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Yann Rolland[a] , Jean-Marc Lardeaux[a], Laurent Jolivet[b]

[a] Géoazur, Université de Nice Sophia Antipolis, Observatoire de la Côte d'Azur, Faculté de Sciences, Parc Valrose, Nice, France

[b] Institut des Sciences de la Terre d'Orléans, Université d'Orléans, F45071 Orléans cedex, France

Abstract

Deciphering orogenic evolution requires the integration of a growing number of geological and geophysical techniques on various spatial and temporal scales. Contrasting visions of mountain building and lithospheric deformation have been proposed in recent years. These models depend on the respective roles assigned to the mantle, the crust or the sediments. This article summarizes the contents of the Special Issue dedicated to 'Geodynamics and Orogenesis' following the 'Réunion des Sciences de la Terre' 2010 conference held in Bordeaux, France. Further, based on the example of the Western Alps-Mediterranean domain we emphasize the possibility to integrate long and short term, plate- to sample-scale, datasets in order to constrain orogenic evolution.

Keywords: Orogeny; Orogenic evolution; Mountain belts; Reconstruction; Geodynamics

1. Introduction

1.1. Open scientific debates

The construction of modern and ancient orogens involves the whole rheological complexity of the continental lithosphere. Depending on the respective roles assigned to the mantle, the crust or the sediments, contrasting visions of mountain building and lithospheric deformation have been proposed in recent years. Some of the main questions that are actively debated in this field are the following:

- Is the continental lithosphere a localizing medium or not?
- What is the part played by the subcontinental mantle in its overall strength?
- Are mountain belts dynamics mostly driven by subduction dynamics?
- What is the difference between mantle delamination and slab retreat?
- How can we define collision versus subduction? Is there a "non-rigid" tectonics?
- What are the respective parts of internal geodynamic processes such as subduction and external processes such as erosion in the building of mountains?

The intensity of the debate is enhanced by the fact that numerous disciplines in Earth Sciences are involved, from field observation to mantle geophysics, through metamorphic petrology, sedimentology, geochemistry, thermochronology, numerical and analogue modelling and others. Data from these disciplines have provided key information for constraining *P–T–t–d* (Pressure–Temperature–time–deformation) paths of buried and exhumed units within orogens, and relate these motions to the evolution of sedimentary basins. Integration of paleomagnetic data to track phases of plate deceleration ascribed to collision and the degree of rotation inside the orogenic belts has allowed quantifying the speed of lithospheric blocks. Such data have provided a long-term basis for the understanding of active tectonics and the localization of resources. The research frontier lies now (1) in the orogens' deeper parts, in the so-called 'roots' of mountain belts, the study of which remains very challenging even while its role in the geodynamic evolution appears to be more and more crucial and (2) in the connection of active and past processes. In this research context, this Special Issue presents a selection of papers following the session 'Geodynamics and Orogenesis' held in the 'Réunion des Sciences de la Terre' meeting in Bordeaux – October 2010.

1.2. Filling the gap between past and active tectonics

One of the main questions posed by the study of the long-term tectonic evolution of orogens is how their history may be used to infer the active processes of a mountain belt. There is a huge temporal gap between the monitoring of crustal motions, indicated for instance by the seismic behavior of active faults, vertical and horizontal motions measured by GPS and paleomagnetic and geochronological methods devoted to finite strain measurements. However, several steps forward have recently been taken by the measurement of long-term strain rates and comparing them to annual rates. Long-term rates are generally obtained by paleomagnetic analysis at the scale of plates. Pioneering work on the oceanic crust undertaken in the late 1960s provided the basis for calculating the velocities of tectonic plates giving rise to the 'Plate Tectonics' model ([Hess, 1962] , [Isacks et al., 1968] , [Le Pichon, 1968] and [Morgan, 1968]). The general image provided by the tectonic plate approach is that of mostly rigid plates deforming at narrow boundaries. Recent geodetic measurements have evidenced annual 'instantaneous' deformation rates similar to geological-scale rates, especially in very active tectonic settings such as the Indian–Asian convergence zone (Zhang et al., 2004). However, it remains difficult to reconcile these plate-scale approaches with those undertaken at the centimeter scale. An example of such an approach is provided by Müller et al. (2000). In their study, very slow deformation rates were obtained. Incremental deformation is featured in rocks by rotating clasts and opening veins. These microscopic markers have been dated providing deformation rate estimates in shear zones. Müller et al. (2000) showed that relatively constant and continuous deformation in a given shear zone lasted over 37 million years, a period comparable to that of an orogeny. Estimated strain rates ranged from 1.1×10^{-15}, rising to 7.7×10^{-15} s^{-1} during a short interval of about 4 million years, far below generally measured tectonic rates. Such data show that deformation is more evenly distributed than expected and, moreover, that lateral strain rate gradients are likely to occur in orogens. To understand the distribution of strain in orogens, methods such as these, developed at macro to microscopic scales are promising although adequate suitable material for analysis is the main limiting factor, which explains a lack of similar studies in recent past.

Further steps forward linking past and active tectonics are currently being undertaken by applying new geochronological methods that allow intermediate results in the Holocene and Quaternary to Pliocene times (10 ka, 2.6 Ma, 5.3 Ma) between active and long-term processes. Methods such as cosmo-nucleide dating have allowed dating fault surfaces including those with lateral offsets (e.g., Sanchez et al., 2010a). The application of small-period (<1 Ma) dating methods allows comparisons between climatic – erosional cycles and tectonic motions. Further developments of dating methods applied to recent (Plio-Quaternary) orogenic evolution are thus likely and promising.

2. Orogenic evolution, the Western Alps 'case example'

Here we summarize the main features of orogenic evolution as can be currently seen from one of the most-studied examples on Earth: the Western Alps of Occidental Europe, which is addressed by several papers in the Special Issue.

One of the main recent discoveries from the Alpine-Mediterranean area is the role of oceanic and continental subduction in the evolution of the Alps orogen, including the so-called "collisional" or "post-collisional" stages. Subduction played as key a role during early continental thickening stages as during the mainly transcurrent post-collisional stage. Neighboring oceanic basin dynamics in the Mediterranean domain are far more rapid than that of collided blocks and control the tectonic motions in the quiescent continental margins. The main mechanism governing ancient and current Mediterranean subduction is slab pull and roll-back of old and dense Tethys oceanic lithosphere (Jolivet and Faccenna, 2000). It is now largely accepted that the formation of the Alps results from the subduction of previously thinned continental margins dragged into the subduction zone. This major result was first inferred from UHP metamorphism of continental crust. Coesite relicts documenting subduction of continental crust at asthenosphere depths (ca. 100 km) were described for the first time in the Internal Alps (Chopin, 1984) and further evidence of UHP metamorphism has been found along other peri-Mediterranean belts (e.g., Liati, 2005). In the Alps, UHP metamorphism of the subducting European slab has been dated at ca. 32.8 ± 1.2 Ma in Dora Maira (Duchêne et al., 1997), while underthrusting and opening of intracontinental foreland basins was dated at 31–34 Ma ([Simon-Labric et al., 2009] and [0075]). This state of 'continental subduction' is intermediate between oceanic subduction and 'Himalayan' continental collision in steady state. As emphasized by several authors (e.g. [Beltrando et al., 2010] and [0075]), the Early Oligocene is characterized in the Alps by a rapid change in tectonic context, which we interpret below as a transition towards post-collisional rotation of Apulia driven by subduction in the Mediterranean domain.

After the rapid (>cm year^{-1}) burial and exhumation of continental crust in the collisional prism (Rubatto and Hermann, 2001), the rate of exhumation decreased dramatically. In the Alps, after 33 Ma, exhumation rates dropped to less than 2 mm year^{-1}, and only slight differential uplift is observed between the different tectonic units (e.g., Schwartz et al., 2007). Therefore, most of the crustal structure of the Alps, including the Ivrea Mantle body intercalation in the upper crust, was already acquired at 33 Ma ([Lardeaux et al., 2006] and [Schreiber et al., 2010]).

Since 30 Ma, steady exhumation of 1 ± 0.5 mm year^{-1} is documented across the Western Alps arc ([Vernon et al., 2009] and [Cederbom et al., 2011]) with a late acceleration ascribed to external climatic causes at ca. 5 Ma. This post 30 Ma subduction phase is accompanied by the onset of strike-slip tectonics reactivating former structures (Fig. 1). Activation of right-lateral faulting occurred mainly along the Penninic Front, connecting the Insubric Line via the Simplon extensional fault (Campani et al., 2010).

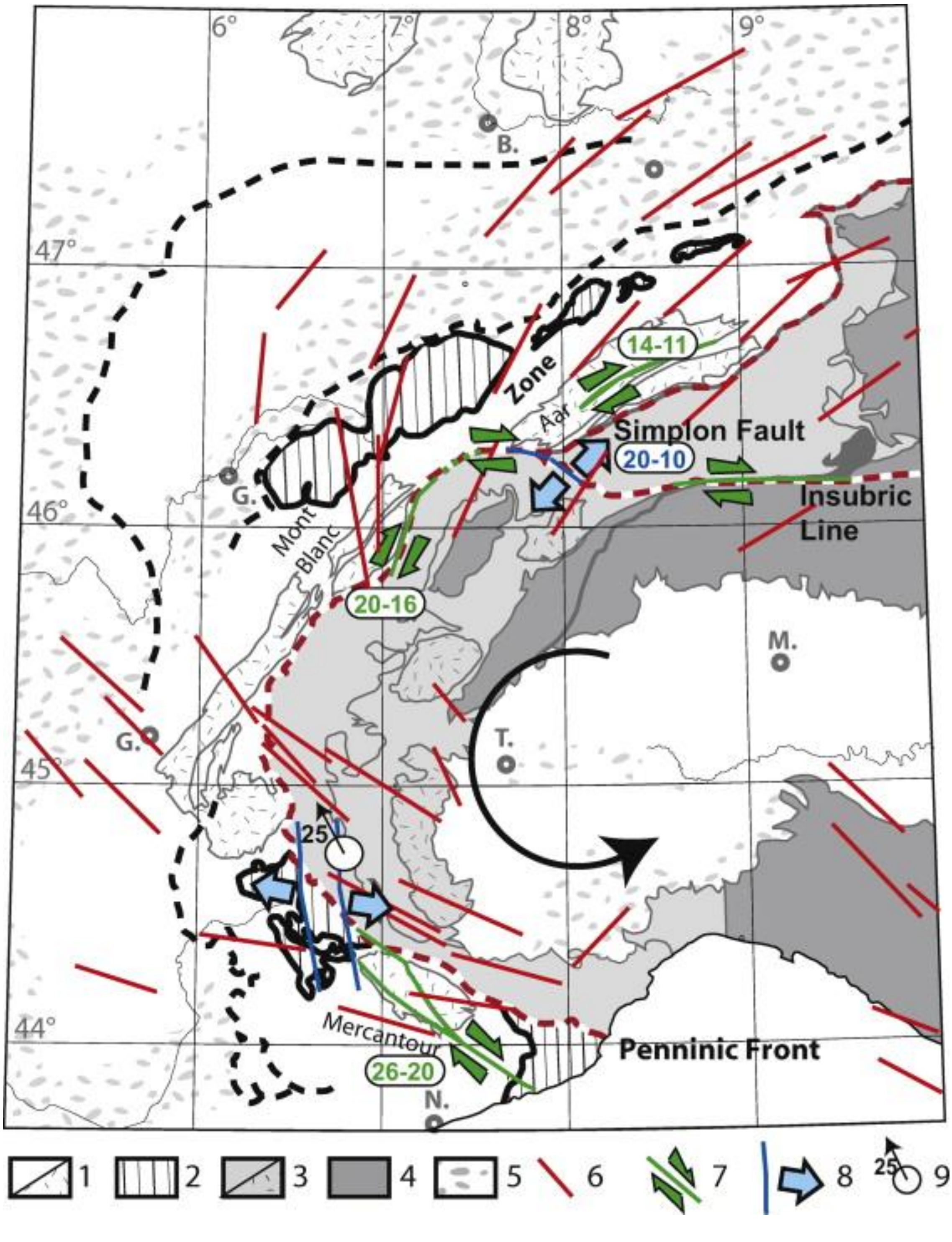

Fig. 1. : Post-collisional crustal and upper mantle strain field of Western Alps with polarities and ages of ductile crustal deformation (references below), and direction of upper mantle deformation inferred seismic anisotropies (Barruol et al., 2011). Age and polarities of displacements are from Rolland et al. (2009a) in the Aar Massif, from Campani et al. (2010) in the Simplon Fault zone, from Rolland et al. (2008) in the Mont Blanc, from Sanchez et al. (2011a) in the Mercantour. The legend displays: 1, the Dauphinois (or Helvetic) zone, rimmed by the Jura and Alpine frontal thrusts. The Dauphinois zone is comprised of a Hercynian crystalline basement (stripped) and its para-autochthonous and allochtonous Mesozoic sedimentary cover (white); 2, the transported klippes of Helminthoid Upper Cretaceous flysch and Internal Briançonnais and Penninic units. Internal Alps comprise: 3, Briançonnais and Piemontais zones, which are made of variably metamorphosed rocks from the continental European margin and the Alpine Tethys oceanic domain; 4, the Austro-Alpine units comprising the Dent Blanche klippe and the Apulian margin; 5, Molasse sediments deposited during the Oligocene to Pliocene lie in the periphery of the Alps. 6, Upper mantle anisotropy defined from systematic SKS splitting measurements (Barruol et al., 2011). 7 and 8, main ductile to brittle post-collisional shear zones: 7, strike-slip shear zones; 8 extensional shear zones. 9, Paleomagnetic data obtained in the Briançonnais Zone of SW Alps indicate minimum ~25° counterclockwise rotation (Collombet et al., 2002).

Ductile mid-crustal deformation is evidenced by mylonites formed in a right-lateral kinematic setting along the Alpine arc. These motions are dated at 26–20 Ma in the South (Sanchez et al., 2011a), at 20–16 Ma in the West (Mont Blanc; [Rolland et al., 2007] and [Rolland et al., 2008]) and 20–12 Ma in the North (Aar; [Challandes et al., 2008] , [Rolland et al., 2009a] and [Rolland et al., 2009b]).

In this context, it becomes clear that extensional faults do not originate from post-collisional gravitational collapse. Several extensional features occur across the Alpine arc (Fig. 1), but they have generally been ascribed to transtensional domains (e.g., Simplon and High Durance; [Sanchez et al., 2010b] and [Sanchez et al., 2011b]). Similarly, transpressional domains (e.g., Mont Blanc; Rolland et al., 2008) also connect with strike-slip faults. Continuous ductile to brittle deformation, seismicity and morphological offsets evidence the permanence of such motions, occurring during the Quaternary ([Sanchez et al., 2010a] and [Sanchez et al., 2010b]). The overall dextral motion that is observed across the Alpine arc contradicts any model of westward indentation of the European margin by the Apulian microplate. In contrast, this observation is clearly in agreement with the counterclockwise rotation of the latter microplate, whose motion is currently ongoing. Paleomagnetic data in the Internal Alps are in agreement with a counterclockwise rotation of about 25° (Collombet et al., 2002). Geophysical imaging of SKS waves in the upper mantle below the Alps also support this view by suggesting mineral anisotropy directions in agreement with an along-belt stretching direction (Barruol et al., 2011). Seismicity is characterized by joint extensional and right-lateral focal mechanisms along the Western arc (Jenatton et al., 2007), which shows that such motion is ongoing at the present.

However, motions are very slow and fall within the errors of available GPS measurements (Delacou et al., 2008). Nevertheless, the question of the driving mechanism of such slow displacement is posed. To understand this, a change in observation scale is necessary. At the Mediterranean basin scale, tectonic motions since at least 20 Ma are governed by oceanic slab roll-back, leading to the opening of Ligurian and Tyrrhenian back-arc basins and the rotation of Corsica-Sardinia ([Jolivet et al., 2000] , [Jolivet and Faccenna, 2000] and [Brun and Faccenna, 2008]). The tectonic motions to the south of the Apulian microplate are still rapid, with cm year^{-1} velocities inferred from GPS, in agreement with rotation of the Apulian block centered near Torino (Delacou et al., 2008). The driver of slow tectonic motions in the Alps should therefore be a far field consequence of subduction occurring to the south of Apulia. Consequently, for the Western Alps case it seems that subduction (even peripheral) played a major role during the pre-, syn- and post-collisional evolution of the orogen.

3. Contributions to this volume

Under the scope of this Special Issue, orogenic evolution is reviewed by Vanderhaeghe (submitted), while case-studies are devoted to documenting some active (Alpine) and inactive (Variscan) mountain belts. Case-study articles provide examples of techniques that can be used to reconstruct the long-term evolution of orogens.

Considering the evolution of active mountain belts, the reconstruction of the early stages of orogenesis is often challenging, because it has been largely obliterated by the later tectonic stages. One indirect approach can be the use of the paleo-magnetic signal recorded in the oceanic crust to reconstruct phases of orogenic evolution. In their paper White and Lister (this issue) revise the available paleo-magnetic data used to analyze India–Asia convergence through time. They propose that the long-term convergence deceleration may not be ascribed to India–Asia collision, while they ascribe short-term episodes of acceleration and deceleration to several accretion events. However, reconstructing the evolution of orogenic domains from sea-floor paleo-magnetic anomalies remains controversial; such features should also be interpreted in the light of profound mantle dynamics. As shown by Müller (2011) mantle plumes are shown to have a significant influence of the pace of Indian Ocean oceanic accretion.

Other papers in the Special Issue are devoted to direct studies of exposed and exhumed rocks in orogens, aimed at allowing the reconstruction of orogenic evolution from mantle roots to the surfaces of mountain belts. In their synthesis of 'Alpine revolution' in the Oligocene, Dumont et al. (submitted) trace the Eocene–Oligocene evolution of SW Alps by a combination of structural geology and foreland basin sedimentology. These authors document a phase of rapid tectonic change and plate reorganization in the Alps during the Early Oligocene that they ascribe to deformation along the western transform boundary of Adria during its northward drift.

The mid-crustal evolution of buried continental crust can be deciphered by a combination of metamorphic petrology, geochronology and kinematics. The relationships between mineral recrystallization in shear bands and closure of unstable isotopic systems therefore represent key information for linking the polarity of tectonic motions with ages and Pressure–Temperature conditions. The two papers following Dumont et al. shed light into mid-crustal evolution of the Western Alps orogen in the same period of time.

In an state-of-the-art thermodynamic approach applied to low-temperature and intermediate pressure rocks, Lanari et al. (this issue) combine compositional mapping of minerals, phengite–chlorite thermobarometry and organic matter (Raman) thermometry to analyze in detail the variation in metamorphic conditions through a given geological domain, the Briançonnais Zone. Variations in the inferred geothermal gradients ranging from 8 to 40 °C/km are ascribed to the evolution of the collisional wedge from early continental subduction to collision at about 35–30 Ma leading to crustal thickening.

In a neighboring area, Strzerzynski et al. (submitted) document a *P–T–t–d* evolution combining thermobarometry and Ar–Ar geochronology in shear zones. These data agree with Eocene burial of the Briançonnais Zone rocks and exhumation of this portion of continental crust by a combination of top to the west and top to the east motions along the main tectonic boundaries at the Eocene–Oligocene transition.

In a way similar to the Western Alps, Rolland et al. (this issue) show that the Caucasus orogen preserves evidence for subduction of the Neotethys ocean followed by collision a small tectonic block, the Taurides–Anatolide–Armenian block. Ages obtained on both sides provide temporal constraints of subduction and accretion of this block, culminating in the final collisional history of the Eurasian and Arabian plates in this area. On the northern side, $^{40}Ar/^{39}Ar$ ages give insights on the subduction and accretion from the Middle to Late Cretaceous (95–80 Ma), while to the south, younger magmatic and metamorphic ages record the subduction of Neotethys and accretion of the Bitlis-Pütürge block during the Late Cretaceous (74–71 Ma). These data are interpreted as a subduction jump from the northern to the southern boundary of the Taurides–Anatolide–Armenian block at 80–75 Ma.

The evolution of the deepest parts of orogens can be traced by several methods including geochemical analysis of major shear zones, and analysis of the fabric patterns of exhumed peridotites. It can be featured in fossil mountain chains, whose deeper parts were exhumed during late collisional processes such as the Variscan chain of Western Europe.

In their paper on the South Armorican Shear Zone, Tartèse et al. (this issue) document, on the basis of combined Ar–Ar geochronology and stable isotopic data, two major phases of fluid circulation including a downward fluid influx at the end of the deformation history, which is linked to crustal-scale exhumation processes.

Kusbach et al. (this issue) provide an EBSD analysis of mineral fabrics preserved in exhumed peridotites in the Bohemian Massif. These data allow them to reconstruct a burial-exhumation history for the lithospheric root. This study demonstrates that it is becoming possible to investigate the deepest orogenic features and reconstruct their evolution from the analysis of rocks exposed at the surface. The integration of petrology and field structural data results in an evolutionary model of the mantle lithosphere root of the orogen. The model includes burial of peridotites below a thickened crustal root, followed by uplift and folding. The degree of mechanical coupling between folded peridotite and granulite in mid-crustal levels is estimated by comparing the studied microstructures with experimental data. Finally, Vanderhaeghe (submitted) presents a synthesis of research devoted to the thermal–mechanical evolution of the crust within convergent settings, which leads to a review of processes and a general conceptual model of orogenic evolution.

4. Concluding remarks

Deciphering orogenic evolution over varied spatial and temporal scales can now be achieved by a combination of techniques. Although ‘filling the gap’ between such varied scales is still challenging, there is increasing interest and progress in the development of a large set of techniques allowing to trace the evolution of orogens from their roots to their tops, and from the long to the short terms.

4.1. Role of the lithospheric root in orogenic evolution

The study of exhumed sub-lithospheric mantle by Kusbach et al. (this issue) has provided a significant step forward in the comprehension of lithosphere strength through time during orogenesis. Indeed, the relative strength of the layers comprising the lithosphere is currently debated ([Jackson, 2002] and [Burov and Watts, 2006]) as well as the impact of the rheology on the style of crustal and lithospheric deformation at convergent plate boundaries ([England and McKenzie, 1982] , [Molnar and Lyon-Caen, 1988] , [Royden, 1996] and [Tapponnier et al., 2001]). From the Kusbach et al. paper in the present Special Issue it appears that mantle and crust are not necessarily decoupled, since both lithologies are found strongly interlayered. Yet, the motor of mantle uplift or extrusion is still unclear. What kind of geodynamic context might favour an extrusion “channel” with such a domal shape? The authors invoke a ‘channel flow’ process, related to the indentation of the Brunhian promontory. In such process the motor of deformation is underthrusting, thus the orogen is still undergoing ‘subduction dynamics’. However, similar deformation could result from some strike-slip deformation (e.g., Cagnard et al., 2006), which is often invoked in such thickened and thermally mature orogens, in ancient Archean to Proterozoic mountain belts (Duclaux et al., 2008), or in modern Himalayan analogues (Mahéo et al., 2004). In the western part of the Variscan chain, Tartèse et al. (this issue) have showed that in the same period of time as in Kusbach et al. crustal-scale chemical transfer is efficient in some right-lateral fault zones. Therefore, the part of strike-slip and underthrusting in crustal deformation of the Variscan chain is not easily constrained. A possible scenario could be that the main tectonic boundaries of the Variscan chains were actually transpressional, with some spatial partition between thrusts and strike-slip faults (e.g., Corsini and Rolland, 2009).

4.2. Thermally 'mature' vs. 'immature' orogens

The degree of coupling between the crustal and mantle parts of the lithosphere is also a function of the balance among surface forces related to plate tectonics, the gravity force related to lateral variations in lithospheric thickness and the buoyancy forces related to density variations ([Artyushkov, 1973] , [Ramberg, 1981] , [Molnar and Lyon-Caen, 1988] , [Molnar et al., 1993] , [Chemenda et al., 1995] , [Ellis, 1996] and [0275]). The impact of the thermal evolution of the crust and lithospheric mantle on the lithosphere's rheology and mechanical behavior is a major issue that is rarely taken into account. This point has been stressed by several authors ([Vanderhaeghe and Teyssier, 1997] , [Vanderhaeghe et al., 2003] , [0275] and [Schulmann et al., 2008]). This makes a big difference in rheological and deformation regimes governing 'thermally mature' orogens such as the Himalayan and Variscan ones with respect to 'thermally immature' ones (e.g., Western Alps). In the Western Alps case example, the special volume contributions clearly show that most tectonic motions leading to the first-order collisional orogenic architecture were achieved in within a very short period of time (~5 Ma) in the Oligocene. This is true for the evolution of flexural basins (Dumont et al., submitted) as well as for the tectonic stacking of units ([0260] and [0325]). After this stacking episode the tectonic motions were slow but constant, mainly driven by the dynamics of Mediterranean subduction (see Section 2). The syn-orogenic extension of the Alps is thus not ascribed to post-collisional collapse. The Alps are not thermally mature enough for such gravitational collapse. In contrast, the extensional features are ascribed to some local accommodation of curved and mainly right-lateral tectonic boundary along rotating Alpulian plate. In turn, this rotation may be ascribed to Mediterranean slab roll-back (e.g., Jolivet et al., 2000).

4.3. 'Thermally intermediate' orogens

Although its orogenic shape and deformation rates are intermediate between the Western Alps and the Himalaya-Tibet orogens (Vanderhaeghe, submitted), similar mechanisms as for these appear to explain the construction of the Caucasus orogen (Rolland et al., this issue). Major Caucasus crustal-scale architecture was acquired in some short-lived collisional phases. However, the distinct 'plateau' shape of this orogen noted by Vanderhaeghe may be ascribed to some significant degree of thermal maturation as quoted by Mitchell and Westaway (1999). Slab break off processes beneath Eastern Anatolia are likely in effect ([Faccenna et al., 2006] and [Lei and Zhao, 2007]) but may not be the sole process explaining the high thermal gradient. Actually, plume activity has been widespread for a long time in this zone ([Rolland et al., 2009b] and [Müller, 2011]), and its effect on the thermal regime of an orogen is likely. In many ways the Caucasus orogeny may be explained by intermediate thermal maturation, one between that of the Alpine and Himalayan orogens. However, the origin of the heating is still a matter of debate, especially that part originating from the mantle versus that formed by in situ in the thickened crust by radiogenic decay reactions.

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