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Notes

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COMMENT

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The new seismic reflection and tomographic data from the Gibraltar region presented by Gutscher et al. (2002) will require a reassessment of the recent tectonics of this part of the Africa-Eurasia plate boundary. We argue here, however, that the data do not support their interpretation in terms of active subduction beneath the Gibraltar arc for the following reasons.

1. Given northwest-directed Africa-Eurasia relative motion in this area, the proposed north-south-trending plate boundary segment would be locally divergent, not convergent. Active subduction would require westward motion of the Alboran domain relative to Iberia, which is not supported by the present-day seismicity. During the Miocene the Alboran domain moved west with respect to both Africa and Iberia, accompanied by active convergence in the external Betic-Rif arc, but shortening in the northern (Betic) sector of the thrust belt ceased by the end of the Tortonian (6 Ma), from which time the Alboran domain moved with Iberia.

2. Estimates of Miocene crustal shortening in the external thrust belt range from 150 to 200 km, affecting sediments deposited in a rifted continental margin setting. These estimates are incompatible with the subduction of a 600-km-long slab of oceanic lithosphere in the past 10 m.y.

3. The tomographic images demonstrate the non-slab-like behavior of a body of fast (presumably cold) mantle, as well as slow regions beneath southwest Spain and Morocco that suggest removal of lithospheric mantle. At depth the fast region thickens to a large blob-like body 200–300 km across in north-south, east-west, and vertical directions. This bears only superficial resemblance to the cartoon of a subducting slab presented in Figure 1 of Gutscher et al. (2002). The disposition of cold material is more consistent with that predicted for an amplifying and laterally propagating Rayleigh-Taylor instability developed from the lower lithosphere of a region of distributed plate convergence (Houseman and Molnar, 2001). Downwelling of cold material is likely to have started ca. 27 Ma (Platt et al., 1998), and may have propagated outward during continuing Africa-Iberia convergence. It is likely, however, that the tomographic images do not adequately resolve the primary downwelling features (on the scale of tens of kilometers) that arise from lithospheric instability.

4. Intermediate and deep seismicity close to this body of cool mantle is cited by Gutscher et al. (2002) in support of active subduction. This seismicity is highly localized, and in no way resembles that of a Wadati-Benioff zone. Intermediate and deep seismicity is in any event likely to reflect phase changes or dehydration-induced fracturing, and does not bear on the question of the oceanic or subcontinental origin of the mantle material involved.

5. The reflection profiles presented by Gutscher et al. (2002) show a young wedge-shaped body of deformed sediment in the Gulf of Cadiz similar to that imaged in industrial profiles from the external Rif. The latter show that although the wedge contains imbricate thrust faults, there are similar numbers of normal faults in the upper part of the wedge (Flinch, 1996). Displacements on the normal and thrust faults are comparable, and appear to be kinematically linked. Flinch (1996)

therefore suggested that young tectonic activity in the wedge is internally driven by gravity spreading (not sliding); the deformation does not produce any net shortening, and hence does not indicate active regional convergence.

6. Gutscher et al. (2002) cite magmatism in the eastern Betics in favor of active subduction. Geochemical data suggest these volcanics were produced by shallow decompressional melting of asthenospheric mantle with varying degrees of crustal contamination (Turner et al., 1999). They are most sensibly related to the active lithospheric extension that was occurring at the same time within the Alboran domain. The volcanic activity is centered more than 400 km east of the postulated subduction zone, and 150 km east of the deepest (600 km) earthquakes. It shows no evidence of westward migration with time, as would be expected if it were related to a retreating subduction zone. The calc-alkaline phase was largely over by 10 Ma: magmatism after this time consisted mainly of lamproites and alkali basalts and migrated north and south out of the Alboran domain. These melts, which reflect progressive melting through old (1.3 Ga) metasomatically enriched lithospheric mantle (Turner et al., 1999), may be a result of the outward propagation of a Rayleigh-Taylor instability from the Alboran domain into the incoming Iberian and African continental lithosphere.

7. Gutscher et al. (2002) propose that the orogenic peridotites in the Gibraltar arc were exhumed along an active subduction zone. These bodies and their crustal envelope experienced high-temperature metamorphism and exhumation during a rapid extensional event that affected the entire Alboran domain ca. 22–20 Ma. The crustal rocks above them preserve an almost continuous section through the orogenic crust, originally 55 km thick, now stretched and thinned to 5 km (Argles et al., 1999). This is not a process normally associated with subduction. The thermal evolution of this crust indicates heating during rapid exhumation. Platt et al. (1998) showed that the only plausible way to explain this thermal history is removal of most of the lithospheric mantle beneath the collisional orogen immediately before exhumation started.

To conclude, we find that the development of a Rayleigh-Taylor instability beneath the Alboran Sea basin provides a more coherent and convincing explanation of these diverse observations than does the hypothesis of a steep subducted slab.

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REPLY**M.-A. Gutscher, J. Malod, J.-P. Rehault***Institut Universitaire Europeen de la Mer, UMR 6538, Domaines Oceaniques, Plouzané F-29280, France***I. Contrucci, F. Klingelhofer***French Research Institute for Exploitation of the Sea, Centre de Brest, DRO-GM, Plouzané F-29280, France***L. Mendes-Victor***Institute of Earth Sciences, University of Lisbon, Rua de Escola Politecnica 58, Lisbon 1269-102, Portugal***W. Spakman***Faculty of Earth Sciences, Utrecht University, Budapestlaan 4, Utrecht NL-3508, Netherlands*

We welcome the opportunity to discuss the geodynamics of the Rif-Betic region and will address the points in the order raised in the comment.

1. There is no rigid Alboran plate. Instead, a portion of the upper plate (the Gibraltar block) is pulled westward by hydrostatic suction, induced by the rollback of the steeply subducting slab (see analog models by Shemenda, 1994). This motion is observed at several Global Positioning System (GPS) stations, with vectors of 5–10 mm/yr in a west-southwest direction (with respect to Eurasia), independent of the 4 mm/yr northwest motion of African plate stations in northwest Morocco (Reilinger et al., 2001). This leads to active opening of the western Alboran Sea, consistent with recent east-west extensional focal mechanisms reported here (Stich et al., 2003), and with the strong crustal thinning (<10 km) and very thick Neogene sediments (>10 km) observed here.

2. The >600-km-long slab is not necessarily Miocene in age. It formed partly by north-northwest-directed subduction of Tethyan lithosphere (since 35 Ma), followed by rapid rollback to the west, since the Miocene. Slab length is not completely expressed as surface deformation. Crustal shortening (as recorded by sedimentary and basement deformation) in the Andes ranges from 100 to 400 km (Kley and Monaldi, 1998), yet thousands of kilometers of the Farallon-Nazca slab have subducted there.

3. Lithospheric delamination and deblobbing models were based largely on north-south tomographic cross sections showing a high P-wave velocity body (cold, apparently detached lithosphere) beneath a low P-wave velocity layer (warm asthenosphere) (see Calvert et al., 2000, their Fig. 12C; Gutscher et al., 2002, their Fig. 4D). East-west-oriented cross sections (Calvert et al., 2000, their Fig. 12B; Gutscher et al., 2002, their Fig. 4, A and B) demonstrate westward continuity with Atlantic oceanic lithosphere, effectively ruling out the deblobbing model. The steep east-dipping slab has a curved, horseshoe shape in three dimensions, similar to the Calabria slab (see the 200 km horizontal cross section of Wortel and Spakman, 2000, their Fig. 2A). Our southern cross section (Gutscher et al., 2002, Fig. 4B) shows a gracefully flexed slab, with a thickness of ~100 km (narrowest here due to its three-dimensional geometry), that in no way resembles a “blob.”

4. Nowhere else in the world does intermediate depth and deep focus seismicity occur in the absence of a subducting slab of oceanic lithosphere. Both types of seismicity occur beneath the Gibraltar arc and southern Spain (Buforn et al., 1991). Numerous subduction zones show a gap in seismicity between ~200 km and 600 km depth (e.g., Colombia, Peru).

5. Active deformation in the accretionary wedge cannot be gravity driven, since the basement and décollement are shown by wide angle seismic data to be eastward dipping (Gutscher et al., 2002, their Fig.

3A). Indeed, Flinch interprets the external Betic-Rif units to be “an accretionary complex . . . (with) some similarity to the Aleutian accretionary wedge” (Flinch, 1993, p. 247). Coeval normal faulting can occur arcward of subduction related thrusts.

6. New geochemical data indicate subduction-related magmatism in the Gibraltar arc until 4.8 Ma, with a shift in geochemistry from calc-alkaline to potassic before extinction, a trend also observed in the Aeolian-Calabrian magmatic arc (Duggen et al., 2003).

7. Syncollisional exhumation (Chemenda et al., 1995) can produce pressure-temperature-time paths similar to those observed in the peridotites, a process not considered earlier. This mechanism is consistent with recent U-Pb dating of zircons, indicating Miocene subduction prior to exhumation (Sanchez-Rodriguez and Gebauer, 2000).

Additionally, active mud volcanoes have now been mapped in all surveyed areas of the accretionary wedge (about two-thirds), but none have been mapped outside (Pinheiro et al., 2002).

In conclusion, subduction and rollback of a narrow east-dipping slab (in an overall north-south convergent system) is an attractive unifying model, able to explain a variety of phenomena: surface deformation, kinematics, magmatism, exhumation, backarc basin formation, deep mantle processes, and the horseshoe shape of the Betic-Rif orogen. More importantly, it makes testable predictions. We invite Platt and Houseman (and others) to propose tests to discriminate between the delamination model and the subduction model. We plan bathymetric surveys in the Gulf of Cadiz to examine the morphology and continuity of active thrust faults in the accretionary wedge and to complete the inventory of mud volcanoes. We eagerly await acquisition of additional GPS data. We suggest, let's collect the necessary evidence and then put the case to rest.

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