

# **How Plate-forming Processes Explain Structure and Shortening in Fold-thrust Belts\***

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## **Introduction**

Fold-thrust belts (FTBs) are archetypical tectonic features adjacent to collisional orogens, where structural traps account for 14% of discovered oil reserves. After decades of field and seismic surveys, detailed geological interpretations have emphasized their high degree of structural complexity. This has dampened academic research interest and impetus towards the understanding of larger scale geodynamic processes related to their development. A recently discovered relationship between structure of FTBs and plate-forming processes (Mouthereau et al., 2013) should stimulate new novel research efforts.

FTBs express processes by which plate convergence in collisional orogenic belts is accommodated by accretion within the continental lithosphere. Two dominant tectonic modes are observed in FTBs, thin-skinned and thick-skinned ([Figure 1](#)). Thin-skinned style characterized regions dominated by underthrusting, suggesting simple-shear subduction of the underlying crust. Thick-skinned styles are characteristics of regions involving deeper basement-involved deformation where reverse reactivation of inherited discontinuities is a common geological feature, inferring pure-shear deformation of lithosphere.

Several local factors may explain variations of structural styles and tectonic evolution between thin- and thick-skinned. Among them, tectonic inheritance or interactions with sedimentation/erosion are particularly invoked. At larger scale, temporal/spatial changes in plate-boundary forces or variable crustal mechanical properties related to the abundance of weak mineral phases or fluids and inherited continental lithospheric strength exert a dominant control.

## **Methods**

Identification of the first-order controls on FTB deformation styles requires an approach based on the distribution of shortening in orogenic belts and mechanical analysis of basement in foreland basins.

Estimates of crustal shortening were obtained from an analysis of about 50 geological cross-sections from 30 collision belts ([Figure 2](#)). Each section was constructed and restored using balancing techniques constrained by stratigraphic data from wells, seismic reflection profiles and field geological mapping. Crustal shortening,  $R$ , is calculated as a ratio, in percent, of the amount of horizontal shortening accumulated since the initiation of deformation, to the original, undeformed length of pre-collisional stratigraphic markers. Errors on shortening data account for the number of individual shortening estimate and scattering of measurements with confidence interval of 95%. It is 20% on average. In thrust belts where shortening is constrained by a single restored cross-section, a consistent average error of 20% was assumed. Cross-sections were carefully selected so that inferred shortening values best capture the long-term evolution of fold and thrust belts. Such single data are provided for large-scale cross-sections that aim to combine years of structural analysis. Hence, shortening is not necessarily less well constrained in case of one single measurement.

Shortening estimates were obtained from matching the same external parts of collisional belts, where syn-convergence burial can be considered limited. This required the preservation of cross-sectional area during deformation, which is a prerequisite for using balancing techniques and providing robust shortening estimates. With this approach, the compilation is intended to show shortening of the same pre-collisional portions of the lithosphere.

Plate strength can be constrained by using the effective elastic thickness,  $T_e$ , a proxy for the long-term strength of the lithosphere.  $T_e$  values have been derived from a global compilation of 18,633 individual  $T_e$  estimates for continent and ocean obtained both from inverse (i.e. spectral) modeling based on spectral admittance and coherence between Bouguer gravity anomaly data and forward modeling of the gravity anomalies and the present-day topography/bathymetry. A large majority of the estimates are based on spectral methods, which do recover high  $T_e$  but have difficulties recovering how high  $T_e$  is if the latter exceeds 65-70 km. Therefore, spectral  $T_e$  data used for the study were limited to 65 km then re-gridded with a limit of 85 km to incorporate the data from forward models (e.g., in foreland basins).

Because our global  $T_e$  data set reflects the strength of the lithosphere at the onset of shortening or the cumulative effect of all the loads that have acted on the lithosphere through time, we should also consider the shortening relationship with the age of the lithosphere at the time of collision. We can calculate this age from the difference between the age of the foreland basement and the age of shortening,  $t_{T-S}$ , which can be considered as a proxy for the long-term strength of the lithosphere.

## **Results and Interpretation of Global Distribution of Shortening in FTBs and Plate Strength**

[Figure 3a](#) shows that the amounts of shortening estimates vary significantly between the world's orogenic belts. Shortening is strongest in the Himalayan and the North-America Cordilleran fold and thrust belts, where it reaches 52% to 71%, and weakest in the peri-Mediterranean and Alpine domains, where it is in the range of 23% to 46%. The sub-Andean thrust belts are characterized by intermediate values of 30% to 42%. Simple deformation models of thrust wedges ([Figure 4](#)) show that the largest shortening is expected in regions characterized by both a high convergence rate and a shallow-dipping detachment in the sedimentary cover (thin-skinned tectonic style). Evidence for this process is provided by seismological data in Himalayan thrust belts, where the underthrusting of an eclogitized cratonic lower crust and mantle is imaged beneath the Tibetan plateau. Conversely, the smallest amounts of crustal shortening are typical for the regions exhibiting crustal-scale ramps,

connecting brittle upper layers to ductile mid- to lower crust in a relatively short distance. This process is observed in seismic reflection profiles of the Western Alps. A range of shortening values may, therefore, reflect different properties of the preexisting lithosphere, independently from plate convergence rates.

The amount of shortening appears partially correlated with  $T_e$  (Figure 3a); this suggests that there may be some relationship between shortening and  $T_e$ . However, Figure 3a includes collisional orogens of different ages, ranging from Paleozoic to Cenozoic and involves lithosphere of different ages, ranging from Proterozoic to Cenozoic. A plot of the shortening  $R$  against  $tT-S$  shows a bimodal distribution (Figure 3b). Thin-skinned thrust belts are associated with foreland ages larger than 1 Ga, with  $R \sim 60 \pm 10\%$  while thick-skinned belts are younger than 1 Ga with  $R \sim 30 \pm 10\%$ . The correlation between the amount of shortening and  $tT-S$  suggests a link between the long-term integrated strength of the continental lithosphere and the structural styles in fold and thrust belts. Interestingly, continental  $T_e$  also shows a bi-modal distribution which may result from a jump-like increase, for given age, in flexural strength.

The dependence of the amount of shortening on the age of the lithosphere at the time of collision suggests control by sub-crustal mantle properties, which are also age-dependent. Shortening data cannot only reflect dependence on temperature, but also on the composition of the lithospheric mantle. For instance, young margins are weakened by stretching and thinning. Together with melt infiltration in the mantle peridotite, the lithosphere becomes mechanically unstable and weaker. Such mechanical weakening of the extended Phanerozoic mantle lithosphere promotes inversion of deeply-rooted normal faults as crustal thrust ramps, but this process is not applicable to cratons that are characterized by an anhydrous depleted sub-continental mantle.

## Conclusions

Our study shows that the amount of shortening and the age of the foreland lithosphere at the time of collision are correlated. Plates appear to strengthen with age not only because of a colder thermal regime but probably also due to dehydration of mantle lithosphere. Deformation of low strength Phanerozoic lithosphere characterized by hot geotherms and weak mantle involves mid-to-lower crustal detachment (thick-skinned FTBs) and shows reduced crustal strain ( $<35\%$ ). Older continents, with higher strength and high-viscosity mantle, promote underthrusting (thin-skinned FTBs), resulting in larger deformation ( $\sim 70\%$ ). The inherited lithospheric strength controls the depths of crustal decoupling and is a function of plate age. Our results emphasize the link between deep Earth and surface processes and their impact on the development of structural styles of collisional orogens, by linking the distribution of crustal strain with the rheological properties of the continental mantle.

## References Cited

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Figure 1. Main tectonic styles observed in FTBs and their relationships with continental lithosphere deformation after (Mouthereau et al., 2013).

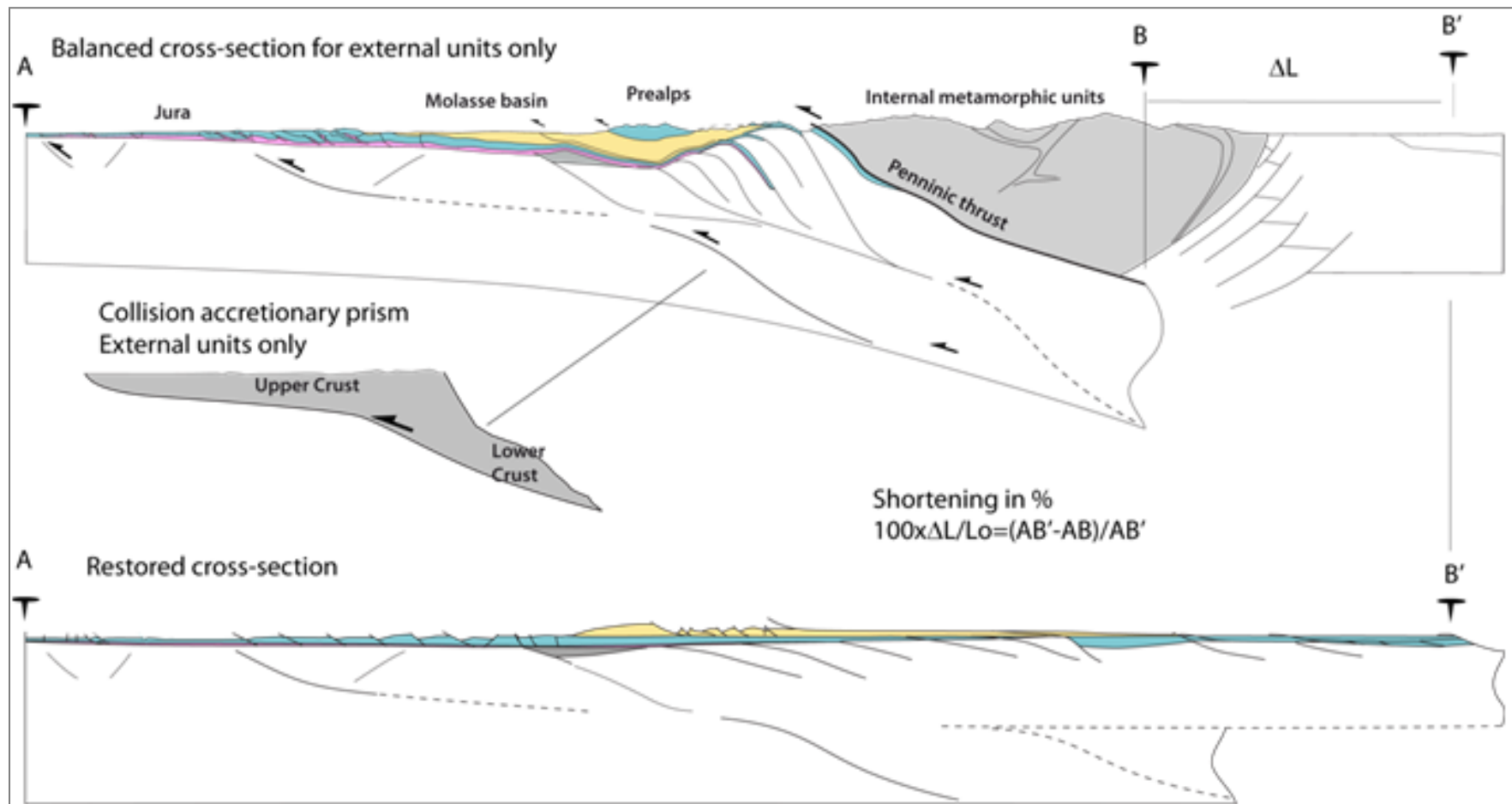


Figure 2. Example of shortening estimates (23%) adopted in this study as constrained from balanced and restored cross-section for the central segment of the European Alps (modified after Burkhard and Sommaruga, 1998, and Mosar et al., 1999; labeled NA in [Figure 3](#)). This segment of the Alps shows shortening of both upper and lower crust of the European plate, shaping an external crustal wedge that reflects a weak lithospheric mantle, consistent with  $T_e$  as low as 10 km. Percentage of shortening is calculated as a ratio, in percent, of the amount of horizontal shortening  $\Delta L$ , to the original, undeformed length of pre-collisional stratigraphic markers  $L_o$ . European crystalline basement in white, Triassic in pink; younger Mesozoic in blue, and Tertiary in yellow.

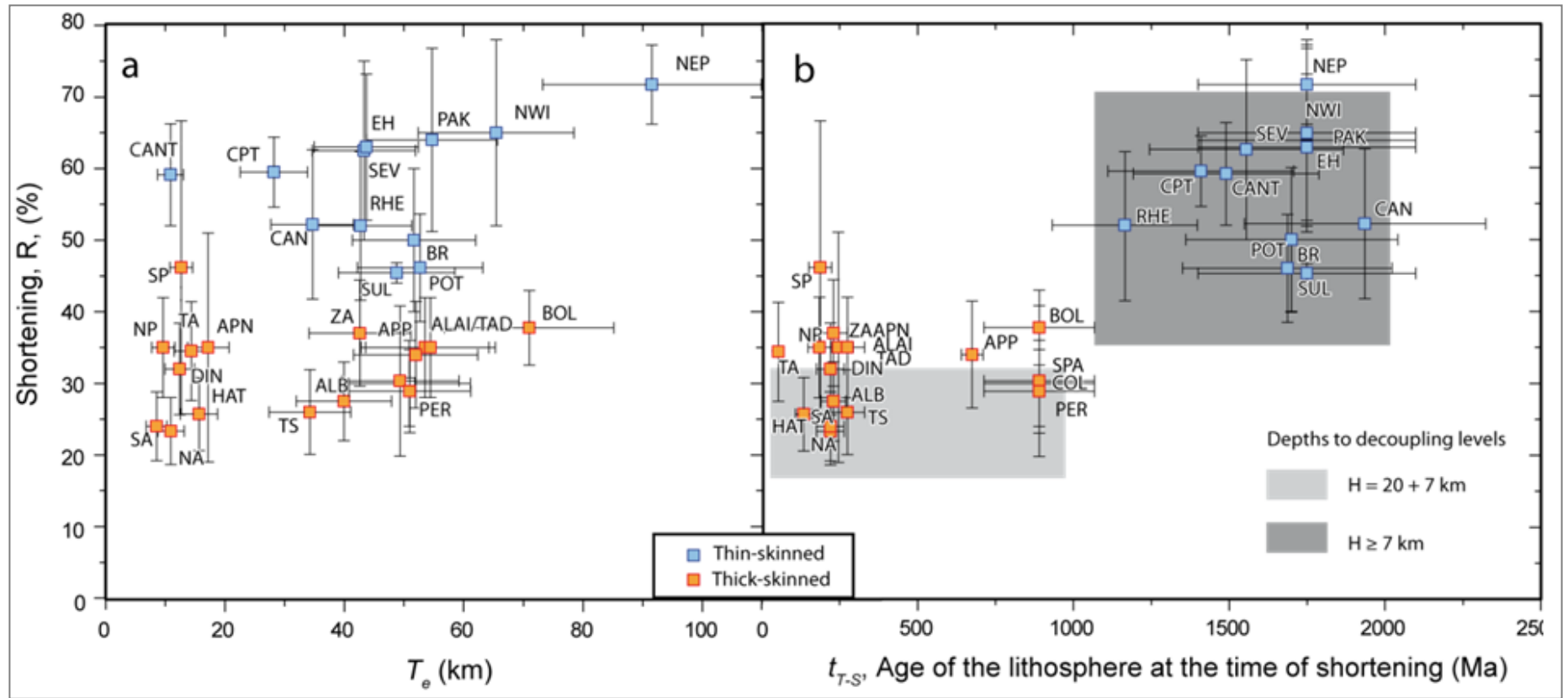


Figure 3. Shortening in thrust belts plotted against proxies of the long-term lithosphere strength (see Mouthereau et al. (2013) for full description). a) Shortening versus  $T_e$  in foreland basins. b) Shortening against age of the foreland lithosphere at the time of shortening  $t_{T-S}$ . Quadrangles in b) denote the range of shortening values predicted by kinematic models (see text).

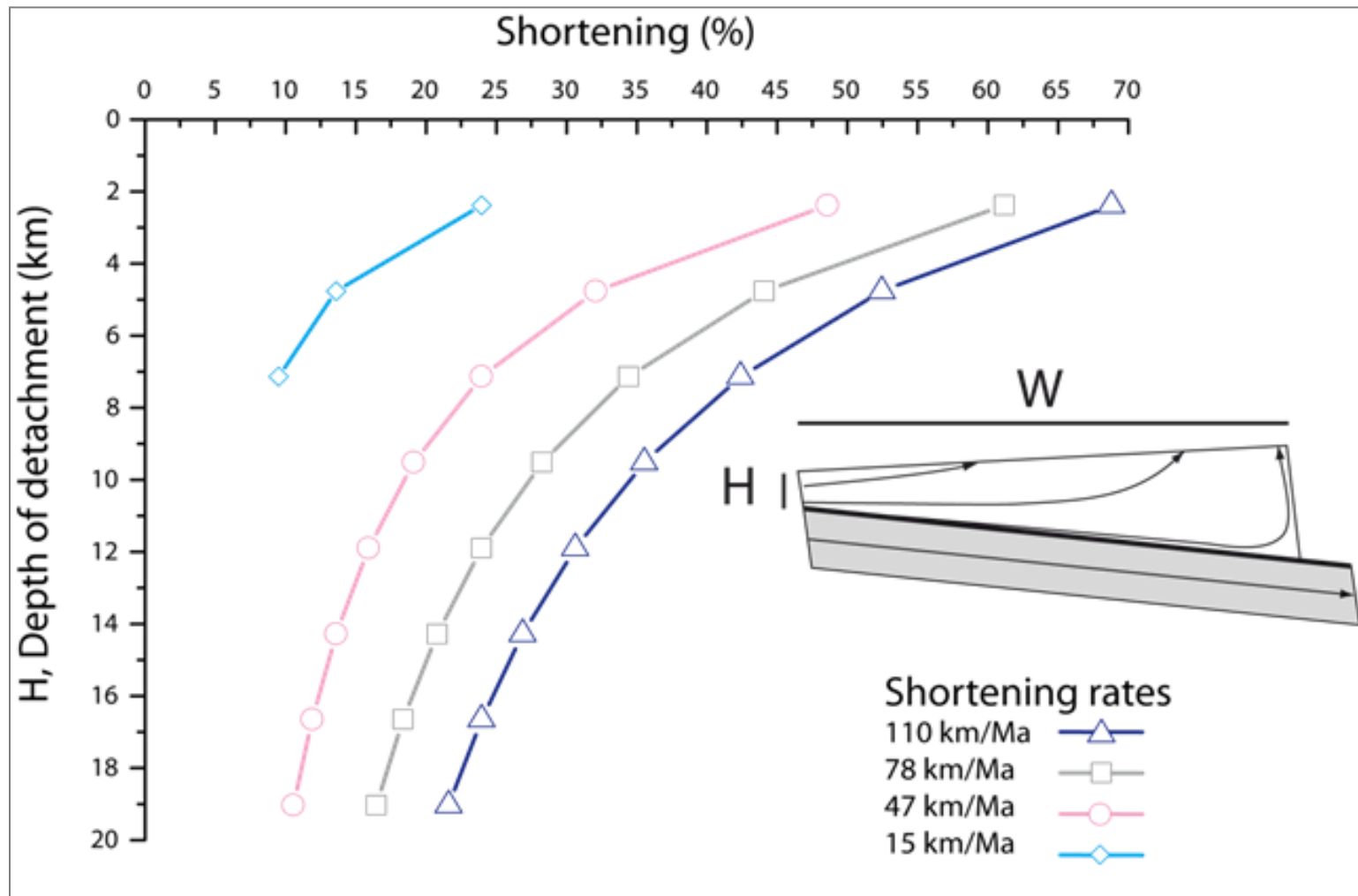


Figure 4. Graph showing the influence of the thickness of accreted material. This depth is controlled by the position and weakness of decoupling levels in the crust. They are related to the inherited rheological layering, which illustrates the role of the thermotectonic state of the crust and lithosphere. The highest percentages of shortening (up to 70%) are expected for high shortening rates, higher than 47 km/Ma in our example, but also for a specific range of detachment depths, here, shallower than 7 km. The lowest (down to 20%) will be found for regions with more variable shortening rates but associated with deeper detachment, typically below 10 km in the middle-lower crust. This indicates that lower shortening is found for regions with more vertically distributed crustal shortening, where deformation typically involves reverse reactivation of inherited faults and basement.