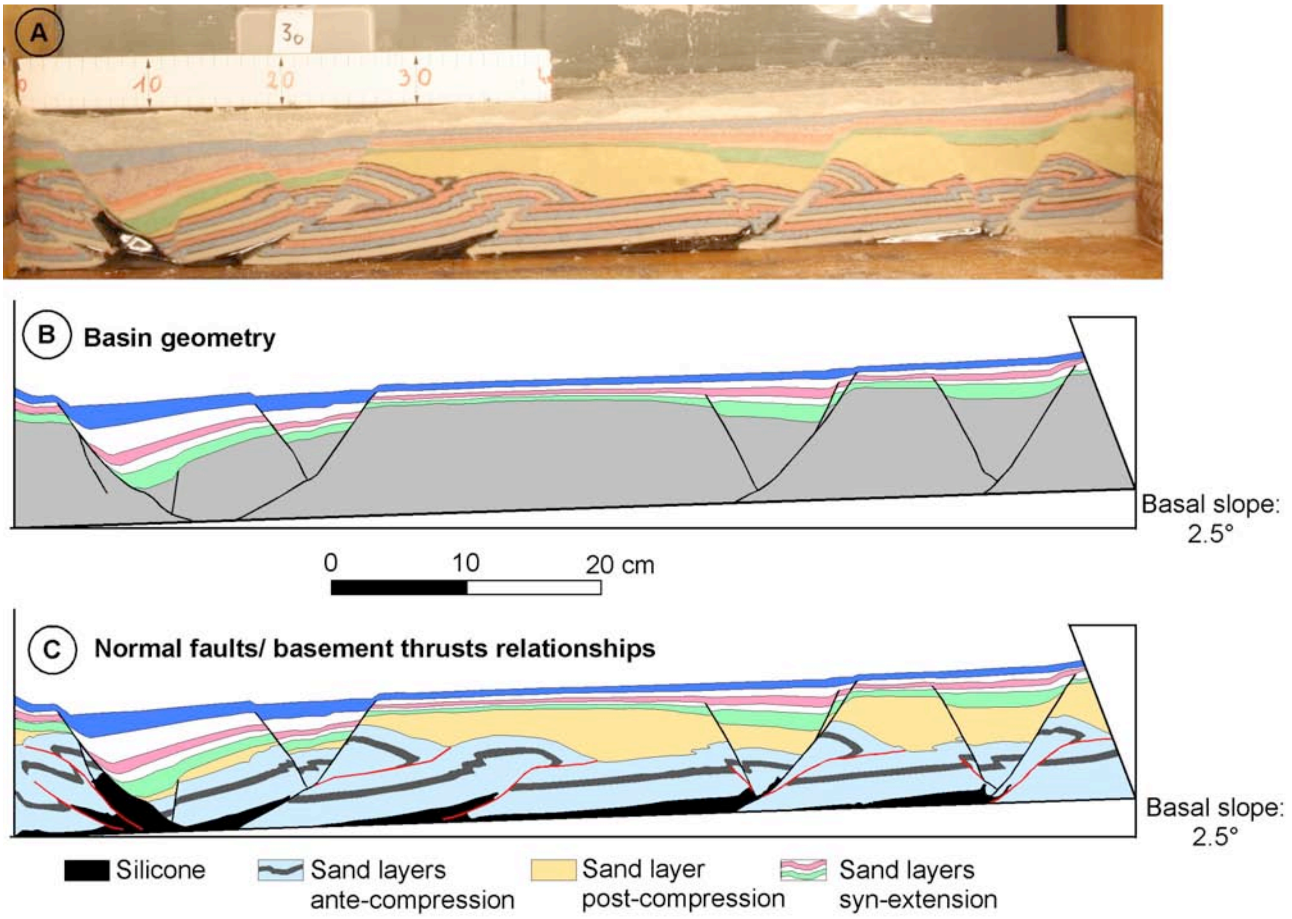

Figure 4. A: Photograph of a section cut near the model's centre (Experiment 1 with a basal slope of 2.5°). Scale in centimetres. B: Interpretation of the final geomety of the extensional stage (extension rate: 23.5%). C. Interpretation of the final geometry of the model illustrating the relationships between normal faults and thrusts inherited from the early compressional stage.

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