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On 1 November 1755 a powerful earthquake shook Portugal, Spain, and northern Morocco, with tremors felt across most of northwestern Europe and as far west as the Azores and as far south as the Cape Verde islands [*Gutscher,* 2004]. Known as the Great Lisbon Earthquake, the event was followed by a devastating tsunami that swept the nearby Atlantic coast with waves 5–15 meters high; tsunami waves 1–5 meters high were also observed in the Antilles [*Gutscher et al.,* 2006]. Following the earthquake, huge conflagrations raged for days in the city of Lisbon, where 85% of buildings were leveled. In total, 40,000–60,000 people are estimated to have perished.

Modern estimates now consider that the earthquake's magnitude was between 8.5 and 9.0, making it among the strongest earthquakes ever felt. But questions on the earthquake's exact mechanism continue to perplex researchers. Also perplexing are observations of extreme stretching of crust in the western Alboran Sea, an arm of the Mediterranean between Spain and Morocco. Could the processes that stretched the crust there be related to the forces that triggered the 1755 earthquake?

A recent hypothesis proposes that the geography and crustal structure in this region have been shaped in large part by the subduction of a narrow strip of oceanic lithosphere beneath Gibraltar, a process that possibly affects the area's tectonics and seismicity to this day [*Lonergan and White,* 1997; *Gutscher et al.,* 2002]. Despite the absence of arc volcanism and shallow-dipping thrust-type earthquakes (two of the characteristic features of active subduction), numerous geological observations provide hints that subduction persists (albeit at rates of less than 1 centimeter per year) and may be capable of generating recurrent great earthquakes like the famous 1755 event [*Gutscher,* 2004; *Gutscher et al.,* 2006, 2009a, 2009b].

The hypothesis of subduction challenges the widely accepted model that the southern Iberia region was shaped by continental delamination—a process by which the bottom layers of thick continental lithosphere detach and sink into the mantle, stretching overlying crust as it sinks—in the wake of a continent-continent collision between Africa and Iberia. Geological and geophysical studies conducted over the past 10 years provide new evidence that weighs in on these two competing hypotheses. Deciding which hypothesis prevails will affect assessments of the long-term natural hazards in this region.

Geological Setting Around Gibraltar Explained Through Each Hypothesis

The geodynamic evolution of the western Mediterranean region over the past 30 million years has been characterized by the slow movement of Africa in a north to northwest direction toward Eurasia, causing the intervening ocean, the Tethys, to be slowly consumed as it was subducted beneath Africa. Paradoxically, in the boundary region between the two large converging plates, there was widespread extension and formation of young oceanic basins caused by subduction and rollback of limited domains of oceanic lithosphere,

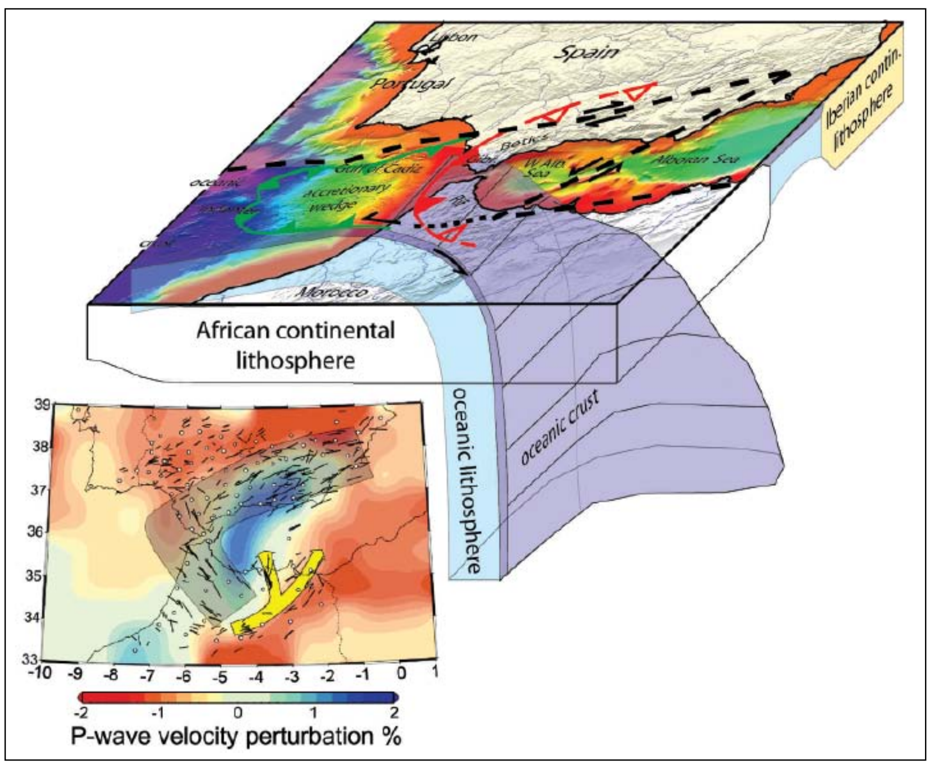

Fig. 1. A three-dimensional block diagram of the lithospheric structure of the region surrounding Gibraltar, with shaded hill relief at the surface. The hypothesized plate boundaries, expressed by crustal seismicity and the GPS velocity field, are shown as bold dashed lines. The Rif-Betic front is shown by red teeth (solid teeth indicate the active portion), and the deformation front of the accretionary wedge is shown by green teeth. The asymmetric shape of the oceanic slab at depth is from tomography. Inset shows fast directions for polarized shear waves in the upper mantle (bars represent 0.5- to 1.3-second time shift), indicating a dominant "flow fabric." This is displayed on a horizontal tomographic slice at 200-kilometer depth, with the blue zone indicating a rapid P *wave velocity anomaly (cold, dense lithosphere) and the yellow arrows indicating a proposed path for return flow behind the slab edge [*Diaz et al., *2010].*

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which triggered rapid movement of independent blocks and back-arc extension at the surface [*Faccenna et al.,* 2004].

The western Alboran Sea constitutes one of these young basins, with thin crust, high heat flow, and thick sediments (>10 kilometers) deposited over the past 15 million years. This basin is entirely enclosed by the westernmost portion of the Alpine-Himalayan fold-and-thrust belt, the Betic mountains to the north, and the Rif mountains in northern Morocco to the southwest. Together, these arcuate mountain belts form the Gibraltar arc (Figure 1). Early tomographic studies performed here showed a cold, dense lithospheric body in the upper mantle linked to deep-focus seismicity beneath Granada (southern Spain) but without a clear connection to scattered intermediate and shallow seismicity [*Seber et al.,* 1996]. Analyses of the pressure and temperature histories of high-grade metamorphic rocks found in the region indicated that they were exhumed rapidly, and this was interpreted to have been caused by dramatic thinning of the lithosphere and an influx of hot asthenospheric material below [*Platt and Vissers,* 1989].

Together, these observations of a dense lithospheric body, apparently detached from the surface with hot asthenosphere above, seemed to offer a classic example for continental delamination [*Calvert et al.,* 2000]. This extreme crustal thinning was considered separately from questions surrounding the origin of the 1755 earthquake. The 1755 earthquake was most commonly explained by movement along faults offshore of southwestern Iberia (e.g., Gorringe Bank) near the major fracture zone separating Africa from Eurasia that connects to the Mid-Atlantic Ridge.

However, those who consider that subduction can explain both observations propose that the strip of oceanic lithosphere, part of the Tethyan oceanic domain that once separated Gondwana (Africa, India, Australia, and Antarctica) from Eurasia, still exists today in the form of a narrow and steeply east dipping slab of oceanic lithosphere below the Gibraltar region [*Gutscher et al.,* 2002]. Over the past 15 million years, this east-west strip of oceanic lithosphere detached itself from the adjacent African continent and sank vertically into the mantle while remaining attached farther west. This caused the slab to bend down and the hinge line to roll back to the west, in turn causing east-west extension in the crust of the overriding plate. This movement also resulted in a small tectonic block, the "Rif-Betic-Alboran" microplate (between the back-arc basin and the subduction hinge), which was drawn to the west in response.

This two-part hypothesis has provoked heated debate in the scientific community. Testing it requires answers to two basic questions: (1) Is the lithosphere beneath Gibraltar observed by tomography a product of oceanic subduction or of continental delamination? (2) Is subduction still active today?

Evidence for Subduction

New seismological results offer insights on the deep geodynamic processes that have shaped the Rif-Betic-Alboran region. A study of the dispersion of teleseismic body waves traveling through the dense lithospheric body in the upper mantle concludes that it must contain a fairly thin (~10-kilometer-thick) low-velocity layer, interpreted to be the oceanic crust at the top of a roughly 100-kilometer slab of subducting oceanic lithosphere [*Bokelmann et al.,* 2011]. These results are not consistent with the delamination model, which requires the descending body to consist of continental lithosphere.

Seismological studies of shear waves passing through the upper mantle can reveal the presence of a dominant "fabric" due to the preferential alignment of olivine crystals. Such studies indicate significantly shorter travel times (arrivals 0.5 to 1.3 seconds earlier) for seismic waves polarized parallel to this dominant fabric (similar to the anisotropic fabric of bamboo or fiberglass). The fast directions in the upper mantle are aligned parallel to the Rif-Betic arc and veer from north-south, just west of Gibraltar, to east-west in southern Iberia, just north of the Betics [*Diaz et al.,* 2010] (Figure 1 inset). This fabric is consistent with lateral (or toroidal) flow around the slab as it retreats to the west. The upper mantle flow pattern below the Gibraltar arc is nearly the mirror image of the pattern observed below the Appenine and Calabrian arc of southern Italy, where rollback subduction is known to occur [*Baccheschi et al.,* 2007]. The delamination hypothesis predicts radial inward flow and fast directions, inconsistent with these observations [*Diaz et al.,* 2010; *Bokelmann et al.,* 2011].

Another recent discovery is based on a wide-angle seismic survey from offshore southern Portugal revealing the presence of a 7-kilometer-thick oceanic crust in the Gulf of Cadiz, 100 kilometers south of the coast and extending beneath the toe of an eastward thickening wedge of deformed sediments [*Sallares et al.,* 2011] (see Figure 1). On the basis of published paleogeographic reconstructions, these workers interpret the crust to be Jurassic in age (about 120–180 million years old) and to represent the small westernmost remnant of the once vast Tethys Ocean. Numerous marine seismic surveys have shown that this crust dips to the east [*Gutscher et al.,* 2002; *Thiebot and Gutscher,* 2006; *Iribarren et al.,* 2007; *Gutscher et al.,* 2009a]. It appears contiguous with the east dipping high *P* wave velocity body beneath Gibraltar seen by tomography [*Gutscher et al.,* 2002; *Spakman and Wortel,* 2004]. These observations of oceanic crust in the Gulf of Cadiz, dipping to the east and connected to a slab of oceanic lithosphere deep below Gibraltar, strongly support the subduction model.

Is Subduction Still Active Today?

Recent geophysical studies on the shallow structure of the Gulf of Cadiz as well as geodetic work on regional kinematics provide some answers to the question on whether subduction is still active.

Multichannel seismic reflection data from the Gulf of Cadiz, which imaged an eastward thickening wedge of deformed sediments, show that it overlies a shallow eastward dipping layer of undeformed sediments [*Gutscher et al.,* 2002; *Thiebot and Gutscher,* 2006; *Iribarren et al.,* 2007; *Gutscher et al.,* 2009a, 2009b]. This geometry is characteristic of accretionary wedges and requires a west directed tectonic push. Recently published multibeam bathymetric data from the southwestern Iberia region highlight the rough surface and the sharp U-shaped boundaries of this accretionary complex [*Gutscher et al.,* 2009b] (Figure 1). The overall westward directed thrusting and transport are expressed by generally north-south trending anticlinal folds at the deformation front (just as north-south oriented wrinkles on a tablecloth indicate east-west shortening). It is also demonstrated by the indentation caused by an east-west trending basement high (marked "Indenter" in Figure 1), a pattern successfully reproduced by analog modeling [*Gutscher et al.,* 2009a].

The morphology and bathymetry of the accretionary wedge, as well as high-resolution seismic data of the deformation front and its lateral boundaries, indicate ongoing compressional and transpressional deformation, with likely prolongations onshore in southwestern Spain and northwestern Morocco [*Gutscher et al.,* 2009a, 2009b; *Maad et al.,* 2010; *Crutchley et al.,* 2011]. In addition, a total of 51 active mud volcanoes have been identified and sampled in the Gulf of Cadiz in the decade following the discovery of the first two in 2001 [see *Gardner,* 2001], all located on the accretionary wedge, highlighting the fluid expulsion related to sediment compaction and tectonic compression within the accretionary wedge [*Medialdea et al.,* 2009].

Finally, geodetic studies of the kinematics in this slowly moving region have improved and now reveal an independent Rif-Betic-West Alboran microplate between Iberia and Africa, moving to the west-southwest at 3–5 millimeters per year with respect to Africa [*Koulali et al.,* 2011]. This is exactly the type of block motion predicted by an active subduction and rollback geodynamic model.

A Convincing Tectonic Scenario

On the basis of this review of recent observations, four main predictions of the active east dipping subduction hypothesis can now be confirmed [*Gutscher et al.,* 2002]. First, east dipping oceanic lithosphere has been observed at shallow (crustal) depths and at great (upper mantle) depths. Second, active dewatering occurs in the accretionary wedge. Third, active tectonic deformation occurs at the wedge's boundaries. Finally, an independent tectonic block between the African and Eurasian plates located south of the Iberian Peninsula is moving slowly in a west-southwest direction.

These results have important implications for regional assessments of natural hazards. This includes the long-term seismogenic potential of the subduction fault plane (the possible cause of the 1755 earthquake), as well as crustal faults in southern Spain and northern Morocco, which may move at rates of 3–4 millimeters per year along the lateral boundaries of this small block. Identification of the potentially active faults related to this system, on land and in the adjacent offshore regions, will be a major focus of research for years to come.

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