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Seismic Data Reveal Eastern Black Sea Basin Structure

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Rifted continental margins are formed by progressive extension of the lithosphere. The development of these margins plays an integral role in the plate tectonic cycle, and an understanding of the extensional process underpins much hydrocarbon exploration.

A key issue is whether the lithosphere extends uniformly, or whether extension varies with depth. Crustal extension may be determined using seismic techniques. Lithospheric extension may be inferred from the water-loaded subsidence history, determined from the pattern of sedimentation during and after rifting. Unfortunately, however, many rifted margins are sediment-starved, so the subsidence history is poorly known.

To test whether extension varies between the crust and the mantle, a major seismic experiment was conducted in February–March 2005 in the eastern Black Sea Basin (Figure 1), a deep basin where the subsidence history is recorded by a thick, post-rift sedimentary sequence.

The seismic data from the experiment indicate the presence of a thick, low-velocity zone, possibly representing overpressured sediments. They also indicate that the basement and Moho in the center of the basin are both several kilometers shallower than previously inferred.

These initial observations may have considerable impact on thermal models of the petroleum system in the basin. Understanding the thermal history of potential source rocks is key to reducing hydrocarbon exploration risk.

The experiment, which involved collaboration between university groups in the United Kingdom, Ireland, and Turkey, and BP and Turkish Petroleum (TPAO), formed part of a larger project that also is using deep seismic reflection and other geophysical data held by the industry partners to determine the subsidence history and hence the strain evolution of the basin.

Testing Models of Lithospheric Extension

The uniform stretching model [*McKenzie*, 1978] has been successful in predicting many characteristics of rifted margins. However, the exhumation of mantle rocks at some margins, e.g., the West Iberia Margin, [*Whitmarsh et al.*, 2001] indicates that at high degrees of extension, the mantle lithosphere can be stretched more than the overlying crust, so that large-scale extension varies with depth.

Such highly stretched regions are normally remote from terrestrial sediment sources, resulting in an incomplete stratigraphic section from which the subsidence history cannot be well constrained. However, the Black Sea differs from these sediment-starved rifted margins in that the surrounding continent has provided an ongoing sediment supply.

The Eastern Black Sea Basin

The Black Sea comprises two deep basins, separated by the mid–Black Sea High (a basement ridge), that are thought to have formed by back-arc extension during the closure of the Tethys ocean [*Zonenshain and Le Pichon*, 1986]. On the basis of gravity and sparse seismic refraction data, the crustal thickness in the center of both basins was thought to be around 10 km or less, and it has been speculated that oceanic crust may be present in both basins [*Belousov et al.*, 1988]. The eastern basin currently lies in a compressional setting associated with the uplift of the Caucasus mountains, but compressional tectonics appear to affect only the edges of the basin [*Meredith and Egan*, 2002].

The present study focuses on the eastern basin, where the main rifting event has been

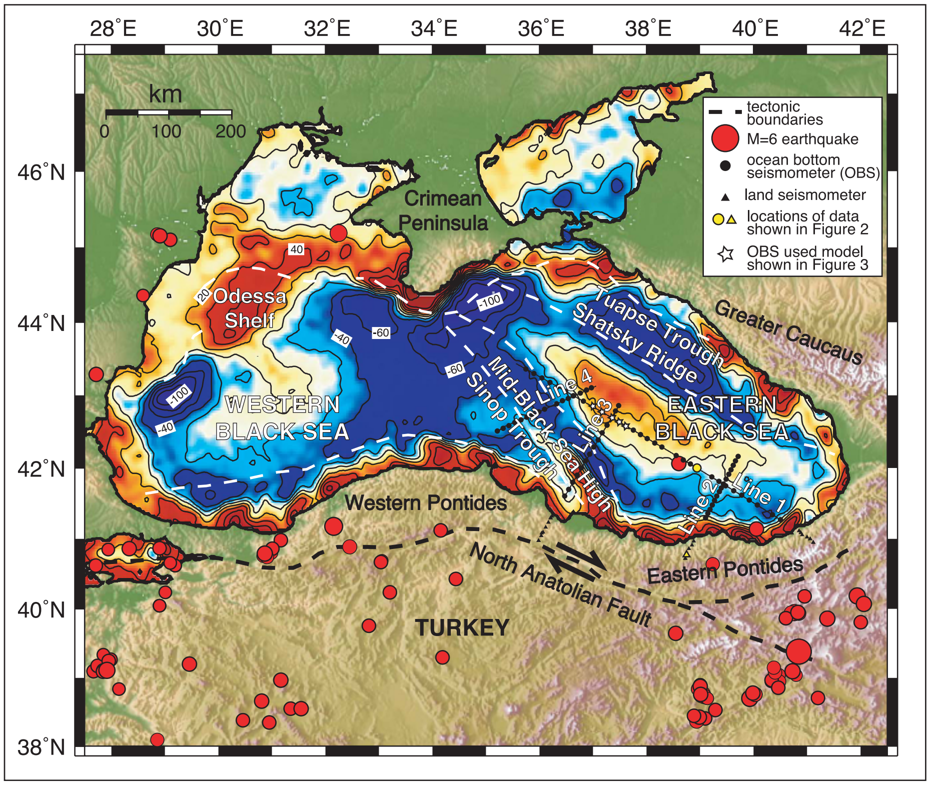

Fig. 1. Location of the seismic experiment with elevation from the General Bathymetric Chart of the Oceans on land, and free-air gravity derived from satellite altimetry within the Black Sea (contoured at 20-mGal intervals). Tectonic boundaries are taken from Robinson et al. *[1996]. Plotted earthquakes occurred during the experiment (2 February to 11 March 2005), and circles are scaled by earthquake magnitude. Earthquakes are taken from the online catalogues of the Kandilli Observatory and Earthquake Research Institute and the European-Mediterranean Seismological Centre.*

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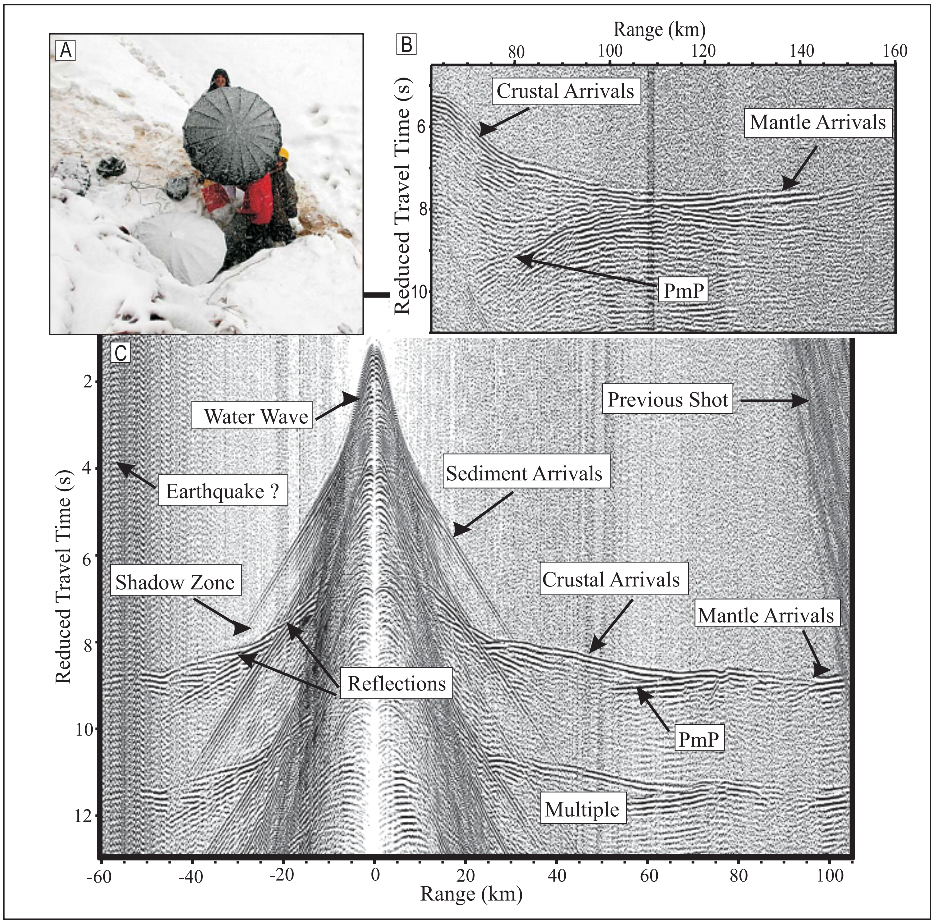

Fig. 2. (a) Photograph of one of the land seismometers being installed; several stations were installed in remote locations and in difficult weather conditions. (b) Record section from a land station (see Figure 1 for location). The arrival labeled PmP is a reflection from the base of the crust. (c) A typical ocean-bottom seismometer record section from the center of the basin (see Figure 1 for location).

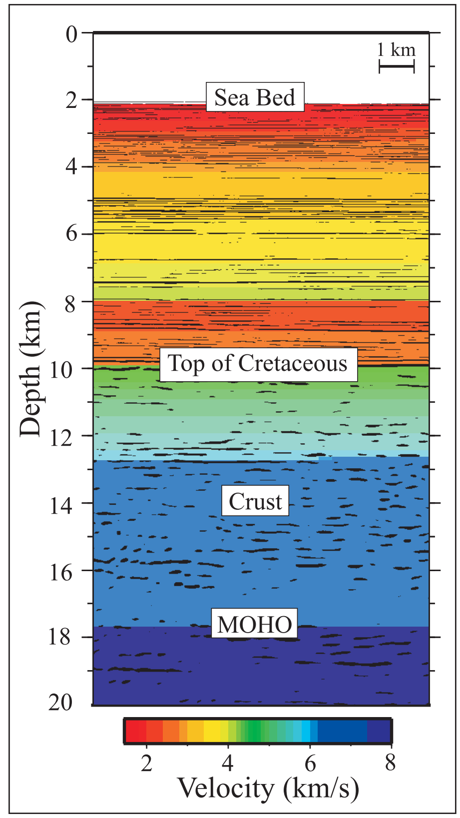

Fig. 3. Initial velocity model for the central part of the basin (for location see Figure 1) overlain by coincident, multichannel seismic reflection data [Robinson et al., *1996] converted to depth using these velocities.*

interpreted by different authors to be as young as Paleocene or as old as Jurassic [*Robinson et al.*, 1996; *Golmshtok et al.*, 1992, and references therein]. Although sediments in the eastern basin that formed during rifting are sparse, previous seismic research [*Belousov et al.*, 1988] suggests a post-rift sediment thickness of up to ~11 km. The basin has many similarities to the oil-rich South Caspian Basin, including the same Oligocene-Miocene Maykop source rock, and ongoing hydrocarbon exploration has led to very extensive seismic reflection coverage.

The 2005 Seismic Experiment

During the 2005 experiment, four long wide-angle seismic profiles, ranging in length from 110 to 470 km, were acquired from different parts of the basin (Figure 1). The profiles were acquired using the R/V *Iskatel*, a Ukrainian vessel equipped with a nine-gun 3140 cubic inch airgun array tuned to provide a seismic source rich in low frequencies. On each profile, between 14 and 34 four-component ocean-bottom seismometers (OBSs) were deployed, and the airguns were fired at 60- to 90-s intervals.

Three of the four profiles had one end close to the coast, and airgun shots also were recorded on up to eight land stations deployed in-line up to 40 km inland. The land and ocean-bottom stations also recorded some local and regional seismicity (Figure 1).

Initial Results

The experiment acquired unusually high quality seismic data (Figure 2). Reflections from the base of the crust and/or refracted energy from the mantle are seen on almost all OBS records and out to source-receiver ranges of up to 190 km on the longest profile.

In addition, there are strong reflected and refracted signals from the crust and overlying sediments. Data quality from the land stations is more variable, but clear reflections from the base of the crust are also common.

The initial analysis has focused on a subset of OBSs from the center of the basin where gravity models indicate that the crust is thinnest [*Starostenko et al.*, 2004]. Observed seismic travel times were compared with those computed from simplified models of crustal structure [*Zelt and Smith*, 1992].

A striking feature of all OBS records from the center of the basin is a prominent shadow zone, where refracted energy is not observed (Figure 2), that results from a thick, low-velocity zone directly overlying a strong acoustic basement reflection (Figure 3). Such a zone is most likely caused by low permeability and high pore fluid pressures, which maintain the porosity well above the value for normally compacting sediments. The acoustic basement in the basin is commonly interpreted to be formed from Upper Jurassic to Lower Cretaceous platform carbonates and Upper Cretaceous volcaniclastic and volcanic rocks, all of which outcrop on the margins of the basin [*Robinson et al.*, 1996].

The basin is 2–3 km shallower than previously inferred [*Belousov et al.*, 1988; *Starostenko et al.*, 2004], so the thermal structure of the basin sediments may differ significantly from existing models.

The Moho lies ~8 km beneath the top of the acoustic basement and ~4–5 km shallower than previously inferred. Intermittent layered reflections suggest that the upper ~1 km of the acoustic basement is sedimentary; the high velocities of this material are consistent with the presence of carbonates and/or volcanic rocks.

Hence, the thickness of the crystalline crust is ~7 km, similar to the thickness of normal oceanic crust. Crustal velocities are lower than those typical of oceanic crust, though they are comparable to those of back-arc oceanic crust. The presence of oceanic crust in the basin is difficult to reconcile with the interpretation of shallow water carbonates forming the top of acoustic basement.

Future Work

This comprehensive data set will allow the determination of whether oceanic crust is present in the center of the basin, the crustal thickness on the margins of the basin, and the degree of crustal extension across the basin. These new constraints on the depths of key seismic horizons will provide more accurate input to the subsidence analysis. An ultimate goal of this research is to determine whether the subsidence can be explained by the uniform stretching model or whether other processes are involved.

Acknowledgments

We thank all those who sailed with us aboard R/V *Iskatel* and assisted with the land program in Turkey. Data acquisition was funded by the U.K. Natural Environment Research Council (NERC) through the Ocean Margins LINK program, by BP, and by TPAO. Ocean-bottom seismometers and the airgun source were provided under contract by GeoPro GmbH, and land stations were provided by the NERC-funded SEIS-UK (Seismic Equipment Infrastructure in the U.K.) equipment pool.

References

Belousov, V.V., et al. (1988), Structure and evolution of the Earth's crust and upper mantle of the Black Sea, *Boll. Geof. Teor. Appl., 30*, 109–196.
Golmshtok, A.Y., et al. (1992), Age, thermal evolution, and history of the Black Sea Basin based on heat flow and multichannel reflection data, *Tectonophysics*, *120*, 273–293.
McKenzie, D. (1978), Some remarks on the development of sedimentary basins, *Earth Planet. Sci. Lett., 40*, 25–32.
Meredith, D. J., and S. S. Egan (2002), The geological and geodynamic evolution of the Eastern Black Sea Basin: Insights from 2-D and 3-D tectonic modelling, *Tectonophysics, 350*, 157–179.
Robinson, A. G., et al. (1996), Petroleum geology of the Black Sea, *Mar. Pet. Geol.*, *13*, 195–223.
Starostenko, V., et al. (2004), Topography of the crust-mantle boundary beneath the Black Sea Basin, *Tectonophysics*, *381*, 211–233.
Whitmarsh, R. B., G. Manatschal, and T. A. Minshull (2001), Evolution of magma-poor margins from rifting to seafloor spreading, *Nature*, *413*, 150–153.
Zelt, C. A., and R. B. Smith (1992), Seismic travel time inversion for 2-D crustal velocity structure, *Geophys. J. Int.*, *108*, 16–34.
Zonenshain, L. P., and X. Le Pichon (1986), The Black Sea and Caspian Sea deep basins as remnants of Mesozoic back arc basins, *Tectonophysics*, *123*, 181–211.

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Carrington, Schwabe, and the Gold Medal

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The mid-nineteenth-century sunspot studies of Heinrich Schwabe and Richard Carrington helped revitalize the then-lagging subject of solar astronomy, ushered in the new field of solar-terrestrial relations, and pointed astronomers toward a more modern view of the Sun's interior. This article recounts a little-known connection between these two astronomers.

Both Schwabe (Figure 1) and Carrington and were wealthy amateurs who pursued precise observational goals to great effect. While Schwabe's monumental result, the discovery of the 11-year sunspot cycle, required 18 years of labor before its announcement and another seven before its acceptance, Carrington's key discoveries were all made within the first six years of his sunspot observations. Schwabe's solar observing career spanned 43 years (1825–1867); Carrington's spanned less than a fifth of that (1853–1861).

The two men met twice, first in October of 1856, when Carrington made a tour of German observatories, and several months later when Carrington returned to present Schwabe the Gold Medal of the Royal Astronomical Society (RAS) for 1857.

The Origins of Carrington's Sunspot Studies

Schwabe's announcement in 1844 of an approximately 10-year cycle in sunspot occurrence lay buried in *Astronomische Nachrichten* until it was updated and publicized in Volume 3 of von Humboldt's influential *Kosmos* series in 1850. Shortly thereafter, in 1852, three scientists (Sabine, Wolf, and Gautier) independently reported the discovery of the sunspot cycle in Earth's magnetic record.

Carrington was inspired by the discoveries of Schwabe and Sabine. As he later [1863] wrote, "That the Solar phenomena, amid the universal subjection to order and law, should alone be subject to caprice could never gravely be entertained by any mind of philosophic training, but till the time of the appearance of the works above referred to, the attempts of several able men had tended to increase a very general conviction that time and labour would be thrown away on such a subject, and that … there was nothing to indicate … that the efforts of a lifetime might not be practically wasted—and have as their sole result an astronomical picture-book."

—Edward W. Cliver

Carrington resolved to systematically track the positions of spots on the Sun in a search for "order and law" beyond that discovered by Schwabe. This sunspot work was begun at his newly established Redhill Observatory, south of London, in late 1853.

Honoring Schwabe

Carrington quickly became a prominent figure on the English astronomical scene for which the RAS served as communal hall. He was elected a Fellow of the RAS in 1851 and became an honorary secretary in 1857, a post in which he was "indefatigable" in support of Society activities. Carrington was very much aware of his own merits [*Lindop*, 1993], and while he could be contemptuous of perceived failings in others, he was gracious to those who met his approval. He was not shy about showing his feelings in either event. Thus at the end of 1855, he petitioned George Biddell Airy, Astronomer Royal and RAS vice-president, to consider Schwabe as a candidate to receive the Society's highest award, the Gold Medal.

In a lengthy letter to Airy, Carrington [1855] reproduced tables of Schwabe's sunspot group counts from 1826–1854 and Lamont's annual means of the daily range of magnetic declination from 1835–1850. In an attachment, Carrington plotted both of these parameters versus time (Figure 2), thus creating an early version of the graphic made famous by Ellis in 1880 that provided sustaining evidence for a Sun-Earth magnetic link during the second half of the nineteenth century [see *Cliver,* 1994].

Fig. 1. Samuel Heinrich Schwabe (1789–1875). Schwabe was a pharmacist who sold his business in 1829 to concentrate on his amateur pursuits of astronomy and botany. To date, no photograph has surfaced of Richard Christopher Carrington (1826–1875).

The heart of the letter, however, is the closing plea, which is as revealing of Carrington as it is of Schwabe and speaks to the motivation of a scientist:

"Mr. Schwabe's merit will, I confidently say, very much grow on the regard of anyone who will in examining the question review the previous history of the subject [sunspot observation]…. Giving all due honour to [work by Scheiner, Wilson, and others] …, we nevertheless find as the result of more than two centuries of observations the still remaining impression that the phenomena were of hopeless complexity, wholly irregular and capricious, and undeserving the attention of the professional astronomer.… It is not everyone who being warned off a subject on which two centuries of fruitless effort had been spent … will take up the same task … and then steadily follow the same plan for another 30 years, and bring