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Editorial

Style of deformation and tectono-sedimentary evolution of fold-and-thrust belts and foreland basins: From nature to models

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1. Fold-and-thrust belts: some recent advances in their description and their understanding

Orogenic systems, including their external fold-and-thrust belts and foreland basin systems, generally evolve from the inversion and imbrication of former continental margins. Continental margins are characterized by displaying along-strike variations in the degree of inherited regional extension (i.e., from limited lithospheric stretching to full necking, leading to mantle exhumation and oceanic accretion). These differences have a fundamental impact on the pre-shortening thermal state of the lithosphere and on structural style development.

Indeed, one of the key processes in fold-and-thrust belts is the reactivation and inversion of pre-existing extensional faults. Inversion tectonics is widespread during the evolution of many orogens and this process can exert a strong control on the structural and mechanical evolution of fold-and-thrust belts (Lacombe and Bellahsen, 2016).

The presence of evaporitic sequences interacting during lithospheric stretching and subsequent thermal subsidence is also a key parameter in the structural styles and deformation distribution of thrust sheets involving inverted basins and salt structures. On the other hand, deformation can also be transferred ahead and downward of the shallow deformation front, leading to frontal imbrication of deep seated structures in cratonic forelands or the sub-thrust region of active fold-and-thrust belts.

Defining the correct structural style of fold-and-thrust belts and understanding the controlling factors are necessary steps towards predicting their long-and short-term evolution, with implications for crustal/lithospheric rheology, mountain building processes and seismic hazard, and for the correct assessment of their potential for hydrocarbon exploration (e.g., Butler and Mazzoli, 2006; Lacombe et al., 2007; Poblet and Lisle, 2011; Lacombe et al., 2016). For these reasons, fold-and-thrust belts and adjacent foreland basin systems represent outstanding places to investigate (active) deformation and surface processes and the way these processes interact to shape mountain belts. On a short-time scale, the pattern of deformation of fold-and-thrust belts provides information on crustal mechanics, the sequence of active faulting and its relation to large earthquakes; on a long-time scale, the structure and dynamics of the fold-and-thrust belt -foreland basin systems offers unique insights into the influence of structural, thermal and rheological inheritance, together with coupling between surface and deep processes.

During the last ten years, significant advances have been made in the description and understanding of fold-and-thrust belts and foreland basins. Among (many) others: better definition of structures at depth (seismic imaging, 3D visualization/ geomodelling, better appraisal of geometrical uncertainties); use of analogue and numerical modelling to constrain long-term and short-term surface and deep processes; applications of thermochronology (detrital thermochronology for sediment routing and paleo-burial estimates, coupled thermochronological and 2D/3D mechanical/kinematical modelling); recognition of the influence of salt and salt tectonics; renewed conceptualization of fold-fractures relationships and new ways to unravel paleostress history.

1.1. Imaging structures at depth in fold-and-thrust belts and addressing uncertainties

Our view of the geometry of fold-thrust belts relies on the interpretation of field data, borehole data and seismic lines. Classically, geoscientists collect a large amount of outcrop and geophysical data and interpret them to arrive at a plausible geometric or steady state model. Such a model can then be used as a basis for kinematic restorations or mechanical considerations. While this approach has been successful for many years, improving our understanding of fold-and-thrust belts as well as finding oil and gas reservoirs, a topic that becomes more and more recognized is to take the uncertainties associated with the input data into account. This emerging field may yield new fundamental insights on subsurface geometries, and consequently may provide different kinematic and mechanical solutions of a study area. Field data are subject to possibly large uncertainty, due to vegetation cover or variable erodibility of different rock types (Moosdorf et al., 2018), which may lead to overrepresentation of less erodible rocks in the measurements. This is particularly an issue for the location of faults, as fault rocks are commonly easily eroded. Vegetation cover is a common problem in fold-thrust belts, as they form the foothills of orogens, an area commonly inhabited and cultivated. These uncertainties will often make possible different equally viable interpretations of field data. Some of these uncertainties can be reduced by combining them with subsurface data, i.e. borehole measurements and

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seismic images. However, these two data sets are similarly associated with uncertainties, and it has been shown using synthetic seismic images that interpretations may have a strong bias depending on the expertise of the interpreter (Bond et al., 2007). Even when interpreters are all familiar with the area, different interpretations of the same high-resolution seismic section may be offered, as pointed out by von Hagke and Malz (2018).

For future research in fold-and-thrust belts addressing these uncertainties will be an important way forward. At the moment there are two main directions. First, presenting not only one plausible model, but arriving at a wide range of possible models, ideally associated with a quantitative estimate of the respective uncertainties. This requires a probabilistic approach, and has successfully been applied to a wide range of areas (Bond, 2015; Wellmann and Regenauer-Lieb, 2012; Wellmann and Caumon, 2018). This approach at least partly circumvents the bias introduced by the subjectivity of the interpreters. However, the full complexity of geological systems often cannot yet be captured. Therefore it is essential to include as much geological information as possible, appreciating the 4-D nature of structures (e.g. Duffy et al., 2018; Hessami et al., 2001; Ruh and Vergés, 2018; von Hagke et al., 2016). To that respect, 3D structural modelling using various geomodelling softwares (e.g., Caumon et al., 2009; Pellerin et al., 2015) may be of great help in testing the geometrical and kinematical compatibility of structures from various geological or seismic sections (Turrini et al., 2014), performing meaningful kinematic restorations (Durand-Riard et al., 2011) or performing seismotectonic studies at a regional scale (Turrini et al., 2015). Second, and maybe even more importantly, models of the subsurface structure of fold-thrust belts should be not only tested with respect to their kinematic plausibility, but their mechanics needs to be understood. This has exemplarily been shown for the interpretation of triangle zones (von Hagke and Malz, 2018), but is equally applicable for any structural model. Understanding the mechanics of fold-thrust belts and their detachments has progressed much in the last few years, partly because of the increasing strength of numerical models and increasing resolution of micro-structural techniques. The mechanics of shale and salt-detachments become increasingly known (see reviews by Morley et al., 2017, 2018 for shale detachments, and summary below for salt detachments). Addressing the mechanics of fold-thrust belts and their respective detachments also will partly shift focus of field-based research from the regional scale to the outcrop scale, where individual key structures have to be analyzed at high resolution. At the same time, it is necessary to explore the parameter space of what is responsible for fault weakness, the influence of evolving and transient rheologies, or the influence of mechanical stratigraphy on geometries. This is best done with a combination of numerical and analogue models. However, a sound understanding of the structures in the field, using classic geological field techniques combined with digital mapping (Fernández et al., 2004), drone imagery (Pavlis and Mason, 2017), LiDAR and photogrammetry studies at regional and outcrop scales will remain essential, and a cornerstone of research applied to fold-thrust belts (Tavani et al., 2014; Corradetti et al., 2017; García-Sellés et al., 2011, 2018).

1.2. Analogue and numerical modelling of tectonic processes in fold-and-thrust belts

Analogue and numerical modellings are rather mature geoscientific tools used to understand the dynamics of fold-and-belts, accretionary wedges and orogens for several decades. Recent methodological advances, both experimental and numerical, allow nowadays simulating key geoprocesses and their coupling at various time scales at high resolution and in 3D.

With the advent of high-resolution monitoring techniques and accurate rheological characterization of rock analogue materials, analogue modelling has transformed from a concept-testing qualitative tool to a quantitative simulation technique (see reviews by Rosenau et al., 2017; Graveleau et al., 2012).

On the methodological side recent efforts in analogue modelling focus for instance on the use of image-processing software to generate 3D voxel (i.e., *volumetric pixel*) models of the internal structure of sandbox models; this technique allows producing arbitrary virtual sections (i.e. inlines, cross-lines and depth slices) through sandbox models based on the reconstruction from cross-sectional images in a similar manner to 3D seismic data (Dooley et al., 2009; Granado et al., 2017). These voxels can be converted into seg-y files to be loaded to seismic interpretation software platforms (Roma et al., 2018) to generate 3D structural static models; these models can later be populated with properties to carry out dynamic simulations (i.e., fluid injection, production, etc.). Kinematic monitoring of model surfaces and volumes, on the other hand, can be carried out using digital imaging techniques (Galland et al., 2016; Boutelier et al., 2019; Toeneboehn et al., 2019; Adam et al., 2013; Poppe et al., 2019) including time adaptive imaging (Rudolf et al., 2019). Dynamic monitoring using stress sensors measuring lateral push (Ritter et al., 2018a, 2018b; Cruz et al., 2010; Souloumiac et al., 2012) or pressure sensors providing in-situ observations (Moulas et al., 2019) improved greatly our understanding of the force balance and work budget in experimental tectonic systems. A number of new analogue materials mimicking brittle-elastoplastic and viscoelastic behaviour of rocks in a more realistic (often complex) way have been developed and characterized recently (Di Giuseppe et al., 2009, 2015; Abdelmalak et al., 2016; Brizzi et al., 2016).

In parallel to methodological advances, studies dedicated to critical assessment of the reproducibility of experiments (Cubas et al., 2010; Santimano et al., 2015) and their boundary conditions (Souloumiac et al., 2012) raised awareness for uncertainty in analogue modelling and the relation between intrinsic and extrinsic variability of experimental observations. Community benchmarks including material characterization (Klinkmüller et al., 2016; Rudolf et al., 2016) and comparison of analogue and numerical models (Schreurs et al., 2016, Buiter et al., 2006; Buiter, 2012) has moreover helped validate established analogue and numerical modelling techniques.

Based on methodological advances, applications of analogue modelling developed in recent years towards ever shorter timescales: while classical sandbox modelling of orogenic systems and fold-and-thrust belts (Borderie et al., 2019, Saha et al., 2016) as well as lithospheric scale multilayer models (Munteanu et al., 2019) represent the state-of-the art in analogue modelling of tectonic processes at the million year time scale, approaches to model geomorphologic (Graveleau et al., 2011, Guerit et al., 2016) and seismic cycle time scales (Rosenau et al., 2017) have entered the stage with the perspective of understanding tectonic evolution across all relevant time-scales.

The deeper our understanding of shallow earth deformation processes, the more complicated their modelling, however. It is for these matters that numerical modelling is gaining importance in geoscience as applied mathematical codes aid at providing a better control on geological processes involving fluid pressure, mineral reactions, surface processes etc., which cannot, or only in a very limited way, be implemented experimentally. Moreover, modern computer processing power allows running many realizations simultaneously, testing the effect/s of different parameters in parallel resulting in a generally wider parameter space to be tested numerically compared to analogue models. Finally, complex geometries as well as depth-dependent rheologies and their change with temperature (i.e. thermo-mechanical) and accumulated strain (i.e., strain-weakening, strain-hardening) can also be modeled more accurately, and their influence on the resulting realizations, numerically constrained. These are possibly the great advantages of numerical methods in comparison to traditional analogue modelling; however both techniques need to be regarded as complementary, and not mutually exclusive.

There are three main numerical methods currently applied to fold-and-thrust belts: discrete element methods (also referred to distinct element methods, Burbidge and Braun, 2002), finite element methods (Simpson, 2011; Erdős et al., 2014a; Bauville and Schmalholz, 2015), and finite difference methods (Ruh, 2019). More rarely, discrete element methods are used because of their limitations in resolution with respect to geological systems. All numerical methods are challenged by the increasing demand for 3D “cross scale” (in space and time) models requiring massively parallelized codes to be developed (Kronbichler et al., 2012; van Dinther et al., 2013; Ruh et al., 2013) implementing adaptive time-steps and meshes as well as the most efficient and reliable mathematical formulations of deformation laws (Pipping et al., 2016; Herrendörfer et al., 2018; Glerum et al., 2018).

Future work on numerical modelling applied to fold-and-thrust belts should address the following points: the controls of inheritance from passive margins stages, including thermal effects, fault orientation and strength in 2D/3D, as well as sedimentary basin architecture and mechanical properties of the basin-infill (i.e., changes in pore-fluid pressures), include the presence of several décollements with variable strengths, underlying basement steps, as well as the existence of previous salt structures, and *non-layer cake* stratigraphies.

1.3. Fold-and-thrust belts and the thermochronology toolbox

Thermochronological age dating of various minerals is a key tool in Earth sciences to quantify landscape evolution and the metamorphic and tectonic history of orogens and sedimentary basins (Wagner and Reimer, 1972; Brown et al., 1994; Reiners and Brandon, 2006). Thermochronology provides information on the temperature history of minerals and rocks. Thermochronometric datasets provide cooling ages, which is the time elapsed since a mineral cooled below a certain temperature. In fold-and-thrust belts, the application of low-temperature thermochronometers is ideally suited, as the method is sensitive to the uppermost few kilometers of the crust. Commonly used techniques are fission track dating and (U-Th-Sm)/He dating on zircon and apatite. Different thermochronometers are sensitive to different cooling intervals. For instance whereas the apatite fission track system is sensitive to temperatures above approximately 110 °C (depending on apatite chemistry), the apatite helium system records cooling below ~60 °C (Wolf et al., 1996; Farley and Stöckli, 2002). In fold-thrust belts, analyzed samples commonly derive from foreland sediments that have been incorporated later into the orogenic wedge. This implies that dated grains may have a complicated time-temperature history, starting with cooling in the hinterland, transport through the drainage area, deposition and burial (and consequently heating) in the basin and later exhumation in the fold-and-thrust belt (Fitzgeral et al., 2019). The youngest exhumation history in the fold-and-thrust belt can be complex in itself due to repeated activity of the same fault at different times. These complex t-T paths provide some challenges to be interpreted correctly, however, by integrating thermochronological data from the orogen, the foreland as well as the fold-thrust belt it is possible to provide a comprehensive picture of the t-T history of a mountain belt. Thermochronological data from fold-and-thrust belts provide also information on the provenance history of the sediments, estimates of maximum burial, as well as timing and rates of deformation. The strength of low-temperature thermochronometry has been successfully exploited in many fold-and-thrust belts in the world, as for instance in the Andes (McQuarrie et al., 2005; Barnes et al., 2006; Savignano et al., 2016), the European Alps (von Hagke et al., 2012, 2014), and the Pyrenees (Beamud et al., 2011; Mouthereau et al., 2014, Ternois et al., 2019). It has to be noted that thermochronometric ages cannot be directly translated into time of deformation (Mora, 2015). Particularly for fold-and-thrust belts, where sediments are commonly dated, thermochronometric ages may be associated with uncertainties due to unknown provenance ages, hydrothermal fluxes, low crystal quality due to rounded grains, limited amount of grains that can be analyzed, or unrecognized zoning of the grains. These uncertainties provide exciting future pathways for thermochronological age dating, and future research on fold-and-thrust belts should strongly follow advances in thermochronological methods, as this may help reduce the uncertainties of proposed geological models.

An example for the successful combination of thermochronometry and structural geology is the newly emerging field of coupling thermochronological data with kinematic restorations. Sequential restoration of balanced cross sections is a powerful tool in structural geology, as it allows one to: (i) draw a reliable picture of the changing geometry of deforming geological structures through time; (ii) determine the original position and dip of the structures; (iii) calculate the amount of shortening; (iv) define timing of basin formation and evolution, and (v) extrapolate rates of tectonic processes, such as exhumation and erosion (Bulnes and McClay, 1999). Relying on pioneering works in contractional settings (Bally et al., 1966; Dahlstrom, 1969, 1970; Mitra and Namson, 1989), kinematic restoration of balanced cross sections has been applied progressively both in extensional and inverted basin areas (Coward, 1996; Bulnes and McClay, 1999). In the oil industry, this technique is routinely used to evaluate the position of source rocks and model hydrocarbon generation, expulsion and migration, as well as to analyze structural traps in terms of timing and geometry (Buchanan, 1996). However, this method alone can be inadequate in case syntectonic deposits are not present/well preserved (Almendral et al., 2015; Mora, 2015; Granado et al., 2016a). Coupling cross-section balancing and restoration with thermochronological constraints provides the possibility to define the various stages of deformation and to quantify both their extent and timing, in the lack of a syntectonic sedimentary record or in conjunction with it (Andreucci et al., 2013; Mora, 2015; Castelluccio et al., 2016; Chapman et al., 2017). However, the shift from a temperature (i.e. related to the movement of the sample through the isotherms) to a space domain (i.e. the depth of the sample during time) requires combining kinetic and thermochronological information within a coherent model capable of taking into account variations in the distribution of the isotherms in a dynamically active scenario. Another issue to take into account is the role of topographic evolution during time and the way in which it interacts with isothermal surfaces. In fact, wavelength of the relief, exhumation rate and heat advection strongly perturb the isotherm state (Stüwe et al., 1994; Mancktelow and Grasemann, 1997; Braun, 2002; Reiners and Brandon, 2006). Consequently, understanding better landscape evolution (Braun et al., 2012), drainage reorganization (Yanites et al., 2013), or rock erodibility (Moosdorf et al., 2018) is important for a correct interpretation of thermochronological data and consequently the tectonics of fold-and-thrust belts. In the last few years, successful results have been obtained with software dedicated to both inverse and forward modelling of thermochronometric data (Fillon and van der Beek, 2012; Almendral et al., 2015; Erdős et al., 2014b; Castelluccio et al., 2015; Ternois et al., 2019). Forward modelling uses thermochronometric ages calculated starting from kinematic restoration integrated with thermal parameters. The output is a model of low-temperature thermochronometric ages along a geological cross-section, which can be compared with measured apatite/zircon fission track and/or (U-Th-Sm)/He cooling ages on samples collected along the profile. The comparison with measured and modeled ages allows in turn improving the structural model through an iterative process.

1.4. Influence of salt and salt tectonics in fold-and-thrust belts

The critical taper theory states that the external geometry and internal deformation of fold-and-thrust belts is a function of the coefficient of friction of their basal décollement (Davis et al., 1983). This has been the basis for the current modern understanding of fold-and-thrust belts. The importance of layered evaporitic sequences -commonly referred to as *salt* for short- as preferential décollements in fold-and-thrust belts has also been recognized for a long time (Davis and Engelder, 1985). Salt is inherently weak, and contrary to most rocks whose strength increases as a function of depth, salt's strength depends on its viscosity and on the applied strain rate, meaning that at high strain rates salt will undergo brittle failure; at geological strain rates however, salt will flow (Jackson and Vendeville, 1994). For such differences in mechanical behaviour, the structural styles in salt-detached fold-and-thrust belts are markedly different to those contractional systems developed over frictional décollements (Smit et al., 2003; Granado et al., 2017). In this sense, the latter are constituted by thrust faults and related folds (Jamison, 1987) which tend to display a dominant forelandward vergence largely developed in footwall thrust sequences. In their simplest scenario, salt-detached fold-belts tend to show a regular spacing of narrow symmetric anticlines separated by broader *box-like* synclines; these anticlines are commonly detachment folds, or transported detachment folds, which wavelength is controlled by the thickness of the dominant mechanical unit (Mitra, 2002). Detachment folds are usually cored by salt and can reach several kilometers of structural relief; due to crestal erosion and/or faulting, salt can eventually extrude as diapiric structures (Santolaria et al., 2014). To attain such amplitudes, detachment anticlines need severe syn-orogenic sedimentation on their immediate synclines (Izquierdo-Llavall et al., 2018; Borderie et al., 2019). Salt-cored detachment folds commonly plunge gently towards their periclinal terminations; however steep plunges can also be attained in short distances compared to their lengths depending of the distribution of underlying salt. Thrusts and reverse faults in salt-detached systems display no preferred sense of transport given the low friction or even frictionless nature of saline décollements. For the same reason, salt-detached fold-and-thrust belts commonly display an extremely narrow cross-sectional taper when compared to those belts detached along frictional horizons, hence being comparatively wider, with deformation concentrated at the edges of the salt basin (Davis and Engelder, 1985; Jaumé and Lillie, 1988). Thrust salients are also typical features of salt-detached fold-and-thrust belts, being commonly related to the distribution of the underlying salt décollement and to lateral variations in décollement efficiency (Becker, 2000; Jackson et al., 2003; Muñoz et al., 2013).

Some of these well-established structural templates remain true and applicable, but only when a stratigraphy of uniform thickness (i.e. *layer-cake*) is involved. However, as most fold-and-thrust belts develop from the incorporation of rifts and passive margins basins in the shortening system, contrasting structural styles will develop depending on which parts of the basins are involved. In the case of rift to passive margins salt basins (Rowan, 2014; Granado et al., 2016b; Kukla et al., 2018), significant structural complexities differing from those templates described earlier can arise. For instance, many salt-detached and salt-influenced fold-and-thrust belts display structural styles which include: i) multiple structural orientations for folds and faults; ii) strong changes in fold plunges; iii) large panels of completely overturned stratigraphy (i.e. *flaps*); iv) mechanical contacts omitting or repeating stratigraphy; v) severely deformed evaporite bodies, or their equivalent salt welds, bounding structural units of markedly different sizes and aspect ratios, and contrasting stratigraphic thicknesses and facies (i.e. *non-layer cake* stratigraphy).

All these complex structural styles have been sometimes explained by invoking several deformation phases, strike-slip tectonics, or even the gravitational emplacement of thrust sheets. It has not been until recently that early salt tectonics processes inherited from the rift to passive margin stages have been taken into consideration. As salt is the weakest stratigraphic units involved in the developing fold-and-thrust belt, shortening would be first focused on those inflated salt structures, influencing the formation and orientation of structures immediately around them (Duffy et al., 2018; Snidero et al., 2019). Diapirs and salt walls can be squeezed depending on their orientation in respect to shortening, to eventually neck-off forming sub-vertical welds (i.e. secondary welds); with ongoing shortening, sub-vertical welds may become reactivated as thrusts, reverse or transpressive faults, also depending on their orientation with respect to the direction of shortening (Rowan and Vendeville, 2006; Duffy et al., 2018; Granado et al., 2018; Roma et al., 2018). Depocenters related to early salt structures such as rollovers will become inverted, and along with minibasins if present, will be incorporated and transported along the weak basal décollement, imbricated by later thrusts, and undergo rotations along vertical and/or horizontal axes (López-Mir et al., 2014; Saura et al., 2016; Granado et al., 2018; Snidero et al., 2019). All these processes will be strongly influenced by syn-orogenic erosion and sedimentation (Izquierdo-Llavall et al., 2018).

To summarize, the structural styles of contractional salt-detached and salt-influenced fold-and-thrust belts are largely dependent on the relative thickness of salt and its overburden, the lateral distribution of salt previous to shortening, and whether early salt structures and related depocentres are present (Hudec and Jackson, 2007).

1.5. Fracture analysis and paleostress/paleopressure reconstruction in fold-and-thrust belts

The reconstruction of the past kinematic and tectonic history in fold-and thrust belts requires constraints on the evolution through space and time of both stress and strain which affected sedimentary (and basement) rocks. Fractures are the most common response of brittlely deformed rocks submitted to tectonic stresses and are therefore classical and reliable palaeostress indicators (Lacombe et al., 2011). In addition, in carbonate rocks of low matrix permeability, the characteristics of the fracture network play a fundamental role in hydrocarbon migration and reservoir quality (Casini et al., 2011). A good understanding of the mechanical and chronological development of the meso-scale fracture network is therefore key for tectonic analysis as well as natural resources exploration and waste repositories studies.

A recent step forward in the understanding of fracture occurrence in fold-and-thrust belts is related to the recognition, in addition to fold-related meso-structures, of the widespread occurrence of pre-folding fracture sets. These fracture sets may have originated from far-field earlier tectonic events unrelated to the phase of thrusting and folding or from foreland flexuring and along-foredeep stretching (Tavani et al., 2015) and even from differential compaction controlled by deep-seated faulting before the foreland domain has become part of the fold-and-thrust belt (Tavani et al., 2018). This points towards the need to carefully consider pre-existing fractures, possibly unrelated to folding, to build realistic conceptual fold–fracture models. Moreover, a blind spot for most fracture analyses has been for long the lack of constraints on the absolute timing of fracture development. This absolute timing is never resolved through field-based geometrical relationships, so the relevance and meaning of some fracture sets with respect to regional deformation can be disputable, especially in regions that underwent polyphase tectonics. Recent developments in absolute dating of calcite cements of veins within folds using the U/Pb technique (Parrish et al., 2018; Hansman et al., 2018; Beaudoin et al., 2018) have brought the proof of the time relevance of meso-scale structures to regional fold-and-thrust structures, hence have helped refine the tectonic history.

Providing constraints on paleostress orientations and magnitudes and how they evolved during geological history is a challenging but important task that can lead to major breakthrough in the appraisal of long-term mechanical and paleohydrological behaviour of the upper crust. Improvement and application of new paleopiezometric techniques (e.g., calcite twinning and stylolite roughness paleopiezometry) calibrated in the diagenetic conditions of pressure and temperature have recently helped refine the tectonic and paleostress history in the Apennine fold-and-thrust belt (Beaudoin et al., 2016). Stress quantification provides insights into the burial history independently of any assumption on the past geothermal gradient, the overall long-term mechanical behaviour of the crust, the degree of coupling between the cover and the basement and the way orogenic stresses are transmitted from the plate boundary to the (far) foreland (Beaudoin and Lacombe, 2018).

Last but not least, reconstruction of fluid (over)pressure and its evolution in fold-and-thrust belts and sedimentary basins is of prime interest for both academy (e.g., fault reactivation) and industry (hydrocarbon generation and migration). The use of hydrocarbon-bearing fluid inclusions, when developing contemporaneously with aqueous inclusions, provides a direct access to the pore-fluid temperature and pressure of cemented fractures or host rocks at the time of cementation and hydrocarbon trapping, in line with the tectonic evolution (Roure et al., 2010). Alternatively, the combination of the calcite twinning paleopiezometer with fracture analysis and rock mechanics tests has led to pioneering reconstructions of fluid (over)pressure evolution during the different stages of foreland shortening (e.g., Sevier-Laramide foreland, Amrouch et al., 2011; Beaudoin et al., 2014).

2. Content of the special issue

This special issue of Tectonophysics, sponsored by the International Lithosphere Program, presents a new collection of 27 papers dealing with different aspects of fold-and-thrust belts and foreland basins evolution, such as structural geology, geomorphology, exhumation, sediment transport, dating, seismicity, surface processes and basin dynamics during pre-and *syn*-collision stages, analogue or numerical modelling approaches, in addition to regional case studies. Some of these contributions were presented as part of a session devoted to this topic at the 2018 European Geosciences Union General Assembly in Vienna (Austria). The aim of this session was to assemble a broad group of Earth scientists interested in fold-and-thrust belts and peripheral basins spanning a broad array of tectonic settings, geographical locations, and geological times. This volume presents a collection of some of the diverse research that is being carried out on this topic. We believe that these studies contribute to a better understanding not only of fold-and-thrust belts in particular, but also of orogenic processes and of the rheology of the continental lithosphere in general, and that this volume will help promote new contacts between interdisciplinary earth scientists.

2.1. Structural inheritance and inversion tectonics in fold-and-thrust belts

The role of inherited structures for the geometry of later tectonic events has been recognized since a long time. However, a dynamic understanding of the role of inherited structures on fold-thrust belt geometries is often lacking. Granado and Ruh (2019) address this research gap by modelling the role of inversion of a half-graben during shortening using finite differences. In their experiments they test how the strength of the inherited fault as well as different fluid pressure in the *syn*-rift sediments and strength of the upper décollement are reflected in the structural style of foreland fold-and-thrust belts. A straight forward result is that a weak inherited fault will be easily reactivated, influencing the kinematics and consequently structural style. Weak syn-rift sediments favor hanging-wall bypass thrusting. Generally the strength ratio of upper and lower décollement is key to understanding fold-and-thrust belts. The results of numerical models can be applied to natural examples. The authors selected the Helvetic nappes of the European Alps, and the Malargüe fold-thrust belt and the Salta Rift System, both in the Argentinian Andes as case studies for their models. They can show a first order geometric comparison of nature and experiments, indicating a quantitative comparison of the rheologies used in the model with paleo-rheologies in nature is possible.

Espurt et al., (2019a) combined field geological, structural, paleotemperature and sub-surface data together with deep geophysical data to build a new 210 km-long crustal scale balanced cross-section across the Central Pyrenean belt. Along the section, the belt corresponds to the inversion of the Mesozoic Pyrenean Rift system, which consisted in a hyper-extended relay zone of two metamorphic zones with exhumation of continental lithospheric mantle. Comparison between present-day crustal geometry and sequentially retro-deformed stages (lower Santonian, upper Jurassic and lower-middle Triassic) of this section shows that the Pyrenees were superimposed onto a complex structural template affected by the Variscan orogeny and subsequent Permian rifting, that in turn controlled subsequently the geometry of the Mesozoic rifting and the building of the upper Cretaceous-lower Miocene Pyrenean orogen. This study puts emphasis on the long-term influence of inherited tectonic crustal fabric in the evolution of orogens.

Using a kinematic forward lithosphere deformation model (RIFTER), Gómez-Romeu et al. (2019) produce flexural isostatically compensated, balanced geological sections across the Western Pyrenees. The tectonic evolution of both the original rift and the subsequent orogeny are investigated in order to obtain new insights into the role of extensional structural inheritance in the development of collisional orogens. The proposed model shows how, following an extensional stage characterized by a hyper-extended rift system that also led to mantle exhumation, Pyrenean shortening included two main stages. A pre-collisional stage produced inversion of the hyper-extended rift system, whereas a *syn*-collisional stage involved the southern proximal rift domain, resulting in the formation of the Axial Zone and the Iberian pro-foreland.

Munteanu et al. (2019) present results from state-of-the art lithospheric scale analogue modelling of compressional systems. Based on a systematic series of analogue models the authors investigate the structural imprint of local crustal weaknesses on the deformation front in contractional settings. The model setup features brittle (granular) and viscous (fluid) multilayers similar to a continental lithosphere. Because the models rest on a dense low viscosity fluid (similar to the asthenosphere) they are isostatically balanced and applied lateral forces are transmitted throughout the model domain. In the model, the crustal weaknesses are effectively localizing early stage deformation. Depending on the size, shape, number and location of the weakness zones either laterally continuous but bent structures evolve nucleating at the weak spots and growing laterally into stronger lithosphere or discontinuities (transfer zones) form separating strong and weak lithospheric domains. This study highlights that crustal weaknesses inherited for example from an earlier rifting phase needs to be considered as a source of along-strike irregularity of orogenic structures.

Martins-Ferreira (2019) integrates seismic interpretation (calibrated by well logs) and field data to investigate the relationships between fault reactivation and thrusting in the cratonic region of central Brazil. The study area is located between the opposed-verging Brasília and Araçuaí Neoproterozoic belts, which formed during the initial stages of West Gondwana amalgamation. Seismic interpretation suggests a tight relationship between shallow folds and thrusts and rift inversion. Reverse-slip reactivation of inherited normal faults exerts a clear control on thrust ramp nucleation. Widespread thrusting occurs over buried rifts characterized by multiple inverted faults, whereas sedimentary successions overlying non-rifted basement are not significantly affected by thrusting and folding. Furthermore, the development of salients and recesses characterizing the Brasiliano-Pan Africano orogen appears to be controlled by the morphology of buried rifts.

Tavani et al. (2018) analyzed meso-scale fractures and faults exposed in the Triassic to Miocene sedimentary succession of the Lurestan region (Zagros Belt). The authors document development of syn-sedimentary extensional fractures formed during Early Jurassic rifting then in response to foreland flexuring and along-foredeep stretching during Late Cretaceous-Eocene and late Miocene-Pliocene pulses of convergence. These repeated extensional episodes produced oblique-slip reactivation of inherited basement structures, above which differential compaction and subsidence prevailed during tectonically quiescent periods. The fractures related to differential compaction add to the complexity of the 'tectonic' pattern formed during true tectonic (extensional and compressional) pulses, leading to a complex articulated fracture network. This study emphasizes how meso-scale structures may be relevant to regional-scale tectonics and highlights the role of tectonic inheritance in fold-and-thrust belts at all scales.

2.2. Deformation of basement rocks in fold-and-thrust belts

The paper by Searle et al. (2019) provides a review of the geology of the Caledonian Moine Thrust zone in the Loch Eriboll region, NW Scotland. In addition to already published maps, the authors use new maps, balanced and restored cross sections from fieldwork at Loch Eriboll together with a cross-section from the Moine thrust hinterland to infer geological processes including sequence of thrusting, shortening estimates and regional tectonic implications for this famous fold-and-thrust belt in the NW Scottish Highlands. The authors suggest in a rather provocative way that two major crustal-scale thrusts that extend down into the upper mantle imaged on seismic profiles across the foreland, the Outer Isles and Flannan thrusts, are unrelated spatially or temporally to the Moine thrust sequence and speculate on the regional significance of these thrusts. Finally, the authors reflect on the metamorphic sequence overlying the Moine Thrust and draw parallels to Himalayan style orogenesis.

Bellahsen et al. (2019) use the case study of the Bielsa basement unit in the Axial Zone of the Pyrenees to provide new insights into the modes and style of upper crustal shortening in orogens. In the study area, distributed strain associated with widespread, minor shear zones appears to predate strain localization along major crustal ramps (as constrained by zircon fission-track data). The authors suggest that chemical weakening – in the form of feldspar sericitization – exerts a major control on basement rheology during the early stage of distributed shortening. Sericitization is widespread, and occurs not only in ultramylonites, ultra-cataclasites and phyllonites, but also in un-deformed granodiorites. Based on these observations, the authors propose that the strength of the upper crust was very low at the onset of shortening, due to a high thermal gradient and fluid circulation that induced large-scale sericitization in greenschist facies conditions.

2.3. Geomorphic signatures of tectonics and surface processes in fold-and-thrust belts

Obaid and Allen (2019) focus on the Zagros fold-thrust belt, which forms one of the best-exposed examples of and active fold-thrust belts in the world. Therefore, it is perfectly suited to investigate the role of climate on landscape evolution in an actively deforming system. The authors use geomorphic indices such as normalized channel steepness index or integrated relief and hypsometric index to test how geomorphology is a sensitive indicator of tectonic processes. The geomorphic indices show differences between different regions, correlating with climatic differences. A possible interpretation is that wetter conditions retard plateau growth, whereas dry climate allows for plateau growth, as the river draining the area have lower stream power (which is partly also a function of rock erodibility). This does not imply that climate drives landscape evolution. Instead, a positive feedback exists, where tectonics forms topographic barriers that control precipitation. Despite local differences, there is topographic similarity along five relatively evenly distributed swath profiles across the Zagros. Similar strain rates or similar overall shortening may explain this topographic similarity across the belt.

Sanchez Nassif et al. (2019) combine forward modelling and structural reconstruction to link tectonic steps to erosion rates from the Argentinian Precordillera Jachal section. Their workflow successfully articulates at each time steps forward kinematic modelling and alpha calculation following the Coulomb wedge analysis to deduce the cumulative erosion budget. Their methodology allows to obtain the sequence of deformation as well as the associated erosion rates on the basis of geological field evidences such as tectonic features and preserved sedimentary structures, without any additional t-T data. Applied to the example of the Jachal section, the authors validate their analysis with the comparison to the published section and thermochronological data, showing a two-stepped evolution of the erosion rates (1 and 1.3 km/Myr) associated to the activity of the Niquivil fault.

2.4. Active tectonics and seismicity in fold-and-thrust belts

The Hengchun Peninsula at the southern tip of Taiwan is of global importance, as it is one of the few locations in the world where an accretionary prism is exposed on land. Furthermore, the area is seismically very active and constraining the geometries of the structures is important for geohazard assessment. Deffontaines et al. (2019) address this using a new high-resolution digital terrain model and SAR images. The authors conclude that the peninsula consists of two ramp structures at depth, and that the Hengchun Fault, interpreted as the major tectonic lineament of the peninsula, extends towards the offshore. This study stimulates the debate on the geometry of the structures of the Hengchun Peninsula and in other systems, showing the high uncertainties at depth despite extensive data coverage. The study particularly highlights the need for further research, as a nuclear power plant is located close to the Hengchun Fault.

Mescua et al. (2019) integrate field and wellbore data to discuss the stress field in the frontal sector of the Malargüe fold-and-thrust belt (Andes of Argentina). Surface observations indicate N-S thrusts and active NW to WNW and ESE strike-slip faults in the study area. Inversion of fault kinematic indicators, combined with borehole breakout data and a mini-frac test, constrain the Quaternary to recent stress state, which is characterized by a subhorizontal, E-W oriented maximum principal stress, and by intermediate and minimum stresses with similar magnitudes that are locally interchanged, producing a setting in which reverse and strike-slip faults are alternatively active. The implications of the recognized structures for earthquake hazard are examined.

Rivas et al. (2019) analyzed seismic activity in the Precordillera in the Andean backarc region of Argentina where a long record of large and damaging earthquakes in the last century exists. In the northern part, which is poorly known either seismically or in terms of style of deformation, the authors determine seismic locations, seismic moments, moment magnitudes, focal depths and focal mechanisms for local earthquakes over the periods 2000–2002 and 2007–2010. Overall the results agree with the E-W compression and shortening in the Andean northern Precordilleran backarc region. The results further provide new constraints on the patterns of earthquake distribution and on the Andean backarc crustal deformation.

2.5. Exhumation and sediment routing in fold-and-thrust belts

Odlum et al. (2019) investigate the geological history of the South-Eastern Pyrenees, from the *syn*-rift period to the syn-orogenic period. With the combination of several detrital proxies such as U/Pb and (U—Th)/He on Zircons as well as U/Pb on rutiles and with an extensive mapping of the bedrock ages dated with the same techniques, the authors retrace the source of the sediments deposited from early Cretaceous to Oligocene times. By doing so, they provide a geological scenario of hinterland exhumation, foreland basin evolution, and sediment routing system of the south Eastern Pyrenees.

Buford Parks and McQuarrie (2019) present a study on the Central Andes highlighting the importance of thermal, flexural, and kinematic models for understanding the evolution of fold-and-thrust belts and orogens. The authors present a compilation of thermochronological data and use them as independent tests for different structural models. The authors show that with this method it is possible to gain insights on the sequence and rates of deformation and the plausibility of different geometric models can be tested. Coupling with flexural models shows that an additional geodynamic driver for uplift may be present, such as mantle delamination, isostatic attainment, or lower crustal flow. Apart from insights on the geologic evolution of the Central Andes, this contribution provides a tool for assessing kinematic models in fold-and-thrust belts in general.

Based on the integration of field geology, seismic interpretation, apatite fission track and (U—Th)/He (AHe) dating, as well analogue modelling, Chang et al. (2019) investigate the tectonic evolution of the

Kalpin fold-and-thrust belt. As this mountain belt accommodates crustal shortening between the Tianshan and the Tarim Basin, unravelling its architecture, modes and timing of development may significantly improve our understanding of the tectonic evolution of central Asia. The timing of thrusting, constrained by low-temperature thermochronometry, implies a southward propagation of Cenozoic deformation. Combined inverse and forward thermal modelling is used to obtain information on the cooling and deformation of specific thrust sheets, while sandbox models are used to simulate and confirm the thrust sequence. The results are effectively used to provide new insights into the timing of deformation at the northern margin of the Tarim Basin.

2.6. Salt processes in fold-and-thrust belts

Based on a new regional balanced cross section, Espurt et al., (2019b) present and discuss a new interpretation of the Provence fold-and-thrust belt. The system is described as a Mesozoic halokinetic salt province above a basement with strong structural inheritance, which has been subsequently shortened during the Pyrenean and Alpine orogenies. They analyzed the geometry and timing of deformation and provide estimates of the amount of pre-orogenic contraction. This paper highlights the major role of halokinetic processes and shows that a significant amount of folding in fold-thrust belts can result from an early halokinetic fold system developed during the pre-contractional passive margin evolution.

On the basis of field data, Snidero et al. (2019) describe and interpret the stratigraphic and structural relationships between the Hormuz salt and its overburden around the Darmadan anticline in the eastern Fars region of the Zagros fold-and-thrust belt (Iran). Their model describes for the first time Late Jurassic-Early Cretaceous halokinetic sequences indicative of passive diapirism, followed by early squeezing and tilting of the diapir's flanks during the Campanian-Maastrichtian. They furthermore show that second order structural features indicate secondary welding during upper Miocene times. Their work supports that the present structural trends of the Zagros fold-and-thrust belt in the eastern Fars region are the result of the reactivation of pre-existing salt structures.

2.7. Case studies

2.7.1. Andean fold-and-thrust belts and basins

Barrionuevo et al. (2019) report on the structural kinematics of the Malargüe fold-and-thrust belt, and the control imposed by the local stress field on magmatic and hydrocarbon fluid migration. They propose that the structural framework controlling the magmatic activity corresponds to inverted Mesozoic normal faults and Cenozoic thrusts, with oblique structures showing strike-slip kinematics. Miocene dykes and sills were emplaced in relation to strike-slip and reverse faults, respectively. Structural analysis suggests local switches from compressional to strike-slip/compressional likely related to the similar values of the minimum ($\sigma3$) and intermediate ($\sigma2$) principal stress with an E-W oriented maximum principal stress ($\sigma1$), favouring the emplacement of igneous intrusions and hydrocarbon migration through both thrusts and sub-vertical strike-slip faults.

Ronda et al. (2019) present a series of balanced and sequentially restored geological sections across a segment of the Southern Patagonian Andes between 46 and 48°S. Opening of the Austral-Magallanes basin and the Rocas Verdes back-arc oceanic basin as a result of Jurassic extension were followed by Cretaceous to Cenozoic shortening. A regional westward-dipping listric detachment, interpreted as formed during Jurassic extension, was reactivated during Andean shortening as the main thrust detachment for the basement structures and the fold and thrust belt. Based on the occurrence of angular unconformities and growth strata, three main shortening stages have been recognized by the authors: (i) an early (Late Cretaceous) stage associated with positive inversion and closure of the northernmost Rocas Verdes basin; (ii) a Miocene stage (between 18 Ma and 10 Ma), which produced most of the shortening; and (iii) a late (younger than 7 Ma) stage involving out-of-sequence thrusting in interior of the belt, possibly associated with the onset of glaciations and glacial erosion.

2.7.2. Peri-Mediterranean fold-and-thrust belts and basins

Masrouhi et al. (2019) provide an extensive tectono-sedimentary study of the Southern Atlas front in Tunisia. By a combination of field observations, well correlation and seismic profiles interpretation, they propose a series of restored cross-sections across the particular area of the Chott basin. The authors conclude on a mixed thick- and thin-skinned structural style with an efficient décollement level defined by the Triassic evaporites. From their reconstruction, they also find a decreasing amount of shortening from West to East, of a relatively small amount (from 7% to 1%) that is explained by the inversion pattern. Masroushi et al. documents that this area, and the Chott basin in particular, is a large Mesozoic roll-over structure that was reactivated during Alpine orogeny.

In their paper, Khomsi et al. (2019) provide a review of the known structural architecture of the Atlas and Tell fold-and-thrust belts. Whereas the major tectonic steps accounting for the development of the eastern Maghreb structures are rather well constrained by seismic data and structural analyses, the overall configuration at depth, as well as the deep architecture of the underlying basement remain poorly understood because only few wells yet penetrated deeper than the Triassic series in the Atlas and adjacent foreland basin. The paper is intended at giving an overview on the deep structural features affecting the Pan-African basement in the eastern Maghreb by means of tentative regional cross-sections, in order to stimulate exploration of deep hydrocarbon plays with particular focus on the pre-Triassic series.

Based on seismic profiles and field observations, Balestra et al. (2019) propose a 3D numerical model of the Apennine-Maghrebian chain in the Mt. Kumeta and Mt. Rocca Busambra in Sicily. Their model builds up on cross-section restoration based on interpreted seismic profiles. They are incorporated to the 3D geomechanical model to provide a full and comprehensive view of the studied area, especially useful when seismic data is of poor quality. By applying that technique, the authors revisit the geological cross-sections by testing two-end member scenarios with a one- or two-stepped structural sequence. They find that the along-strike variation in structural style observed in the Trapanese unit is controlled by structural inheritance rather than by a polyphase history.

Vitale et al. (2019) present a review on the stratigraphy, petrology, deformation and metamorphism of the oceanic, sedimentary, magmatic and metamorphic successions from northern Calabria to the Campania region of southern Italy (i.e., the Southern Ligurian Domain). These rock units underwent subduction (Eocene) to be subsequently exhumed and exposed (Tortonian). Deep-basin successions in the easternmost sector (close to the continental margin of Adria) were obducted and frontally accreted (Aquitanian-Burdigalian). The tectonic transport for the obducted successions was dominantly to SE, however new data provides a mean eastward-directed transport during tectonic exhumation. Petro-chemical comparison between the Southern Ligurian Domain mafic rocks with the corresponding rocks in the Alps, Corsica and northern Apennines suggests an ocean continental transition setting for the Ligurian Domain. Early orogenic stages of the southern Apennines-northern Calabria system were characterized by a complex kinematic evolution of the subduction system, including the migration of the basal and roof decollements within the subduction channel.

Oliva-Urcia et al. (2019) present a new magnetostratigraphic section from the Southern Pyrenees to date the Oligocene-Miocene Pyrenean succession. They detail a 5-km section of continental *syn*-tectonic sediments and link their magneto-stratigraphy results to the activity of the Gavarnie and Guargua thrust sheets, active from 31 to 24 and from 24 to 21 Ma, respectively. They also refine the dating on the latest deformation phase, of ~5 Myr younger than previously published and the dating the Upper Riglos thrust system at 21 Ma. Finally, they also derive the sediment accumulation rates through time that they correlate to first- and second order tectonic activities, as well as to the signal of Ebro basin closure at 36 Ma.

2.7.3. Fold-and-thrust belts and basins of eastern Europe

Tomek et al. (2019) investigate the tectonics of the northeastern Variscan belt, in particular the tectonic history of the Moravosilesian Culm Basin. Using structural, paleomagnetic and magnetic anisotropy data, the authors argue that the basin underwent a change in deformation history from early compression to late strike-slip dominated tectonics. Such a switch in kinematics is important, as it provides the opportunity to test how earlier structures are influencing later deformation phases. Similarly, this study shows that from studying foreland fold-thrust belts at the regional scale, inferences can be drawn for the entire orogen and its plate tectonic context. The authors conclude that, as opposed to some previous studies, the strike-slip deformation did not play a major role during continent-continent collision in the area.

In order to analyze the timing of late-stage Neo-Tethys subduction and subsequent continent-continent collision in central Turkey, Gülyüz et al. (2019) integrate field mapping, low-temperature thermochronometry and structural analyses – including inversion of fault slip data – on the Upper Cretaceous to Eocene infill of the Haymana basin. The results of paleostress analysis point out that this basin, located at the junction between the Izmir-Ankara-Erzincan and the Intra-Tauride suture zones, underwent initial N—S to NNE-SSW extension until the middle Paleocene, followed by N—S synsedimentary shortening and coeval E-W directed extension (possibly reaching the middle Miocene). Apatite (U—Th)/He cooling ages indicate that exhumation of the southeast portion of the basin started in the early Oligocene, while the northwest part was exhumed during the early Miocene. The differential uplift and unroofing of the basin fill is tentatively related to the progressive NW-ward activation of a major fault bounding the basin to the north, within the framework of the evolution of the whole basin from an extensional forearc depocentre (Late Cretaceous to early Paleocene) to a foreland basin during the subsequent collision between Taurides and Pontides.

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