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PREFACE

Introduction: tectonic evolution and mechanics of basement-involved fold-and-thrust belts

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Defining the structural style of fold-and-thrust belts is an important step for understanding the factors that control their long- and short-term dynamics, for comprehending seismic hazard associated with them, and for assessing their economic potential. While the thin-skinned model (no basement involvement) has long been the driving methodology for cross section construction and restoration of foreland fold-and-thrust belts, a wealth of new geological and geophysical studies have shown that they are often thick-skinned, that is, basement-involved.

Before proceeding, it is appropriate to first define what is meant by the term "basement", since it has a wide range of definitions in the literature. In general terms, basement is often defined as; 1) any deformed (often crystalline) rock that underlies a specific stratigraphic sequence, 2) any rock (metamorphic or igneous) that is below the rocks of economic interest, or 3) having distinct seismic reflectivity patterns or physical properties. Not infrequently, all three of these definitions are applied to fold-and-thrust belts by different authors, leading to disparate interpretations of the role and/or degree of basement involvement.

In basement-involved fold-and-thrust belts, shortening involves a significant part of the crust above a deep ductile detachment and may even be distributed throughout the whole crust. Depending on the thickness of basement/crust which is involved in the deformation, some authors additionally distinguish basement-involved thin-skinned and thick-skinned tectonic styles. Whether this distinction should be made or not, a major difference between thin-skinned and thick-skinned end-member models is that the amount of shortening is more often less in a thick-skinned fold-and-thrust belt, especially if reactivation and inversion of extensional faults takes place.

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Indeed, one of the key processes by which basement becomes involved 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. For example, basement fault reactivation may induce localization of thrusts and folds, result in the incorporation of crystalline thrust sheets into the fold-and-thrust belt, cause out-of-sequence thrusting and folding of shallow thrust sheets, and lead to the development of accommodation structures such as lateral ramps.

In some cases, however, extensional faults may not exist in the basement, or may not get reactivated despite being suitably oriented. In fact, reactivation of extensional faults is a highly selective process that depends not only on the orientation of the faults with respect to the applied stress field and on the friction along the fault planes, but also on the contrast of strength between the inherited fault zones and the surrounding crustal rocks. This points toward the importance of rheology : not only is the rheology of a structurally homogenous crust markedly different from that of a crust in which pre-existing fault zones are suitably oriented for reactivation, but even in a pre-fractured crust, brittle thickness and strength are strongly dependent on the nature of the geotherm. More generally, basement involvement in shortening requires/reflects an overall specific thermo-mechanical behavior of the lithosphere, e.g, a young thermo-tectonic age, so the lithosphere is generally rather hot, hence mechanically weak.

Basement-involvement in fold-and-thrust belts also raises the questions of the way the orogen is mechanically coupled to the foreland and how far-field orogenic stresses are transmitted into the foreland through the crust and mantle lithosphere. These questions hold not only for common fold-and-thrust belts that developed on the lower plate, but also for those fold-and-thrust belts that formed within the upper plate. In both cases, far-field stresses have been shown to extend well far into the plate, more than 1000 km inboard from the active margin. The Appalachians, the active Sierras Pampeanas, and the Laramide uplifts are examples of this. In the case of the latter two famous examples, that illustrate basement-involved deformation in the retro-foreland, even more specific boundary conditions appear to be necessary to transfer stresses far into the upper plate, like those encountered in flat-slab subduction setting that is often associated to high shear stresses along the subduction interface.

This special issue of *Geological Magazine* presents a collection of 18 papers dealing with different aspects of basement-involved fold-and-thrust belts. Some of these contributions were presented as part of a session devoted to the tectonic evolution and mechanics of basement-involved fold-thrust belts at the 2015 European Geosciences Union General Assembly in Vienna (Austria). The aim of this session was to assemble a broad group of Earth scientists interested in the thick-skinned style of deformation in fold-and-thrust belts 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 currently 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.

The table of content of the Special Issue covers a large range of contributions, including general considerations on the involvement of the basement in shortening in fold-and-thrust belts, analogue and numerical modelling of basement-involved fold-and-thrust belts, fractures in basement-cored anticlines, as well as a number of regional studies, with papers dealing with well-known fold-and-thrust-belts such as the Andes, the Alps, the Carpathians, the Zagros, the Alborz, the Caledonides, China and Taiwan.

* General

Lacombe and Bellahsen provide a review of the state of knowledge on basement-involved shortening in foreland fold-and-thrust belts on the basis of the examination of selected Cenozoic orogens. After describing how structural interpretations of fold-and-thrust belts have evolved through time, the authors address how and the extent to which basement tectonics influence their geometry and their kinematics, and emphasize the key control exerted by lithosphere rheology, including structural and thermal inheritance, and by local/regional boundary conditions on the occurrence of thick-skinned tectonics in the outer parts of orogens.

* Analogue and numerical modelling approaches of basement-involved fold-and-thrust belts

Lafosse et al. present a series of thermo-mechanical numerical models to evaluate the role of burial in the inhibition of the reactivation of pre-existing extensional faults during inversion processes. They compare their modeling results to the style of inversion of inherited half-grabens in the external Western Alps. They show that the role of the temperature, especially through tectonic burial, is critical for the inversion of extensional faults inherited from former rifts or passive margin in mountain belts. ***Koyi et al.*** investigate the effect of strike-slip faulting in the basement on the structural evolution of overlying evolving fold-and-thrust belts. Analogue modelling results show that observed deformation within the cover sequence depends on the temporal relation between basement and cover sequence deformation. They furthermore provide a detailed comparison to the Zagros and Alborz Mountains, where basement block rotations have been suggested to affect the structural evolution of the mountain belts. ***Burberry and Palu*** demonstrate a series of analogue experiments to illustrate the reactivation potential of pre-existing deep-seated structures during compression. Additionally, they studied the effect of coupling/decoupling between cover and lower section on the structural evolution of fold-and-thrust belts. Comparison to the southern Sawtooth Range, Montana, leads to predictions of underlying active inherited faults. ***Yu and Koyi*** conduct analogue experiments in order to reconstruct the evolution of the Bohai Bay Basin, China. They argue that previous kinematic explanations do not fully support natural observations and propose a two-stage tectonic model, from extension to rotation, to explain the Cenozoic structural evolution and complexities.

* Fractures in basement-cored anticlines

Laubach et al. report an analysis of fractures in the Cretaceous Frontier Formation sandstones in the basement-involved (Laramide) Table Rock anticline, Wyoming. They study fracture-hosted porosity and quartz distribution along with crack-seal texture and fluid inclusion assemblage sequences in isolated, bridging quartz deposits and show that open fractures can persist through protracted burial and uplift in foreland basins. Fractures oriented at a high angle to current maximum compressive stress remain open and are weak mechanical discontinuities for millions of years even at great depth.

* Regional case studies (1): Andes

In their first paper, ***Branellec et al.*** performed a structural study of the basement-involved Malargue fold-and-thrust-belt, focusing on the relationships between basement and cover deformation with respect to paleogeography and structural inheritance. They propose a new cross-section along the Rio Grande valley together with a kinematic scenario of deformation propagation. In their second paper, ***Branellec et al.*** use satellite imagery and field observations to investigate two active faults located on the eastern border of the San Rafael Block (Argentina) close

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to, or within the epicentral area of the Villa Atuel destructive earthquake that occurred in the San Rafael area on May, 30th 1929. Geological and morphological observations reveal a late Pleistocene activity and show that the southern Mendoza Province is still undergoing shortening. ***Mescua et al.*** focus on a segment of the Andean foreland fold-and-thrust belt between 30º and 36º S, where they propose that the composition of the basement and the geometry of extensional basins, features inherited from the Precambrian to Early Mesozoic geologic history of the western Gondwana/South American margin, controlled Andean upper-crustal deformation and determined the development of thick- and thin-skinned belts and shortening localization. ***Martino et al.*** conduct a structural study in the Sierras Pampeanas of Córdoba (Argentina) and propose that oblique lineaments probably correlated with the pan-Gondwanan trend and which deeply affect the crust down to the Moho controlled, together with Paleozoic ductile shear zones, nucleation and development of Tertiary brittle faulting. They also show that while in Sierras Pampeanas it has been traditionally considered that high-angle reverse faults limit mountain range blocks, in some places low angle reverse faults (thrusts) may have also produced block uplifts. ***Bellahsen et al.*** report surficial structural data along the eastern side of the Sierra de Pie de Palo (Sierras Pampeanas) in the Andes of Argentina. They propose that at the Sierra scale, the current rounded shape of the Andean structure is the result of Plio-Quaternary amplification of a pre-Andean inherited antiform which is related to an East-verging fault-propagation fold instead of a West-verging fault-bend fold. They further propose a model of deformation of mica-rich foliated basement rocks at shallow depth where foliation-parallel slip can act as the main folding mechanism. ***Perez et al.*** propose a balanced cross-section across the Eastern Cordillera and Subandean Zone of southern Peru and provide constraints on Cenozoic Andean shortening accommodated by thick- and thin-skinned retroarc fold-and-thrust belts. They further propose that earliest Andean deformation and structural compartmentalization of the Eastern Cordillera was linked to selective inversion of inherited Permo-Triassic basement-involved normal faults that guided subsequent thick- and thin-skinned deformation. Low temperature thermochronology data supports Eocene to late Miocene exhumation, likely driven by normal fault reactivation and protracted Eastern Cordillera deformation. ***Japas et al.*** integrate new and available structural, kinematic, geophysical and paleomagnetic data from the Neogene Sierra de los Colorados, Argentina, to investigate the effect of basement-involvement in the Pampean flat-slab segment of the southern Central Andes. They detected three different kinematic populations documented in the Neogene sedimentary sequence, shifting from a thin-skinned towards a thick-skinned mode of deformation. The initiation of basement-involved deformation is interpreted to be related to local magma-induced mechanical weakening and/or strong interplate coupling as a result of flat-slab subduction. ***Fuentes et al.*** provide new insight into the structural and tectonic evolution of the Malargüe fold-and-thrust belt located in the Andes of Argentina. With new data of the synorogenic foreland basin fill combined with structural cross sections and surface maps, they constrain the temporal and geometric linkage between basement faults and the overlying thin-skinned thrust belt. Furthermore, they offer fresh input leading towards understanding related hydrocarbon systems in the area.

*** Regional case studies (2): Alps and alpine-type belts**

Pfiffner reports thin-skinned, thin-skinned basement-involved and thick-skinned styles of deformation in the Alps. He shows that thin-skinned tectonics associated with evaporite detachment occurred early during orogenesis, followed by basement-involved thin-skinned tectonics in the Penninic nappe system due to originally thinned continental crust that was heated and subducted to great depths. The earlier formed thrusts were subsequently intricately folded. Thick-skinned tectonics involving the entire upper crust took place in the latest collision phase in the Helvetic- Dauphinois nappe system, possibly related to a deep crustal detachment controlled by the breakdown of feldspar and formation of phyllonites. ***Granado et al.*** provide evidence from reflection seismic datasets, cross section construction and calculated fault displacement profiles that are integrated with gravity data, recent and historic earthquakes, lithospheric rheology, and thermochronological studies to look at involvement of crystalline basement by basement fault reactivation (in extension and shortening modes) beneath and ahead of the external parts of Alpine-Carpathian thin-skinned fold-and-thrust belt.

*** Regional case studies (3): Caledonides and Taiwan**

Rice and Anderson examine three models for restoring basement rocks coring tectonic windows in the Scandinavian Caledonides using balanced cross-sections and branch-line restorations of four transects.Despite along-strike variability in the geology of the four transects, they suggest that the basement in these transects is allochthonous. ***Yang et al.*** present the pre-orogenic fault architecture of the Eurasian margin and then investigate how selected faults become reactivated by far-field stress to the west of the deformation front of the Taiwan orogen, or become reactivated as strike-slip faults or thrusts within the foreland fold-and-thrust belt. They go on to briefly discuss the possible mechanical conditions for reactivation of faults that are oriented at a high angle to the convergence and the implications of this for the recent tectonics of Taiwan.

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