Curved orogenic belts, back-arc basins, and obduction as consequences of collision at irregular continental margins

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INTRODUCTION

The formation of highly curved orogenic belts is still debated (Rosenbaum, 2014). Proposed mechanisms include processes associated with deformation along thinned fold-and-thrust belts (Marshak, 1988), gravitational spreading (e.g., Edey et al., 2020), or along-strike migration rate variations of plate boundaries (Rosenbaum and Lister, 2004). The latter includes processes such as plate rotation, trench rollback, or indentation during continental collision (Rosenbaum, 2014; Rosenbaum and Lister, 2004).

The Alboran and Banda arcs are two modern systems that are associated with trench rollback and diachronous continental subduction along strike (Spakman and Hall, 2010; van Hinsbergen et al., 2014). Both regions experienced trench rollback against a highly nonlinear passive margin (see Fig. 1), where continental lithosphere subducted diachronously along the trench (Pownall et al., 2016; Spakman and Hall, 2010; van Hinsbergen et al., 2014). In the Banda region, continental material initially (15 Ma) subducted at Seram (Spakman and Hall, 2010), coinciding with trench rotation, and this was followed by continental subduction (4 Ma) at Timor, in the south (Fig. 1A). Oceanic subduction is now ceased, with collision occurring along the entire continental margin. The tectonic history of the Alboran Basin in the western Mediterranean is debated (van Hinsbergen et al., 2014). Most models agree that the slab retreated westward into the narrowing Alboran embayment since 30–20 Ma (Fig. 1B).

Both regions share puzzling geological features, such as extensional basins in the upper plate (Pownall et al., 2016; Watts et al., 1993), and exhumed subcrustal continental lithosphere (Frasca et al., 2017; Gueydan et al., 2019; Pownall et al., 2014). The Banda system involves ophiolite obduction (Ishikawa et al., 2007), but this has not been identified in the Alboran arc. The world’s largest subcontinental mantle exposures, the Ronda and Beni peridotites in the Alboran arc (Gueydan et al., 2019), have been suggested to have been exhumed by gravitational collapse after slab break-off (Platt and Vissers, 1989; Van der Wal and Vissers, 1993), by thrusting of an older Jurassic rifted margin (Tubia et al., 2009), or by hyperextension of the overriding plate before, and thrusting during, continental collision (Frasca et al., 2017; Gueydan et al., 2019; see Fig. 1C). It is unclear in these examples how the geologic evolution is linked to the highly arcuate geometry and irregular shape of the subducting continental margin, if at all.

The aim of this study was to examine evolving plate stresses during irregular continental subduction and the formation of curved orogenic belts, to provide a better understanding of the drivers and controls of the geologic evolution. We show that localized tensional stresses during the initial stages of irregular margin collision cause short-lived back-arc rifting or spreading centers that are rapidly inverted once continental subduction spreads along the trench.

COLLISION WITH IRREGULAR PASSIVE MARGINS

We investigated the stress regime evolution during continental collision with an irregular margin (Fig. 2) in a model space of 3300 by 3960 by 660 km in size. The finite element code Citcom (Moresi et al., 1996; Zhong et al., 2000; Magni et al., 2014) solves the conservation equations for momentum, energy, mass, and composition. We used a visco-plastic rheology including diffusion and dislocation creep, lithospheric yielding, and an upper-limit viscosity (Magni et al., 2014; van Hunen and Allen, 2011). We did not apply external forcing; all dynamics were driven by internal buoyancy forces. Subducting and overriding plates were separated by a weak zone and decoupled from neighboring plates by weak transform faults to permit toroidal mantle flow (van Hunen and Allen, 2011; Magni et al., 2014). Continental lithosphere was free to move toward the trench and collide with the overriding
plate as the intervening oceanic basin closed. The continental crust was initially 40 km thick; the underlying mantle lithosphere extended from 100 km depth close to the trench to 150 km in the far-field area to mimic the thicker plate interior (Fig. 2B). The subducting passive margin included an oceanic embayment of (along-strike) width $w_b$ and breadth (here used for the across-strike width) $b_b$, with flanks that sat at an angle $\alpha$ with respect to the convergence direction. To study the impact of this embayment on the evolving stress distribution, we varied the flank orientation angle $\alpha$ constant.

The convergence-parallel stress field, $\sigma_{xx}$, was computed to investigate the stress localization that could be responsible for the observed normal or thrust faulting.

Figure 3 depicts the model evolution of a subducting continent including an oceanic embayment $w_b = 1000$ km by $b_b = 600$ km. Initially, negative buoyancy of the oceanic slab drives subduction, trench rollback, and uniform extension in the overriding plate in all models (Fig. 3A). Initial continental subduction at the sides of the embayment locally reduces subduction velocities, and trench rollback stops (Fig. 3B). Trench retreat continues, however, at the oceanic embayment on the passive margin. With the local onset of continental collision (Fig. 3B), stresses start to vary significantly along the trench and upper plate. There is localized compression in collision regions, while extension close to the oceanic embayment continues to exert slab pull and trench retreat. The differential stresses cause yielding and rupture of the overriding plate. Opening of a back-arc spreading center (Fig. 3C) briefly increases convergence velocities by a factor of three (Fig. 3A). Shortly (< 5 m.y.) after onset of back-arc spreading, the oceanic embayment is completely subducted, and this is followed by continental subduction (Figs. 3D–3F).

During this last stage, slab break-off along the entire subducted margin ends subduction and allows the subducted continent to begin exhumation.

Subduction of smaller embayments (Fig. 4B) does not rupture the overriding plate to produce back-arc spreading, but it still thins the overriding continent; crustal thickness reduces from the initial 40 km to as little as 8 km (Fig. 4B; Fig. S1 in the Supplemental Material). These models show a two-stage stress evolution from extensional to a compressional stress state within 10 m.y. after initial collision (Figs. 3E and 3F). During this last stage, slab break-off along the entire subducted margin ends subduction and allows the subducted continent to begin exhumation.

Subduction of an irregular passive margin allows formation of curved orogenic belts and a two-stage stress evolution from extensional to compressional states in the overriding plate during collision. Our models show how localized thinning or rupturing of the overriding plate occurs during local initial collision, while oceanic subduction continues elsewhere. Stress inversion and compressional deformation take place in a second stage, during full continental

**DISCUSSION AND CONCLUSION**

Subduction of an irregular passive margin allows formation of curved orogenic belts and a two-stage stress evolution from extensional to compressional states in the overriding plate during collision. Our models show how localized thinning or rupturing of the overriding plate occurs during local initial collision, while oceanic subduction continues elsewhere. Stress inversion and compressional deformation take place in a second stage, during full continental

**Supplemental Material.** Detailed figures of the model evolution, as well as a short description of the methodology and parameters used. Please visit https://doi.org/10.1130/GEOL.S.15062262 to access the supplemental material, and contact editing@geosociety.org with any questions.
Such features are probably common in collision zones, given the naturally irregular shape of passive margins (Dewey and Burke, 1974).

Many numerical models of continental collision have focused on linear passive margins (Schliffke et al., 2019; van Hunen and Allen, 2011) or oblique collision (Bottrill et al., 2014) to study slab break-off and exhumation of subducted continental crust. Compressional stresses and resulting topography during continental collision are controlled by plate coupling (Faccenda et al., 2009), rheological flow laws (Pusok et al., 2018), and buoyancy ratios and convergence velocities (Pusok and Kaus, 2015). Also, lateral compositional variations along strike on the subducting plate can trigger the formation of back-arc spreading centers (Magni et al., 2014; Menant et al., 2016), under the precondition of nonlinear rheology (Pusok et al., 2018). Our models combined these approaches and showed that the resulting stress inversion from extensional to compressional states in the back-arc basins is similar to sequences proposed for the obduction of ophiolites (Cawood and Suhr, 1992) or hyperextended continental
only increase marginally. (B) Thickness of hyperextended overriding crust (no back-arc formed) or breadth (i.e., spreading perpendicular distance) of newly formed oceanic back-arc domain upon continental subduction along entire trench for all studied parameters. Asterisks denote models where emplacement becomes very narrow at its tip. In such models, slab breaks off before full subduction of oceanic emplacement (see Fig. S2 [see text footnote 1]). Values for Newfoundland and Alboran and Banda arcs are estimates based on Cawood and Suhr (1992), Gueydan et al. (2019), and Spakman and Hall (2010).

Diachronous continental subduction has further been suggested to have formed young back-arc ophiolites by thrusting onto a continental margin during large-scale continental collision in the Caledonide orogen (Cawood and Suhr, 1992; Slagstad and Kirkland, 2018). During Baltic-Lauraic collision, diachronous initial collision in Newfoundland (Cawood and Suhr, 1992) and Norway (Slagstad and Kirkland, 2018) coincided with extension, as shown by mafic layered intrusions and ophiolite creation, while obduction is dated ~15–20 m.y. later. With the onset of back-arc spreading predating continental subduction along the entire trench by ~5 m.y. and predating compression in the back-arc area by ~20 m.y. in our models, we estimate obduction within the period 5–20 m.y. of back-arc formation, similar to the observations. The limited (trench perpendicular) ophiolite size (<100 km) in the Norwegian Caledonides and Newfoundland hints that the newly formed spreading center must have been small during onset of collision, and the spreading center was close to the main suture where the back-arc obducted.

In conclusion, collision of a continent with an irregular passive margin not only can form highly arcuate orogenic belts, but it can also cause complex geological processes in the overriding plate resulting from the associated transient stress changes. Such a setting causes localized crustal thinning, rapidly followed by crustal shortening, and it provides an ideal intrinsic mechanism for obduction of ophiolites or a hyperextended continental margin, without a need for any far-field forcing or preexisting weaknesses in the upper plate.

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