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From paleostresses to paleoburial in fold–thrust belts: Preliminary results from calcite twin analysis in the Outer Albanides

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ABSTRACT

This paper presents a new approach to constrain paleoburial and subsequent uplift by folding in fold–thrust belts, combining differential stress estimates from mechanically-induced calcite twins with the assumption that stress in the upper crust is in frictional equilibrium. Calcite twin data were collected from pre-folding veins in late Cretaceous limestones from the Ionian zone in Albania in order to (1) determine Paleogene–Neogene stresses associated with the development of the major vein sets in the frontal anticlines of the Outer Albanides and (2) estimate paleoburial of the Cretaceous reservoir rocks during pre-folding flexural subsidence of the foreland. The first vein set (set I) trends N140 (±20) and the second set (set II) is oriented N060 (±20). Calcite twinning analysis from set I veins reveals a pre-folding N030° extension likely related to foreland flexure; a later pre-folding, NE-directed compression (LPS) is identified either from one or from both vein sets in the samples from the Saranda anticline; this NE compression is instead recorded by twinning in set II veins from the Kremenara anticline during late stage fold tightening. This NE compression well agrees with independent microtectonic data, regional transport direction and contemporary stress. The differential stress values related to this NE compression are combined with the hypothesis of crustal frictional stress equilibrium to derive first-order estimates of paleoburial of the Cretaceous limestones just before they were uplifted by folding. The ~4 km paleoburial of these limestones estimated in the Saranda anticline is consistent with independent paleoburial estimates from stratigraphy, maturity rank of organic matter, paleotemperature/paleogeothermal gradients from fluid inclusions and predictions of kinematic modelling of the Albanian foreland. Our results therefore place reliable constraints on the amount and rate of vertical uplift of these Cretaceous limestones and yield a promising methodology for better constraining paleoburial and therefore erosion and uplift in fold–thrust belts.

1. Introduction and aim of the study

Thrust belts and foreland basins record both the main phases of orogenic evolution and the coupled influence of deep (flexure, plate rheology and kinematics) and surficial (erosion, sedimentation) geological processes, occurring at different time scales. They constitute important targets for scientists interested in both fundamental and applied (fluids, hydrocarbons) issues.

Vertical movements such as subsidence and tectonic uplift are key factors of the evolution of the fold–thrust belt–foreland basin system. While flexural subsidence and sedimentation prevail in the foreland basin, erosion is the dominant process in the foothills domain that largely controls the paleoburial and thermal evolution of rocks involved in folding. These parameters are of key importance to understand the petrophysical evolution of potential source and reservoir rocks, past vertical motions and hydrocarbon perspectives. Although the use of well logs, BHT and paleo-thermometers such as vitrinite reflectance (Ro) and Tmax is usually sufficient to calibrate the heat flow and geothermal gradients in the foreland, where limited erosion occurred, it is usually not possible to derive an univocal solution for paleo-burial and paleo-thermal gradients estimates in the foothills, if based, for example, exclusively on maturity ranks of the organic matter.

The difficulty of estimating paleoburial, and therefore erosion, in fold–thrust belts has been illustrated recently. On the basis of new studies of hydrocarbon/aqueous fluid inclusions in the Veracruz basin–Cordoba platform in Mexico, previous paleoburial values reported by Ferket et al., (2000, 2003, 2004) were proven to have been underestimated by about 2 km (Ferket, 2006). New numerical fluid flow modelling (Gonzalez Mercado, 2007) has shown that accurate estimates of erosion/paleoburial may have important

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consequences on the prediction of potential source rock maturity and hydrocarbon migration as well as on the erosion/sedimentation mass balance between the belt and the adjacent basin.

Alternate, independent methods are therefore required to decrease the errors in paleo-burial estimates, and to allow more realistic predictions of hydrocarbon generation. Apatite Fission Tracks analyses (e.g., Muceku et al., 2006) can provide access to absolute ages for the crossing of the 120 °C isotherm and timing of the unroofing. Hydrocarbon-bearing fluid inclusions, when developing contemporaneously with aqueous inclusions, can provide a direct access to the pore fluid pressure and temperature of cemented fractures or reservoir at the time of cementation and hydrocarbon trapping. Attempts have also been made to constrain burial depth range using the development of bedding-parallel stylolites to derive a minimum depth (burial depth needed for stylolite formation being estimated to be at least 800–1000 m depending on lithology type: Finkel and Wilkinson, 1990; Railsback, 1993; see also Dunnington, 1967; Nicolaides and Wallace, 1997) and the smectite–illite transformation to derive a maximum depth (e.g., Breesch et al., 2007).

Calcite twins are among the most common stress–strain markers in fold–thrust belts. Calcite twin analyses have been widely used to constrain both the structural and kinematic evolution of thrust belts (e.g., Spang and Groshong, 1981; Lacombe et al., 1993; Rocher et al., 1996, 2000; Craddock and Van Der Pluijm, 1999; Harris and van der Pluijm, 1998; Gonzales-Casado and Garcia-Cuevas, 1999), but also recently to derive differential stress magnitudes during deformational events (Lacombe et al., 1996, 2007). Attention has been particularly focused on the estimates of paleodifferential stress magnitudes at the onset of folding (LPS) and during late stage fold tightening, which has led to the conclusion that at the scale of individual structures, differential stresses recorded by rocks were largely dependent on the paleoburial and subsequent erosional history before and during folding (Lacombe, 2001). In addition, the evolution of paleodifferential stress magnitudes with depth, mostly derived from calcite twinning paleopiezometry, in various tectonic settings has been compared to the modern differential stress/depth gradients deduced from in situ measurements (e.g., Townend and Zoback, 2000): despite dispersion, both independent sets of stress data support to a first-order that the strength of the continental crust down to the brittle–ductile transition is generally controlled by frictional sliding on well-oriented preexisting faults with frictional coefficients of 0.6–0.9 under hydrostatic fluid pressure (Lacombe, 2007).

The goal of this paper is to propose a new method to estimate paleoburial and subsequent uplift by folding in fold–thrust belts, based on calcite twin analysis. This method basically combines estimates of differential stresses from calcite twins with the hypothesis that stress in the upper continental crust is in frictional equilibrium. Taking the Albanian foreland as a case study, we show first that calcite twin analysis provides reliable constraints on the early stages of the tectonic history of the thrust belt, including development of pre-folding vein systems currently observed in folded strata, and related fluid flows. Second, we demonstrate that our new approach places valuable constraints on the amount of burial of the Albanian Cretaceous foreland rocks during flexural subsidence and, therefore, on their subsequent uplift during Neogene folding. This new method therefore allows a better quantification of vertical movements in orogenic forelands.

2. Geological setting of the Albanides

2.1. Structures

The Albanides are a branch of the Alpine orogenic belt, which can be subdivided into an eastern internal zone and a western external zone (Robertson and Shallo, 2000; Nieuwland et al., 2001; Meço and Aliaj, 2000). The internal Albanides consist of thick-skinned thrust sheets with ophiolites in the Mirdita Zone. The external Albanides comprise the Krasta–Cukali, the Kruja and the Ionian zones, the latter being subdivided into the Berati, Kurveleshi and Cika belts (Fig. 1); the Sazani zone is autochthonous and forms the extension of the Apulia platform (Velaj et al., 1999; Meço and Aliaj, 2000; Roure et al., 2004).

The outer zones of the Albanian thrust belt are segmented into two very distinct tectonic provinces by the NE-trending Vlora-Elbasan lineament, with up to 10 km of Oligocene to Plio-Quaternary clastics being still currently preserved in the Peri-Adriatic Depression in the north, and Mesozoic carbonates of the Ionian zone outcropping in the south (Fig. 1A). As evidenced on seismic profiles, the main décollement level is localized within Triassic evaporites south the Vlora-Elbasan transfer zone, with ramp anticlines accounting for the tectonic uplift of Mesozoic carbonates in the Ionian zone. In contrast, the décollement is located within the Cenozoic clastics in the north, where no carbonate reservoir is exposed at the surface (Fig. 1B and C). The Vlora-Elbasan transfer zone can therefore be described as a lateral ramp connecting these two distinct décollement surfaces (Roure et al., 1995). The Vlora-Elbasan transfer zone, however, probably originally formed as a deep seated basement fault with its origin as a Triassic/Jurassic strike-slip zone, which functioned in the early plate tectonic history of the Albanides as a trajectory along which the sub-plates were moved into place to form the Albanides (Nieuwland et. al., 2001).

2.2. Tectonic/sedimentary history

2.2.1. Tethyan passive margin

Tethyan rifting accounts for the development of late Triassic to Liassic tilted blocks and grabens, thick organic-rich dolomitic platform carbonates characterizing the paleo-horsts while Liassic blackshales were deposited in the grabens. Post-rift thermal subsidence resulted in the deposition of deep water cherts during the Middle and Upper Jurassic in the Ionian Basin, whereas prograding Cretaceous carbonate platforms from the Kruja Zone in the east, and from the Sazani Zone in the west, contributed as a distal source for the thick carbonate turbidites deposited in the Ionian Basin during the late Cretaceous and Paleocene (Gealey, 1988; Meço and Aliaj, 2000). These turbidites, which rework platformal carbonate material, are interbedded with finer grained pelagic carbonates, and constitute the main hydrocarbon reservoir of onshore Albania, as well as offshore in the Italian part of the Adriatic.

2.2.2. Fold–thrust belt development

During the Alpine orogeny, the Albanian foothills formed as a consequence of the deformation of the former eastern passive margin of Apulia; the external zones were overthrust during the Neogene (Swennen et al., 2000; Van Geet et al., 2002; Roure et al., 2004).

Up to 10 km of synflexural and synkinematic siliciclastic units have been deposited in the Peri-Adriatic Depression, ranging from near-shore and littoral facies in the east and south, toward deeper water and turbiditic facies in the north and in the west (offshore), providing a continuous sedimentary record of the deformation.

Tectonic loading applied by the hinterland (Mirdita ophiolite) and westward thrusting of far travelled basinal units of the Krasta Zone induced the progressive development of a wide flexural basin, which ultimately impacted the Outer Albanides lithosphere in late Oligocene times. Growth anticlines started to develop in late Oligocene–Aquitanian times in the Ionian Basin, accounting for the development of Burdigalian reefal facies and paleo-karst at the crest of the Kremenara anticline (Fig. 1A and B). This main episode of shortening ended before deposition of Langhian–Serravallian clastics. Collisional deformation likely reached the outermost parts of the Albanides (Cika zone) by Lower–Middle (?) Miocene times.

The second episode of tectonic shortening is best documented near the Vlora-Elbasan transfer zone and farther north in the Peri-Adriatic Depression, where Pliocene backthrusts account for major lateral and

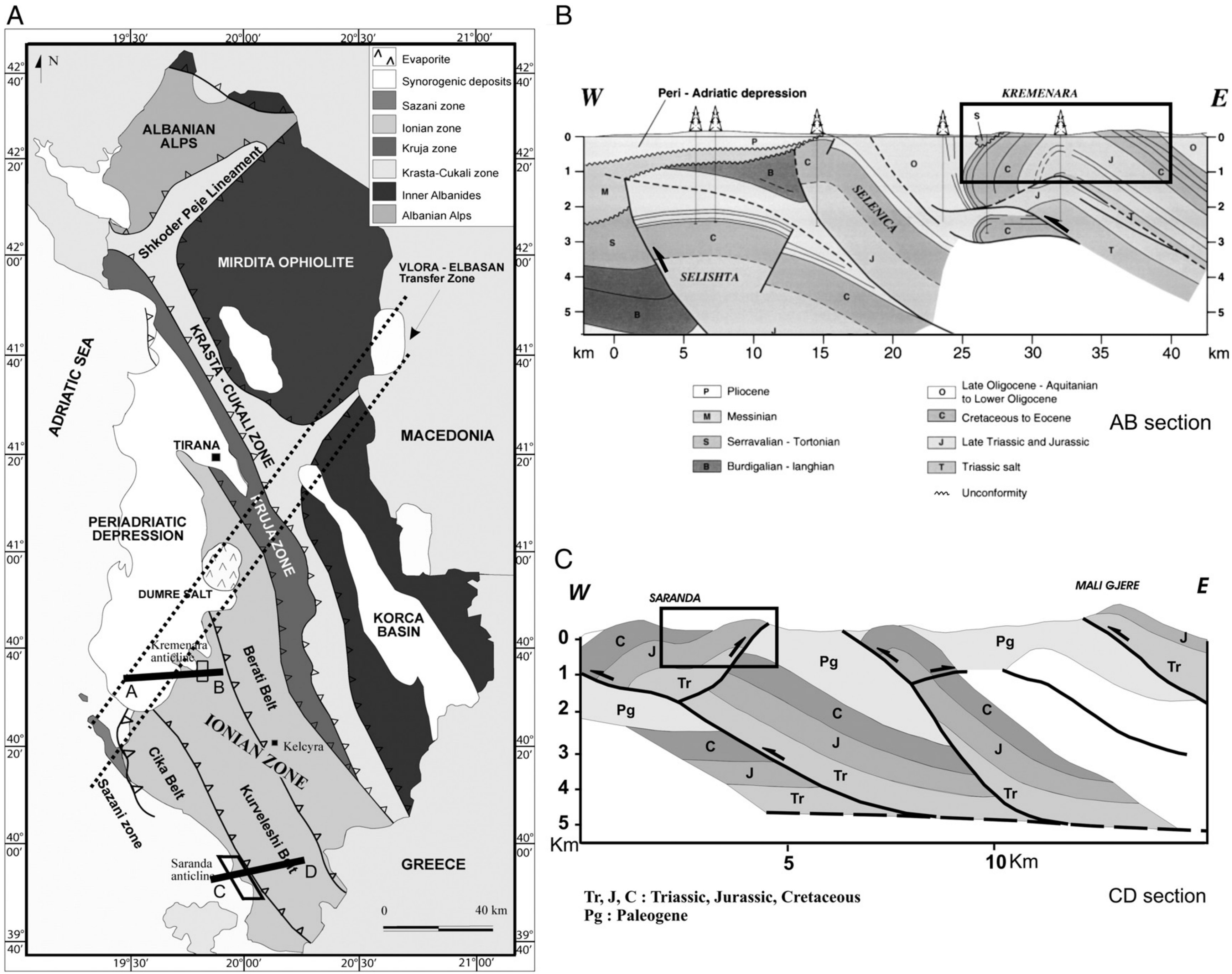

Fig. 1. Structural setting of the study. A. Structural map of the Albanides with location of sections of B and C. B: Geological section across the Kremenara anticline (modified after Van Geet et al., 2002). C: Geological section across the Saranda anticline (modified after Roure et al., 1995).

vertical offsets of a pre-Messinian erosional surface. Nieuwland et al. (2001) also proposed a Pliocene age for the main episode of out-of-sequence thrust reactivation identified on seismic sections. This episode is thought to be the consequence of the sharp increase in basal friction once the thrust front had moved past the outer edge of the main salt décollement, i.e. from Triassic salt onto clastics of the Peri-Adriatic Depression. This out-of-sequence thrusting episode is probably responsible for a significant portion of the folding. Although Neogene deposits are mostly absent from the Ionian zone itself, it is obvious that this post-Messinian tectonic episode also affected, at least partly, the southern part of the Albanian Foothills, increasing for instance the deformation (overturning of the western limb) in the Kremenara anticline (Breesch et al., 2007).

3. Tectonic–microtectonic setting

The Saranda anticline is the outermost fold of the southern external Albanides and belongs to the Cika belt (Fig. 1A and C). This anticline is oriented NNW-SSE and has an asymmetric structure with a subvertical eastern flank (Figs. 1C and 4). The Kremenara anticline (Fig. 1A and B) is oriented NNE-SSW; it is located north of the Saranda anticline and belongs to the inner Kurveleshi belt of the Ionian zone.

The Kremenara anticline has already given rise to several paragenetic and tectonic studies (e.g., Van Geet et al., 2002; Graham-Wall et al., 2006; Dewever et al., 2007; Breesch et al., 2007). Van Geet et al. (2002) carried out a paragenetic study based on cathodoluminescence, and stable isotope (δ^{18}O and δ^{13}C) signatures of vein cements. On the basis of mutual cross-cutting relationships (especially with stylolites) and petrographical characteristics, they recognized four generations of veins and their relative chronology. The earliest vein generation predates bedding-parallel compactional stylolitization. Second and third generations of veins postdate bedding-parallel stylolitization but predate development of LPS stylolites, and were therefore considered as syn-orogenic. The brecciated nature of the host rock and the fact that clasts are often different from the immediate neighbouring vein wall suggest that at least some of the veins of the second generation formed by hydraulic fracturing. A fourth vein generation cuts fold structures and LPS stylolites and therefore postdates folding; although still debated in the Kremenara anticline, this late fracturing event may be related to a reorientation of the compressional stress in the vicinity of the Vlora-Elbasan transfer zone. Finally, an open joint system developed, along which most of the oil seeps occur. The timing of development of these vein generations relative to diagenesis and compaction and their attitude with respect to bedding is rather clear (Van Geet et al., 2002), but the regional orientations of these vein sets and their significance within the framework of the development of the foreland basin and fold–thrust belt remained poorly constrained. Graham-Wall et al. (2006) proposed a more complex model of fracture formation, with a systematic documentation of vein and stylolite orientations. A pre-folding pressure-solution seams/V1 veins assemblage, with vertical stylolitic peaks and vertical veins with a wide range of directions (after unfolding), has been interpreted as an overburden assemblage, whereas a second pre-folding pressure-solution seams/V2 veins assemblage with horizontal stylolitic peaks and vertical V2 veins, both oriented NE-SW (after unfolding), is described as a remote tectonic stress assemblage. Sheared layer-parallel stylolites of the overburden assemblage define mechanical layers which were sheared during folding, resulting in the formation of a series of fold-related fractures with different orientations. Fragmentation zones resulting from pre-folding- and fold-related fracture assemblages in mechanically-defined layers localize incipient faulting. These faults subsequently act as the dominant fluid pathways.

In contrast to the Kremenara anticline, the detailed tectonic evolution (including events of fracture development) of the Saranda anticline and paleoburial/paleothermal histories of outcropping rocks remains unknown. The first vein set identified in Saranda clearly developed early during the tectonic history since they formed before or during bedding-parallel stylolitization. This first set (I) is oriented N140 (±20) and likely predates folding, but its relationship with the regional tectonic evolution remained enigmatic. The second set (II), oriented N060 (±20), is closely associated with LPS stylolites. LPS reduces porosity and consequently increases pore pressure, which may become high enough to create natural hydraulic fractures whose orientation is parallel to the orientation of the maximum horizontal stress prevailing at that time. The set II veins can be considered as reliable indicators of the orientation of the regional compressional stress responsible for folding and thrusting. This set II may be related to the remote tectonic stress assemblage described by Graham-Wall et al. (2006) and possibly to the second or third generations of veins of Van Geet et al. (2002), as observed in Kremenara.

4. Sampling and strategy of study

In this paper, we took advantage of the widespread occurrence of pre-folding vein sets to characterize pre-folding stress orientations and differential stress magnitudes related to Layer-Parallel Shortening (LPS). We make the implicit but reasonable assumption that LPS is recorded coevally by all rock samples of a strata, without any relation to the structural position of these samples after folding. Because LPS reflects stress build-up in horizontal strata, we argue that LPS is likely recorded at the maximum burial just before the onset of folding.

Our method requires identification of pre-folding stress tensors related to LPS, even where the tectonic evolution is polyphase. Sampling in fold limbs helps to constrain the chronology of twinning relative to folding. For example, it might be expected that if a twin set formed during the initial phase of Layer-Parallel Shortening (LPS) and was subsequently tilted with the strata during folding, then one axis of the stress tensor computed from this set should be perpendicular to bedding with the other two lying within the bedding plane. In contrast, late/post-folding twin sets should yield two horizontal stress axes and one vertical one (assuming that the regional stress field is in that orientation), within a range of 10° uncertainty (e.g., Lacombe et al., 2007). Note that a third possibility exists, that twinning occurred during folding, with or without rotation of twins at the grain scale due to flexural slip (Harris and van der Pluijm, 1998), but evidence are few. This limited evidence of synfolding twinning suggests that twinning strain is mainly achieved during the early and late stages of folding, probably during two peaks of stresses which seem to predate immediately folding (LPS) and to prevail after fold tightening (Onasch, 1983; Lacombe, 2001).

To this respect, sampling was carried out in the western flank of the Saranda anticline, where strata are tilted by a sufficient amount to prevent uncertainties on the chronology of twinning relative to folding. There was no need to sample close to the hinge where strata are subhorizontal. Moreover, sampling in the eastern limb, that is cut by a backthrust (Fig. 4), could have led to a bias in differential stress estimates, since the stress field is known to be very inhomogeneous in both orientation and magnitude close to fault zones. Our analysis has focused on homogeneous, poorly deformed, marine limestones of late Cretaceous age, cut by the above-mentioned vein systems. Unfortunately, the fine-grained facies of these limestones did not enable us to carry out analysis of calcite twins within the rock matrix. Therefore, only four samples from Saranda anticline (AL05, AL25, AL26 and AL27) containing set I and/or set II were suitable for our analysis. Despite the low number of samples available for this preliminary study, the results obtained are remarkably internally consistent (see Section 6) and in good agreement with both independent microtectonic indicators and paleoburial estimates (Section 7), which testifies for their reliability. In the Kremenara anticline, a single sample of Cretaceous limestones containing set II veins (DR10) revealed suitable for further calcite twin analysis. Although a single sample obviously does not allow to test their reproducibility, the results obtained with this sample have nevertheless been compared to, and found consistent with, the numerous information available for this anticline (see Section 3).

Thin twins (mean thickness ~0.5 µm) are dominant in the samples (Fig. 3), indicating that calcite deformed below 170 °C (Burkhard, 1993; Ferrill et al., 2004). Twinning strain never exceeds 3–4% (Fig. 3). The distribution of calcite *C* axes in the samples is nearly random (Fig. 2, diagrams a). Our reconstructions therefore meet the assumptions of low finite strain and stress homogeneity required to derive the regional paleostresses of interest. Where possible, calcite twin data were collected from crosscutting set I and set II veins in order to constrain the relative timing of twinning events (e.g., Fig. 2). The relative chronology of veins and bedding-parallel stylolites or LPS stylolites in samples (e.g., abutting or cross-cutting relationships) also helped to constrain the relative chronology of stress regimes determined from the calcite cement of each vein population (e.g., Fig. 3F).

5. Method: determination of paleostress orientations and differential stress magnitudes using inversion of calcite twin data

Mechanical e-twinning readily occurs in calcite deformed at low temperature. Calcite twinning requires a low Critical Resolved Shear Stress (CRSS) which depends on grain size (e.g., Rowe and Rutter, 1990) and internal twinning strain (e.g., Turner et al., 1954; Laurent et al., 2000; Lacombe, 2001), and has only a small sensitivity to temperature, strain rate and confining pressure, therefore fulfilling most of the requirements for paleopiezometry (Lacombe, 2007).

Since the pioneering work of Turner (1953), several methods of stress/strain analysis have been developed on the basis of calcite twin data (e.g., Groshong, 1972; Jamison and Spang, 1976; Laurent et al., 1990; Etchecopar, 1984; Lacombe and Laurent, 1992, 1996; Rowe and Rutter, 1990). Calcite twin data being basically strain data, Groshong's (1972) strain gauge technique is commonly used to produce a strain ellipsoid, while differential stresses are given by the Jamison and Spang (1976) technique. In this paper, we have used Etchecopar's method of inverting calcite twin data (Etchecopar, 1984; see details in Lacombe, 2001, 2007). This method applies to small twinning strains that can be approximated by coaxial conditions, so that orientation of twinning strain can be correlated with paleostress orientation (Burkhard, 1993).

The inversion process takes into account both twinned and untwinned planes, the latter being those of potential e-twin planes that never experienced a resolved shear stress of sufficient magnitude to cause twinning. The inverse problem consists of finding the stress tensor that best fits the distribution of twinned and untwinned planes. The orientations of the 3 principal stresses σ_1, σ_2, and σ_3 are calculated, together with the Φ ratio $[\Phi=(\sigma_2-\sigma_3)/(\sigma_1-\sigma_3)]$ and the peak differential stress $(\sigma_1-\sigma_3)$. If more than ~30% twinned planes in a sample are not explained by a unique stress tensor, the inversion process is repeated with the uncorrelated twinned planes and the whole set of untwinned planes. Where polyphase deformation has occurred, this process provides an efficient way of separating superimposed twinning events.

The stress inversion technique is to date the only technique that enables simultaneous calculation of principal stress orientations and differential stress magnitudes from a set of twin data, therefore allowing to relate unambiguously differential stress magnitudes to a given stress orientation and stress regime. Numerous studies have demonstrated its potential to derive regionally significant stress patterns, even in polyphase tectonics settings (e.g., Lacombe et al., 1990, 1993, 1996; Rocher et al., 2000; and references therein).

An important aspect of calcite twin-based paleopiezometry deals with the existence of a constant CRSS for twinning; this assumption is acceptable for samples displaying nearly homogeneous grain size and internal twinning strain. For samples displaying a mean grain size of ~200–300 µm and deformed between 0° and 170 °C at 2.5% strain, it equals 10 MPa. However, for the same samples deformed at nearly 1–1.5% strain, the CRSS tends to be lower at 5 MPa (Lacombe, 2001). For samples displaying significantly different grain sizes, a crystal size-CRSS relationship adapted from that proposed by Rocher et al. (2004) is further used to improve differential stress estimates.

6. Results

6.1. Paleostress orientations and regimes

In all samples available for this study, calcite twin analysis consistently revealed the main states of stress that prevailed in both the Saranda and Kremenara anticlines. The first stress regime corresponds to a NE-SW compression and/or a sub-perpendicular extension (Fig. 4). The different tensors related to this stress regime are linked by stress permutations: after backtilting, σ_1 is either vertical and associated with a NW-SE trending σ_3 (Fig. 4, AL27, diagram a), or horizontal, with either σ_2 or σ_3 trending NW-SE (Fig. 4, AL25, diagram a and AL05, diagram a). This suggests that NE-SW compression was not a simple stress regime, varying both spatially and temporally throughout the fold from true NW-SE perpendicular extension to true NE-SW compression or a strike-slip regime with NE-SW compression and NW-SE extension. Such stress permutations are common during fold evolution. In the frame of the study, they can well account for the formation of set II veins from which twin data were collected and of associated LPS stylolites (Fig. 3F), but also for the re-opening of bedding-parallel stylolites (Fig. 3F), when strata were still horizontal (e.g., Roure et al., 2005). Inspection of the attitude of the computed stress axes with respect to bedding indicates that twinning recorded compressional stresses mainly during Layer-Parallel Shortening (LPS) in the samples from Saranda, whereas twinning recorded late stage fold tightening stresses in the sample from Kremenara (Table 1). The NE compression, which lies at high angle to fold axes, therefore prevailed during the entire folding history (i.e., from early LPS to late fold tightening).

The second stress regime corresponds to a local, pre-folding nearly E–W extension, which is recorded by pre-folding set II veins (Fig. 4, AL25, diagram b and AL05, diagram b), and likely reflects outer-rim extension/crestal collapse during Saranda fold development.

The third stress regime also occurred before folding. It corresponds to a N030°-directed extension (Fig. 4, AL26, diagram b, AL27, diagram b and AL25, diagram c), with the computed σ_3 axes being nearly perpendicular to set I veins. This regime, therefore, is likely responsible for opening the early set I veins that are generally found tilted within the folded strata and are interpreted as pre-folding veins (e.g., Fig. 4, AL26, diagram b). In this scenario, the vertical attitude of the N120°-trending vein of sample AL25, which suggests a post-folding vein, is somewhat problematic, since this vein is cut by a vein belonging to set II (Fig. 2B) that recorded a pre-folding compression (Fig. 4, AL25, diagram a) and developed during LPS just before the onset of folding. To keep internal consistency of the interpretation, we propose that this vein possibly formed as a transtensional (mixed mode I–mode II) shear vein and was secondarily tilted during folding to its current vertical attitude. This interpretation is consistent with the association of these set I veins with normal faults (Van Geet et al., 2002).

6.2. Paleo-differential stress magnitudes

As mentioned in Section 5, estimates of differential stresses are sensitive to the value retained for the CRSS that is strain and grain-size dependent. To this respect, when the grains measured in a given set of veins (Fig. 2) displayed a wide size range, the twin data were separated into subsets corresponding to nearly homogeneous grain sizes, and these subsets were analyzed separately. In some cases, such analysis

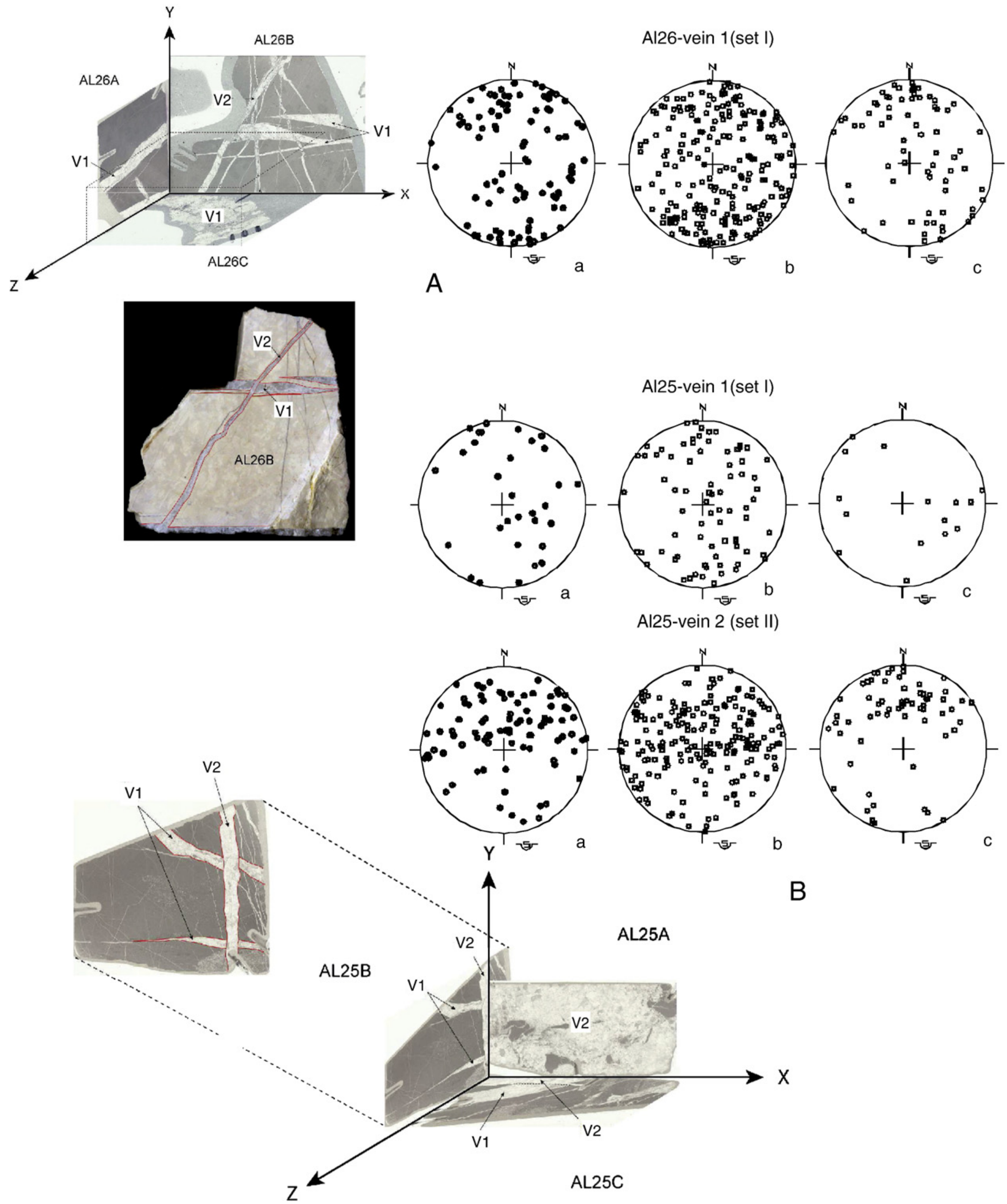

Fig. 2. Sketches showing the two vein sets observed from three mutually perpendicular thin sections in samples AL26 (A) and AL25 (B), from which calcite twin data were collected. Schmidt's lower hemisphere, equal area projection: diagrams a show *C* axes, diagrams b show poles to twinned planes and diagrams c show poles to untwinned planes of calcite grains measured in each vein set. Note the cross-cutting relationships between veins from sets I and II.

was not possible or did not provide any significant result because the number of calcite twin data in this grain size class was too small. When the reduced stress tensors obtained from the different subsets were similar to that obtained from the whole set, we refined differential stress estimates by also considering estimates from these subsets individually. Similarly, internal twinning strain, which was found to be variable from one sample to another (see contrast in twin density in Fig. 3A and E), was also taken into account. The quantitative relationship between the CRSS and both grain size and twinning strain has not yet been precisely calibrated, but we are currently trying to improve the relationship proposed by Rocher et al. (2004) by also taking into account internal twinning strain (e.g., Lacombe, 2001; Laurent et al., 2000). The results are reported in Table 1 and in Fig. 5.

6.3. From paleo-differential stress magnitudes from calcite twins to paleoburial estimates in the Outer Albanides

Lacombe (2007) has shown that paleo-differential stress data against depth suggests a trend of increasing differential stresses with depth, supporting the hypothesis that stress in the upper crust is

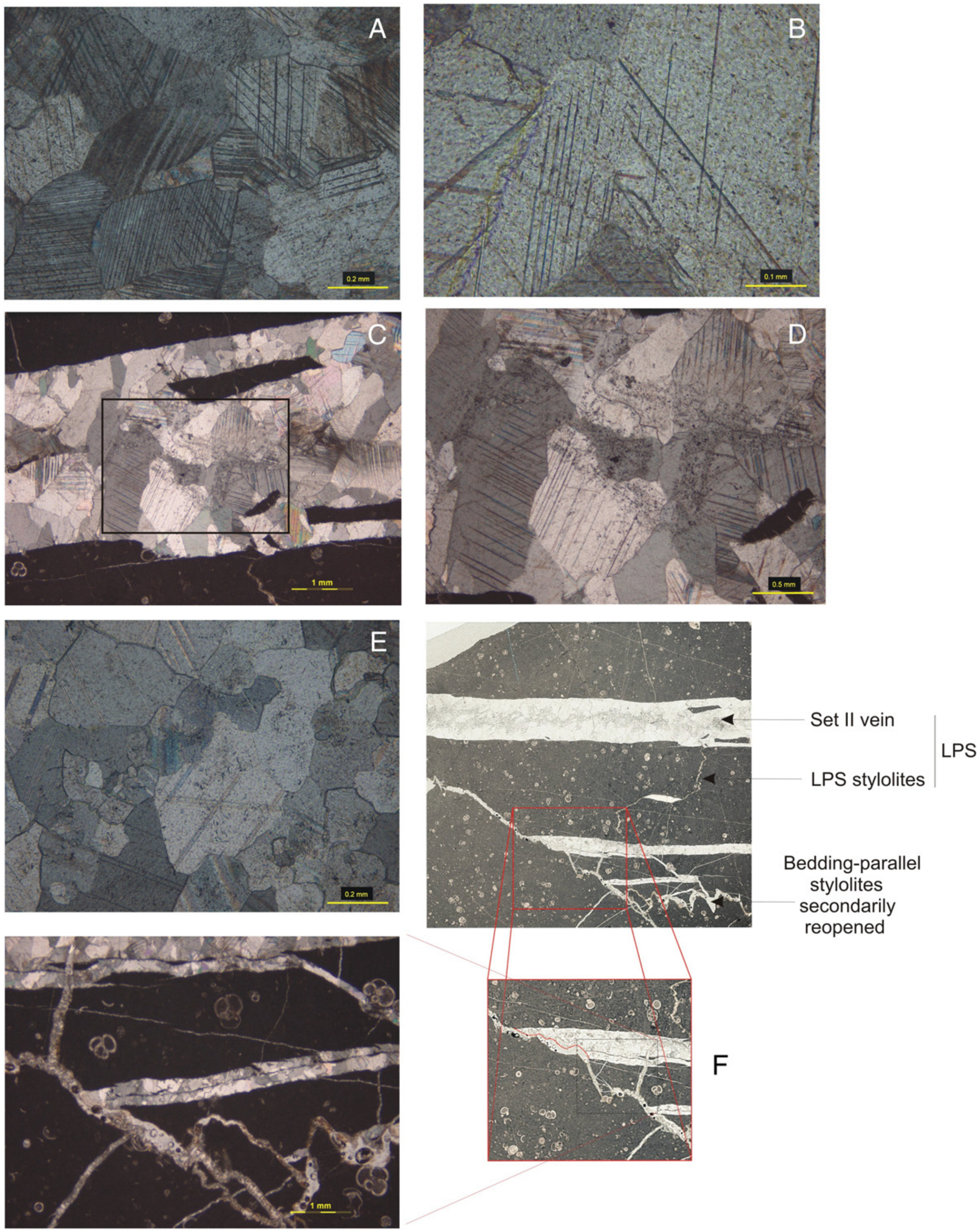

Fig. 3. Examples of twinned calcite grains in veins from Saranda and Kremenara anticlines. A, B: sample AL25, high twin density. C, D: sample DR10. E: sample AL27, low twin density. Note that twinning occurred in the thin twin regime in all samples, suggesting low strain at low (<170 °C) temperature. F: Detailed views of the microtectonic structures in the DR10 sample, with emphasis on the remote tectonic stress assemblage (set II veins and LPS stylolites) and secondarily reopened bedding-parallel stylolites.

probably primarily at frictional equilibrium, which is in agreement with in situ stress measurements (Townend and Zoback, 2000). For given stress and pore pressure regimes, along with knowledge of the differential stress magnitude from calcite twin analysis, one can make use of the relationship between differential stress and depth to estimate the paleodepth of deformation, based on the frictional-failure equilibrium hypothesis. Fig. 5 displays the curves of differential stress values as a function of depth in a crust in frictional equilibrium for both strike-slip (SS) and reverse faulting (R) stress regimes, with values of λ [$\lambda = P_f/\rho g z$ where P_f is the pore fluid pressure, ρ the density of the overlying rocks, g the acceleration of gravity and z the depth] of 0.38 (hydrostatic) and 0 (dry) and for friction coefficient μ values of 0.6 and 0.9 (Lacombe, 2007).

We have focused our estimates of paleodepth of deformation on stress tensors related to the regional compression which may have been recorded either at the very early stage (LPS) or at the very late stage of folding (fold-tightening). Since LPS immediately predates the onset of folding, the related stress tensors were recorded by twinning at the time of the maximum burial. We did not consider further extensional stress tensors.

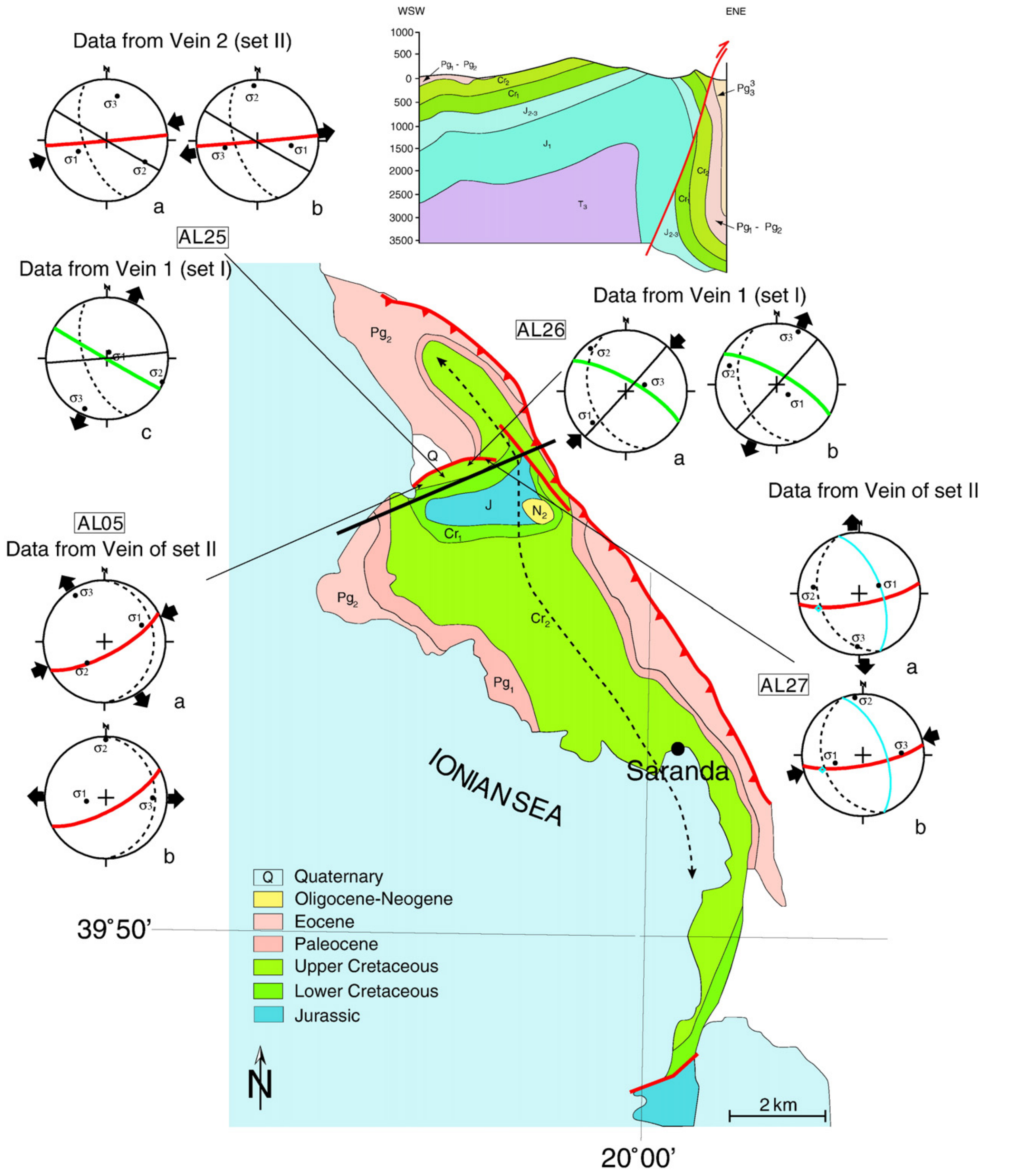

Fig. 4. Detailed map (modified after Albpetrol, 1993, 1995) and geological section of the Saranda anticline, with reported locations of samples and paleostress orientations determined from calcite twin analysis. Stereodiagrams: Schmidt lower hemisphere, equal area projection; all microstructures and computed stress axes are in their current (folded) attitude. Bedding as dashed line, veins as thick continuous lines. For AL27, the thin continuous line is the bed-perpendicular stylolite with its peaks –blue diamond– lying within the bedding. In each diagram, the vein in colour (green: set I; red, set II) is the one from which the stress tensor has been determined. Large black arrows are directions of compression or extension. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The differential stress values associated with either compressional or strike-slip stress regimes (which are commonly found associated with a similar σ_1 direction at the local scale in fold–thrust belts) have been reported on the curves corresponding to compressional and strike-slip regimes. In some samples, the value of the stress ellipsoid shape ratio was low (<0.2) (Table 1), indicating that the values of the principal stresses σ_2 and σ_3 were nearly similar, and hence that σ_2 and σ_3 axes could easily switch between being vertical and horizontal. In such case, the stress value has been reported between the curves.

Reporting differential stress values corresponding to reverse (DR10, AL27), strike-slip (AL26-2) or mixed reverse/strike-slip (i.e., with low Φ ratio) (AL26, AL26-1, AL25, AL05 and AL05-1) stress regimes related to the NE regional compressional trend on the above-mentioned curves allows the probable range of depths at which

Table 1
Results of calcite twin analysis.

Sample	Strike (dip) of bedding	Strike (dip) of vein from which measurements were taken	Trend (plunge) of principal stress axes (°)			Ratio between differential stresses	Total number of data	Number of data consistent with the tensor	Grain size	Mean twin density	CRSS	Estimated peak (σ_1–σ_3) value for pre/post-folding NE comp.
	(°)	(°)	σ_1	σ_2	σ_3	(Φ)	T/UT	T/UT	(μm)	(#/mm)/ ~strain (%)	(MPa)	
AL05	000 (20°E)	062 (72°S)	066 (34)	219 (53)	327 (13)	0.26	345/45	200/43	All grains	~80/mm/	9	96 (±19)
			258 (64)	359 (05)	091 (25)	0.39	149/41	89/36	(50–700)	~4%	9	–
AL05-1			061 (33)	219 (55)	324 (10)	0.2	153/24	105/24	50–300		10	147 (±29)
AL25	160 (60°S)	120 (90°) V1	019 (80)	113 (01)	204 (10)	0.12	78/15	42/14	All grains	60–80/		–
		085 (90°) V2	249 (49)	120 (29)	014 (26)	0.19	200/64	118/55	(100–300)	mm/	10	180 (±36)
		085 (90°) V2	098 (44)	357 (11)	257 (44)	0.36	82/64	47/63		~3–4%		–
AL26	160 (40°S)	120 (75°N) V1	226 (24)	320 (10)	071 (64)	0.27	217/71	99/65	All grains (50–1000)		9	84 (±17)
AL26-1			238 (23)	332 (08)	079 (65)	0.27	100/47	52/39	<100	40–60/	9	116 (±23)
AL26-2			242 (29)	101 (54)	343 (19)	0.66	46/14	29/12	100–300	mm/ ~2–3%	10	89 (±17)
AL27	160 (34°W)	080 (76°S)	068 (62)	278 (25)	182 (13)	0.11	139/56	77/49	All grains	~20/mm /	9	57 (±11)
			254 (51)	352 (06)	087 (38)	0.7	62/56	35/44	(100–300)	~1%	9	–
DR10			244 (56)	053 (34)	146 (05)	0.5	272/100	130/91	All grains	60–80/		–
	010 (38°E)	060 (79°N)	051 (17)	144 (10)	264 (70)	0.49	142/99	73/84	(500–900)	mm/ ~3–4%	6	31 (±7)

Ratio Φ defined in text. T/UT: Twinned/Untwinned planes.

Cretaceous limestones recorded LPS twinning strain before becoming involved in folding and subsequently uplifted to be inferred.

In Saranda, the depth range of the investigated samples at the onset of folding is about 1.5–5 km, with a mean weighted value of around 4 ± 1 km (Fig. 5). This depth range is large, but scattering is mainly due to sample AL27 (Fig. 5). In contrast to the other samples, twinning in sample AL27 recorded a true NE-SW compression (σ_3 vertical, $\Phi = 0.7$) and a sub-perpendicular extension, even though twin data were collected in a NE trending vein (set II) whose formation is rather related to a strike-slip stress regime. In fact, AL27 is the only sample in which such a permutation between stress axes occurred (Fig. 4, AL27, diagrams a and b), both the σ_3 axis of the extensional stress regime (Fig. 4, AL27, diagram a) and the σ_1 axis of the compressional regime (Fig. 4, AL27, diagram b) being consistent

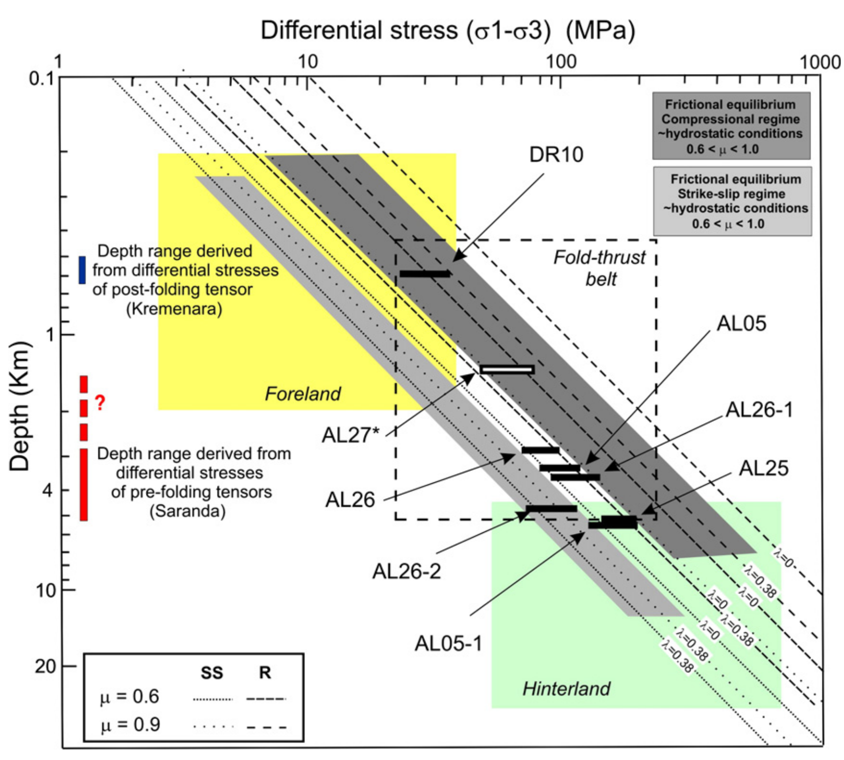

Fig. 5. Differential stress values determined from calcite twins reported on stress/depth curves built for a crust in frictional stress equilibrium (Lacombe, 2007), and derived paleoburial values for pre- and post-folding stress tensors corresponding to the NE compressional trend. Labels -1 and -2 refer to stress estimates obtained from subsets of twin data collected in grains of homogeneous sizes, while others were obtained from the whole twin data set of the sample (see Table 1). Paleoburial derived from differential stress value from sample AL27 (reported in white) is probably underestimated (see text for explanation).

with the opening of the NE trending vein. This may reflect a local inhomogeneity of the stress regime through time (as discussed earlier), leading to a particular record by twinning of the regional compressional/strike-slip stress regime opening the vein (partitioning ?). We therefore argue that the paleodepth determined by reporting the differential stress value from AL27 on the stress–depth curve related to compressional stress of Fig. 5 may possibly be not regionally representative. Reporting virtually the same differential stress value between the strike-slip and compression related stress–depth curves, or even on the strike-slip related stress–depth curve, would increase the derived paleodepth and strongly reduce the range of inferred depth values. As a result, it can be concluded that the mean weighted value of 4 ± 1 km corresponds to the most likely burial depth at the time LPS was recorded by twinning in Saranda (Fig. 5).

In Kremenara, the differential stress values related to the post-folding compressional stress tensor suggest a possible paleodepth of deformation of 0.5–0.6 km at the end of folding (Fig. 5). This places constraints on the depth at which Cretaceous limestones were still buried when folding ended, and, therefore, on the exhumation path of these rocks, between 4 km maximum depth (if burial was of the same order that in Saranda) and the surface where they presently crop out. We, however, have to keep in mind that this estimate is based on a single sample, so this result, although internally consistent (lower paleodepth than in Saranda derived from post-folding stress tensor) has to be confirmed by forthcoming studies.

7. Discussion

7.1. Consistency of paleostress results from calcite twins with microtectonics and Albanian regional tectonics

The formation of pre-folding set I veins can be attributed to overburden stress associated with burial, predating, or coeval with, formation of bedding-parallel stylolites. This set resembles the pressure-solution seams/V1 veins assemblage described by Graham-Wall et al. (2006), but the N140 (± 20) orientation of our set I veins is more homogeneous, and developed under a well-defined N030°-directed extension. We propose that set I veins developed in the basin before folding in response to the flexure of the foreland in front of the advancing thrust sheets, contemporary with burial and possibly under high fluid pressures.

The next structures to form were bed-perpendicular pressure-solution seams with NE-directed peaks and bed-perpendicular veins (set II oriented N060 $\pm$ 20: Fig. 4, AL27 diagrams a and b). These microstructures are similar to the remote tectonic stress assemblage of Graham-Wall et al. (2006). They are attributed to the NE-oriented maximum horizontal compressive stress responsible for fold–thrust belt development; such NE compressional trend was clearly recorded by calcite twinning in our samples. This good consistency is highlighted in sample Al27, where the computed σ_1 axis lies within the bedding plane and is nearly parallel with pre-folding LPS stylolitic peaks (Fig. 4, AL27 diagrams a and b). This NE compressional stress is consistent with the direction of tectonic transport (Velaj et al., 1999), which supports its regional significance, despite being determined from a limited number of samples. The NE compressional stress was mainly recorded by twinning as LPS in Saranda (Fig. 4), and as late-stage fold-tightening stress in Kremenara (Table 1). This compressional trend is also consistent with the N050° azimuth of the contemporary σ_H in the Shpiragu-1 wildcat well (Graham-Wall et al., 2006), which indicates that the orogenic stress regime has likely remained unchanged through the present. It can be concluded that the foreland was first flexed under tectonic loading of inner units (N030° extension), then sustained remote tectonic stress recorded as LPS before being involved in folding in response to the westward advancing of the deformation front, the NE compressional stress prevailing during the entire episode of orogenic shortening (Fig. 6).

Calcite twins also reveal pre-folding, nearly E–W extension recorded in set II veins, nearly perpendicular to the local trend of the Saranda anticline axis, and which can be attributed to extension at the hinge of the growing anticline. Interestingly, newly-formed veins formed in response to this extension have not been observed, even in samples collected close to the hinge. We assume that pre-folding, flexure-related veins could have been reopened during folding, preventing, at least locally, development of newly formed outer rim extensional veins.

7.2. Uncertainties on paleodepth determination using the stress inversion technique

The new approach presented in this paper which combines paleodifferential estimates from calcite twins with the hypothesis of frictional stress equilibrium in the crust allows to derive paleoburial values of Cretaceous limestones now involved in folding at the front of the southern Outer Albanides. The most likely depth at which LPS occurred in Saranda is 4 ± 1 km. Presently, such paleoburial estimates should be considered as maximum values. The first reason is that taking into account the sources of uncertainties for calcite twinning paleopiezometry, only orders of differential stress magnitudes can be sought and reasonably inferred. In addition, paleopiezometry based on calcite twinning (e.g., Jamison and Spang, 1976; Rowe and Rutter, 1990; this study) provides estimates of the peak differential stress (σ_1–σ_3) attained during a particular deformational event of the tectonic history of the rock mass since the differential stresses are computed by taking into account the maximum percentage of twinned planes consistent with the tensor.

A limitation of the approach adopted in this paper is related to the frictional stress equilibrium hypothesis itself. In settings where friction clearly governs stress, the hypothesis of frictional equilibrium implies uniform stress differences at a given depth and a given stress regime, regardless of the “intensity” of deformation, the style of deformation is probably simply a function of the strain rate. Therefore, estimates of maximum (or possible overestimates) of differential stress magnitudes will result in maximum (or possibly overestimated) paleoburial values. One has to keep in mind that many actively deforming forelands are earthquake deficient, especially in the upper 2–4 km in the sedimentary cover, where folds may develop mainly by mechanisms including diffusion–mass transfer and other ductile mechanisms such as calcite twinning. In this depth range, the so-called brittle crust creeps by ductile mechanisms. These mechanisms relieve stresses, so that the differential stress level can be kept beyond the frictional yield that likely prevails at greater depth in the basement. Therefore, the state of stress in the cover may differ from that predicted by the frictional stress equilibrium. This occurs in settings where the cover is detached from the basement, as, for instance, in the salt-based Zagros belt (e.g., Lacombe et al., 2007). The consistency of our estimates with independent paleoburial indicators indicate, however, that this effect remained limited in the Albanian case.

Secondly, assuming that the vertical stress is principal (see recent discussion in Lacombe, 2007), it is generally correct to equate the magnitude of the vertical principal stress to the overburden load ($\rho gz - P_f$); where ρ is the average density of the overburden. g is the acceleration of gravity, z is the depth, and P_f is the fluid pressure. Paleodepth of overburden can be evaluated using stratigraphic data in favourable settings. Actual pore fluid pressure at the time of deformation (and the porosity and the cohesion as well) being unfortunately often out of reach, hydrostatic conditions are usually adopted as the most realistic conditions of fluid pressure. Results obtained in deep boreholes suggest that this assumption is reasonable and justified in most cases (Townend and Zoback, 2000); however, in compression zones, pore pressure may be closer to lithostatic than to hydrostatic.

Finally, the dispersion of paleoburial values around 4 km in Saranda, although likely much lower than 1.5–5 km because of the probable underestimate from sample AL27 (sub-Section 6–3), may be

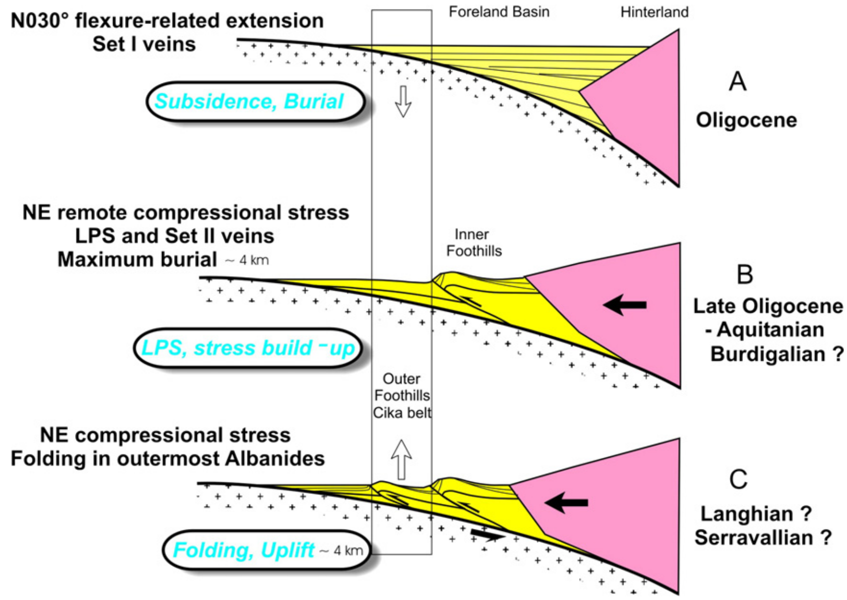

Fig. 6. Schematic sketch of evolution with time of the Cretaceous limestones from the outermost Albanides (Cika belt). These limestones were first buried during Oligocene flexure and probably still during Aquitanian–Burdigalian (?) while they underwent LPS as a result of remote compressional stress, then were uplifted by folding mainly before the pre-Tortonian folding phase. The possible effects of the Plio-Quaternary late folding stage documented in northern Albanides has not been considered.

also partly due to uncertainties on the depth and precise time of record of LPS within the Cretaceous limestones (although all samples were collected in the same fold limb), as well as on the precise location of samples within this formation.

7.3. Consistency of paleodepth estimates from calcite twins with independent paleodepth indicators and new kinematic modelling in the Albanian foreland

In order to test the reliability of paleoburial estimates derived from calcite twin analysis, we first tried to compare them to the thicknesses of sedimentary formations in the Ionian zone, which are, unfortunately, poorly constrained. Above the investigated Cretaceous limestones, at least 2000–2500 m of Paleogene (including the Oligocene flysch) can be considered (e.g., Collaku et al., 1990). Muska (2002) estimated from Genex 1D modelling, a thickness of eroded rocks of nearly 1600 m above Eocene formations. Note, however, that the exact position of the samples within the late Cretaceous is not precisely known, so the thickness of the uppermost late Cretaceous strata could possibly be added to these thicknesses. Furthermore, it is unclear whether or not the complete Oligocene–Aquitanian sequence and later Burdigalian formations were deposited above the Cretaceous limestones before the Saranda anticline developed.

A second way to test our paleoburial estimates is to compare the obtained values with paleodepth derived from geothermal gradients and paleotemperature estimates. Geothermal gradients are very low in the Outer Albanides, at least in the first 5 km below the surface, for which numerous well data are available (Frasheri et al., 1995; Cermak et al., 1996). Average values of 20 °C/km characterize the Peri-Adriatic Depression, whereas current geothermal gradients are in the range of 10 °C/km in the Ionian Basin. The geothermal gradients in the Ionian Basin prior to the erosion of the Oligocene flysch were probably close to those still currently observed in the Peri-Adriatic Depression, having been protected from the high meteoric water flow by the Oligocene seal (Roure et al., 2004). An explanation for these very low values could be that the rapid Neogene and Pliocene–Quaternary sedimentation created a blanketing effect in the Peri-Adriatic Depression. Thus, undercompacted sediments slow down thermal transfers and constitute an efficient barrier between the deep horizons and the earth's surface. Strong karstification and fracturing of Ionian carbonates induced a major influx of meteoric water, which has resulted in a drastic cooling of the first 5 km below the earth's surface. Even negative geothermal gradients occur locally in close proximity to active fluid conduits, such as faults or active aquifers (Roure et al., 2004; Van Geet et al., 2002; Vilasi et al., 2006). Taking into account a low thermal gradient of about 16–20°/km, and paleotemperatures between 40 and 60° derived from microthermometry of paleofluids, the possible depth range is about 2–4 km, consistent with our independent paleodepth estimates from calcite twins in Saranda. Moreover, this result is in line with calcite twinning geothermometry, since thin twinning regime is dominant in the samples (Fig. 3), which indicates that calcite deformed below 170 °C (Ferrill et al., 2004).

Additional constraints are provided by estimates of maturity rank of organic matter in the Ionian Mesozoic series sampled in surface outcrops of the Ionian Basin and Kruja Zone. Euxinic episodes were numerous during the Cretaceous within the entire Peri-Adriatic basinal domain, with synchronous emersion episodes occurring across adjacent intervening platforms (e.g., Moldowan et al., 1992; Jerinic et al., 1994). Thus, bituminous shales and carbonates have been found at the boundary between Lower and Upper Cretaceous intervals in the Kurveleshi unit of the Ionian Basin, as well as in the Upper Cretaceous of the Cika unit of the same basin and within late Cretaceous–Paleocene series of the Kruja Zone. TOC values as high as 26% have been recorded in the Kurveleshi unit, and Ro values lie between 0.48 and 0.53. In the Kruja Zone, TOC values barely reach 4%, and Ro values are lower than 0.5 (Roure et al., 1995). Therefore, it comes that in the outermost Saranda anticline, the rocks are very likely immature; taking into account the low geothermal gradient, these Cretaceous limestones were consequently probably never buried to depths greater than 4–5 km, in agreement with our preliminary estimates of maximum paleoburial just before the onset of folding.

Finally, a new 2D forward kinematic model (using the Thrustpack software) of a regional geological section across the Albanian fold–thrust belt and foreland has been carried out (Fig. 7A), and was further used to predict burial curves (Fig. 7B) to compare to the calcite-twin based paleoburial estimates. The modelled section (Fig. 1B) is located in the vicinity of the Kremenara anticline where seismic and well data are available to constrain the deep architecture (Swennen et al., 1999), in contrast to the Saranda transect (Fig. 1C). Burial curves have been derived for the late Cretaceous reservoir from various tectonic units:

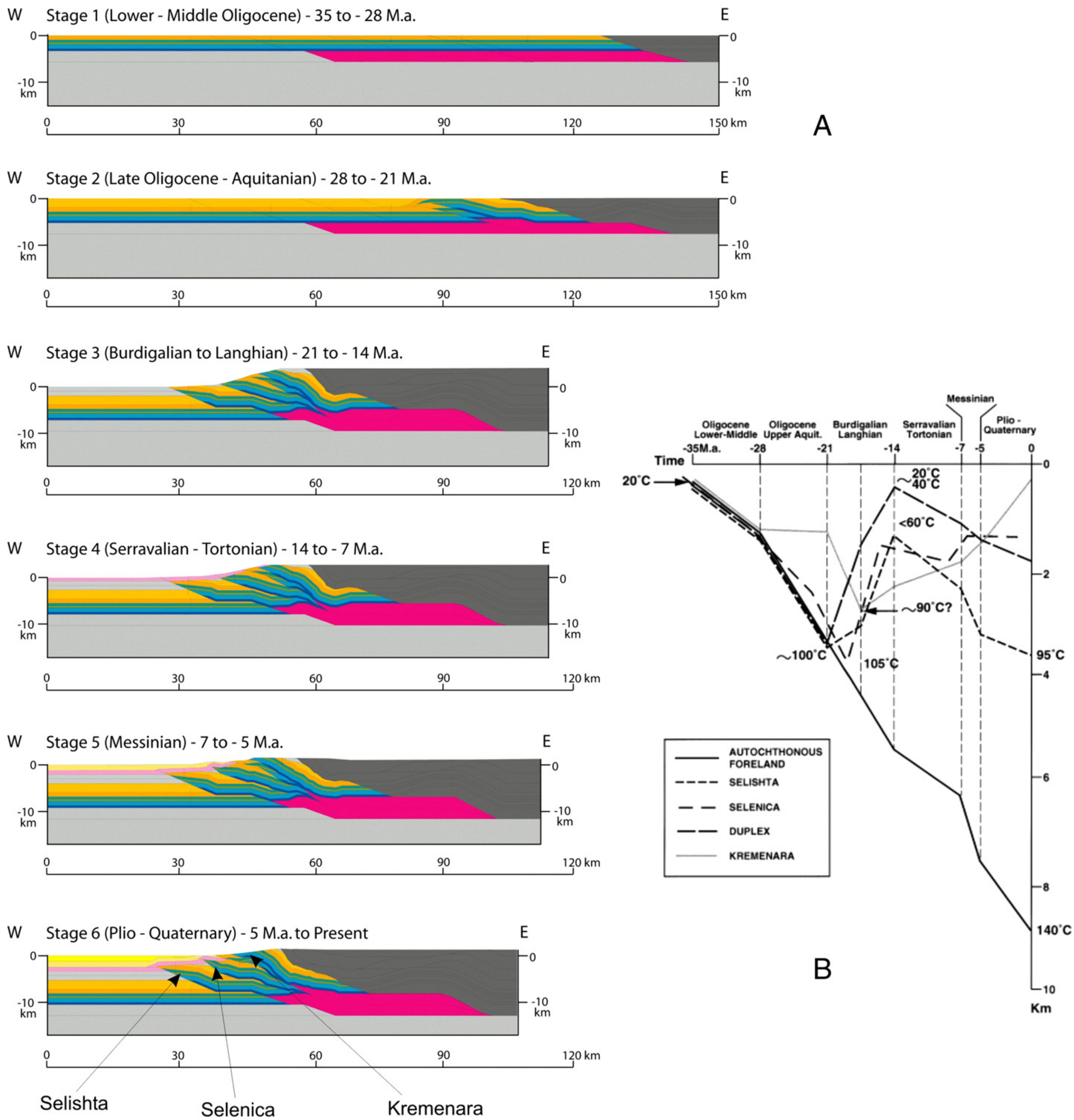

Fig. 7. 2D thrustpack kinematic modelling along a regional transect from the autochtonous foreland to the Kremenara anticline (A) and derived burial-temperature curves of the Cretaceous reservoir rocks (see also Van Geet et al., 2002). The subsurface units correspond to Selishta, Selenica and Kremenara duplex units. For Paleogene–Neogene, the colours indicate the formations deposited during the corresponding stage/time span. For Mesozoic (pre-orogenic), blue-green colours relate to Trias, Jurassic and Lower/Upper Cretaceous. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the foreland autochthon, the still presently buried duplexes of Selishta and Selenica, and the surface outcrops of the Kremenara anticline (Figs. 1B and 7A). An important feature of our model is that only the foreland has been deeply buried beneath Miocene and Plio-Quaternary flexural sequences, whereas the Ionian anticlines behaved as growth structures as early as the late Oligocene–Aquitanian. This model predicts that the Kremenara reservoirs have probably never been buried deeper than 3 km, with maximum temperatures derived from thermal modelling less than 90 °C, which are also consistent with the low T_h (homogenisation temperature) measured on fluid inclusions from cemented fractures (work in progress). Since in Kremenara, the differential stress values related to the late -folding NE compressional stress suggest a possible paleodepth of deformation of 0.5–0.6 km at the time of the record by twinning of the late fold tightening, we derive a maximum amount of syn-folding erosion of 2.5 km followed by a likely post-folding amount of erosion of about 0.5 km. As mentioned above, subsurface data, especially in the offshore part, are still not sufficient to constrain the deep architecture of a structural section running across the Saranda anticline to the foreland autochthon, which prevents a direct comparison of the results of kinematic modelling with maximum burial estimates from calcite twin analysis. It is difficult to say with certainty whether the Saranda anticline has been buried, at least partly, below the Neogene deposits of the Peri-Adriatic Depression. However, because of its outer position (in the Cika belt) compared to Kremenara (Fig. 1A), and because there is no evidence of late Oligocene–Aquitanian growth strata as in Kremenara, it is likely that folding occurred in Saranda later than the late Oligocene–Aquitanian, and that the Cretaceous limestones investigated remained buried until the Burdigalian (ca 20–16 Ma) or even the Langhian (ca 16–14 Ma). In the light of the above modelling, the estimate of a maximum paleoburial of ~4 km for Saranda appears therefore reasonable.

7.4. Integration in the regional fold–thrust belt evolution

The passive margin setting likely ended during the late Eocene, with active folding in the internal Albanides and flexure of the foreland basin subsequently filled by Oligocene flysch. The Lower Oligocene structural regime was, therefore, likely dominated by foreland flexure (Roure et al., 2004), so that compactional stylolites and set I veins in the foreland probably developed before or during the Lower Oligocene. These veins were very likely linked to normal faults, which also developed in response to the foreland flexure (Fig. 6A).

Thrusting/folding in the Ionian zone began during the late Oligocene–Aquitanian, with maximum shortening in the Ionian zone being achieved during the Langhian. It is difficult to discern whether the development of the anticlines is mainly related to the first major folding episode, or to the episode of out-of-sequence thrust reactivation that occurred during the Pliocene–Quaternary and which likely enhanced folding (e.g., Nieuwland et al., 2001). In Kremenara, the presence of the basal Burdigalian unconformity on top of the anticlinal structures is important for putting constraints on the timing of folding in the study area. Depending on the structural evolution during the late Oligocene, maximum burial would have been reached at different times, depending on the position in the fold. Because large thickness variations, growth-fold strata and local reef development had already occurred on top of Kremenara anticline by the late Oligocene–Aquitanian, this period is considered to be synorogenic (Van Geet et al., 2002), with the Kremenara anticline having partly started to form coevally with sedimentation. This implies that LPS stylolites developed between the early and late Oligocene, in the footwall of the frontal thrust, immediately before folding and tectonic accretion of carbonate units onto the allochthon (Fig. 6B and C). This period was also characterized by the development of the generations of veins described by Van Geet et al. (2002) and Graham-Wall et al. (2006), including set II. According to Breesch et al. (2007), this anticline may have been submitted to a second burial stage of about 800–2000 (?)m during the Pliocene, before to become overturned along its western limb during the Plio-Quaternary late folding stage.

For the Saranda anticline, it is possible, as mentioned above, that folding started later than the late Oligocene, possibly in the Langhian (ca 16–14 Ma)-Serravallian (ca 14–11). As a result, since the Cretaceous limestones were buried at a depth of about 4 ± 1 km according to our estimates, one can derive a mean rate of exhumation by folding of these Cretaceous limestones in the range 0.3–0.8 mm/yr. This rate is, however, poorly constrained, because neither the exact timing of the onset of folding, nor the relative contribution to folding of pre-Langhian/Serravalian and Plio-Quaternary thrusting events in southern Albanides are known.

8. Conclusions

In this paper, we present a new method to estimate paleoburial and subsequent uplift by folding in fold–thrust belts, based on calcite twin analysis. This method basically combines estimates of differential stresses related to LPS with the hypothesis that stress in the upper continental crust is in frictional equilibrium. Assumption is made that LPS is recorded coevally in a strata without any relation to the structural position of the samples after folding. Because LPS reflects stress build-up in horizontal strata before the onset of folding, it is likely recorded at the maximum burial, just before subsequent uplift. Paleodepth values inferred from differential stresses related to LPS therefore yield an upper bound for burial and constrain the amount of subsequent exhumation/vertical movement. Paleoburial estimates from post-folding stress tensors place additional constraints on the depth at which rocks were still buried when folding ended, and, therefore, on the exhumation path of these rocks toward the surface. A major interest of this method is that it can potentially be carried out anywhere twinned calcite occurs. It only requires that LPS-related stress orientations and related differential stress magnitudes be unambiguously determined, even where the tectonic evolution is polyphase. In the absence of other paleodepth indicators, applying this new promising method in fold–thrust belts will provide valuable constraints on the amount of burial of foreland rocks during flexural subsidence and of their subsequent uplift during folding, thus leading to a better quantification of vertical movements in forelands.

This new method has been tested in the Albanian foreland. Although the results presented in this paper are still preliminary and need to be confirmed by an extended collection of suitable samples, this approach allows derivation of paleoburial of Cretaceous limestones that are presently involved in folding at the front of the southern Outer Albanides. Calcite twin analysis provides additional constraints on the early stages of the tectonic history of the Albanian foreland thrust belt, including the successive stages of development of pre-folding vein systems currently observed in folded strata and related fluid flows. For the Saranda anticline for which subsurface data are still not sufficient to build a well-constrained structural section running across this anticline to the stable foreland, consistent paleodepth estimates point towards a maximum burial of about 4 ± 1 km. This result is consistent with independent information on paleoburial derived from stratigraphy, maturity rank of organic matter, paleotemperature/paleogeothermal gradients from fluid inclusions and predictions of kinematic modelling in the Albanian foreland.

In a next future, a promising way to reduce the range of uncertainties on paleoburial estimates and, therefore, on paleodepth of deformation in fold–thrust belts will be to combine the use of tectonic stress/paleopiezometric indicators such as calcite twins with the systematic use of paleothermometers (such as vitrinite reflectance, illite crystallinity, or fluid (mixed hydrocarbon/aqueous) inclusions coupled with numerical modelling of the thermal evolution of tectonic units (work in progress).

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