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Tectonic Significance of the Thrust Parallel-Normal Faulting in the Northern Makran Accretionary Wedge of Iran and Pakistan

İran ve Pakistan'da Yer Alan Makran Yığışım Karmaşığının Kuzeyinde Bindirmeye Paralel Normal Faylanmanın Tektonik Önemi

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Abstract: The recent seismicity indicates that the normal fault induced intermediate-depth earthquakes occur along with the thrust-related earthquakes at the Makran region. The focal mechanism solutions of the earthquakes and the geological data show that the strikes of normal faults and thrusts are nearly parallel to each other. This paper suggests that some of the normal fault-related earthquakes in Makran region indicate the normal faulted northern margin of a pinched crustal wedge structure. The Jaz Murian and Mashkel depressions are located on the hanging wall of this margin. This suggestion differs from the classical view that interprets all normal fault-related earthquakes in this region as intraslab earthquakes in the northerly subducting oceanic lithosphere.

Keywords: Seismicity and tectonics, subduction zone processes, pinched crustal wedge, Indian ocean

Öz: Makran bölgesinin yakın zamandaki depremselliği, normal fayla ilişkili orta derinlikteki depremlerin bindirme ile ilişkili depremlerle birlikte meydana geldiğini göstermektedir. Bu depremlerin odak mekanizma çözümleri ve jeolojik veriler, normal fayların ve bindirmelerin doğrultularının neredeyse birbirine paralel olduğunu göstermektedir. Bu çalışma, Makran bölgesindeki normal faylanmayla ilişkili depremlerin bazılarının bir kıstırılmış kabuksal kama yapısının normal faylı kuzey kenarını işaret ettiğini öne sürmektedir. Jaz Murian ve Mashkel çöküntü alanları bu kenarın tavan bloğunda yer almaktadır. Bu öneri, bölgedeki normal faylanma ile ilişkili tüm depremleri, kuzeye doğru dalan okyanusal litosfer içerisindeki 'dalan levha içi depremleri' olarak yorumlayan klasik görüşten farklıdır.

Anahtar Kelimeler: Depremsellik ve tektonik, dalma-batma zonu süreçleri, kıstırılmış tektonik kama, Hint okyanusu

INTRODUCTION

The Makran region is part of the Tethyside orogenic collage (Şengör et al., 1988) and is composed of an E-W trending Makran accretionary wedge, 900 km in length and extending between the Strait of Hormuz and Karachi (Pakistan) (Figure 1).

The Makran subduction belt is different from its counterparts elsewhere in the world. The average distance between trench and volcanic arc in subduction zones is 250 km but in Makran the volcanic arc developed at an average of 550 km away from the trench.

The subduction of the Arabian plate under the Helmand and Lut blocks of the Eurasian plate started in Early Cretaceous times (White and Ross, 1979; Berberian and King, 1981). GPS data indicate that this subduction is also active today (Reilinger et al., 2006; 23.6 ± 1.7mm/yr) (Figure 1).

Earth scientists working on accretionary wedges have realized that different tectonic styles such as subduction erosion, active accretion, subduction without accretion, and even normal faulting can develop at convergent plate boundaries and these structures are examined by Coulomb wedge and elastic models (Dahlen, 1984; 1990; Xiao et al., 1991; Yin, 1993).

It is documented that some of the subduction zones have normal faulting coeval with thrusts in the rear of accretionary wedge (Cashman and Kelsey, 1990). Moreover, Wheeler (1991), Harms et al. (1992), Ring and Glodny (2010) determined that an extrusion wedge bounding by thrust and normal faults can explain the exhumation of ultra-high-pressure rocks in a subduction setting and the extrusion wedge's normal faulted margin named as a shortening-induced normal fault (Ring and Glodny, 2010).

Many ancient orogens also have active normal faults during accretion (Platt, 1993). A well-known example is the Himalayas. The normal faulting lying parallel to the Main Central or Boundary Thrusts has been determined and it is suggested that these structures might be simultaneously active (Burg et al., 1984; Burchfiel and Royden, 1985). In order to explain the structures in the Himalayas, Chemenda et al. (1995) performed tests on a physical model, considering erosional unloading and demonstrating the rising of a crustal slice bounded by thrust and normal faulting. Beaumont et al. (2001) suggested that a low viscosity channel model could explain normal faulting coeval with thrusting in the Himalayas, and Grujic et al. (2002) provided age data to show the synchronous development of the Main Central Thrust and the South Tibet detachment.

A similar miniature structure, resembling the Himalayan case, has been determined in Central Anatolia, Turkey (Seyitoğlu et al., 2000; 2009) and named the Eldivan-Elmadağ pinched crustal wedge after Fossen (2000) introduced the expression "pinched crustal wedge". It has been suggested that this neotectonic pinched crustal wedge structure, having thrust faulted eastern and normal faulted western margins, developed as a result of NW-SE compression between the right lateral North Anatolian Fault Zone and its splay, the Kırıkkale - Erbaa Fault Zone.

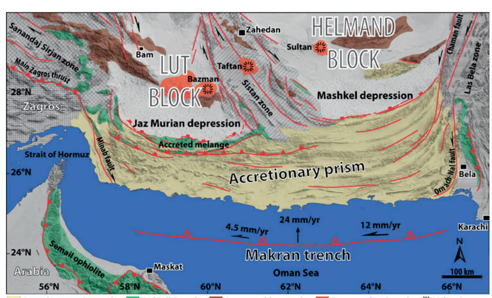

Figure 1. The main tectonic elements and simplified geological units of the Makran area. Compiled from the Tectonic Map of the Middle East (1991), Ramezani and Tucker (2003), and the International Geological Map

of the Middle East (2009). The slip rates are from Reilinger et al. (2006).

SEISMICITY OF MAKRAN

The International Seismological Center (ISC) records show that the seismicity of Makran is low relative to other regions of Iran, but the Makran region experienced significant earthquakes having magnitudes of 8.0 and 7.7. The depth of seismicity in Makran ranges from 1 km to 186 km, getting deeper towards the north (Farhoudi and Karig, 1977; Jacob and Quittmeyer, 1979). Although shallow earthquakes are located all over the Makran region, the historical and instrumental records indicate that large earthquakes are of intermediate depth in Makran (Byrne et al., 1992). Although hypocenter errors discussed in Maggi et al. (2000), intermediate earthquakes are located at the north of Makran belt under the Jaz Murain and Mashkel depressions (Figure 2a). The focal mechanisms of these earthquakes generally indicate normal faulting and their epicentres lie parallel to the Makran subduction belt. The overall evaluation of focal mechanism solution of earthquakes indicate that thrust, normal and strike slip fault related earthquakes have hypocenters shallower than 50 km, but some normal fault related earthquakes have deeper hypocenters (Figure 2a).

Beneath the Makran subduction belt maximum depth of seismically coupled (seismogenic) zone is 80 km that is deeper than the counterparts in Pacific region (after Tichelaar and Ruff 1993). This situation indicates that some of the normal fault related earthquakes can be evaluated as intraplate seismicity in the overlying lithosphere rather than intraslab earthquakes in the underlying lithosphere (Figure 2b).

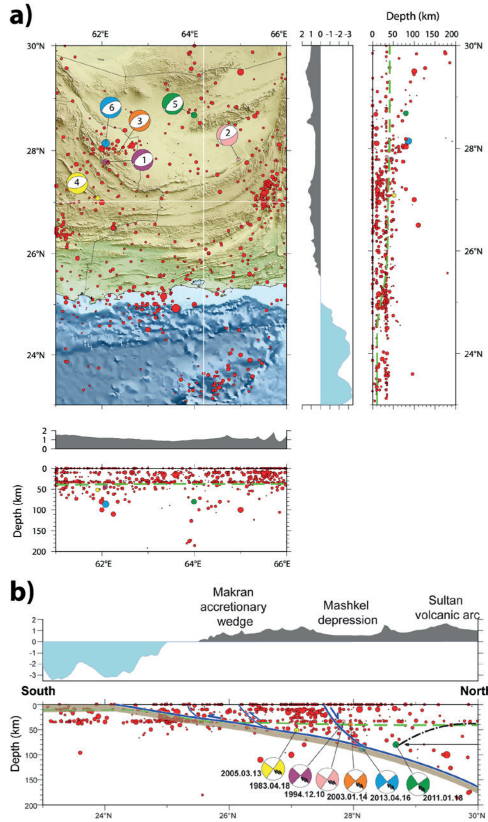

Figure 2. a) Seismic activity of the Makran accretionary belt and Mashkel depression. The data were collected from the ISC catalogue. Cross section lines along latitude and longitude are shown as solid lines on the map. Dashed lines in the cross sections indicate Moho depth obtained by CRUST1.0 model (Laske *et al*. 2013). Topography is plotted on the top of each cross section. Topography and bathymetry data are provided from http://www. marine-geo.org/portals/gmrt/. b) Cross section of the overall seismicity perpendicular to the Makran trench. The proposed structural style of the Makran subduction belt is similar to the pinched crustal wedge limited by normal and thrust faults. The side views of normal fault related focal mechanism solutions are presented with different colours, see Figure 2a for their map view. The khaki-grey

strip represents the subducted oceanic crust. The dash-dot line and arrow indicate maximum depth of seismic coupling of the plate interface (after Tichelaar and Ruff, 1993). Multi-coloured dots indicate hypocenters of normal fault related earthquakes. The dashed line indicates moho depth obtained by CRUST1.0 model (Laske et al., 2013).

The N-S cross sections of the Makran area indicate that the some of the intermediate normal fault related earthquakes can be evaluated as having occurred due to bending of the oceanic lithosphere (Figure 2b). In contrast, the rest of the normal faulted earthquakes in the region are regarded as due to intraplate seismicity in the overlying lithosphere and they show a close relationship with a normal fault bounding the southern margin of Mashkel depression (Figure 2b).

DISCUSSION AND CONCLUSION

The normal fault related earthquakes have intermediate depths on the north of the Makran accretionary wedge and are generally evaluated as intraslab earthquakes (Jacob and Quittmeyer, 1979; Astiz et al., 1988; Laane and Chen, 1989; Maggi et al., 2000). The hypocenter distributions of these earthquakes are located under the Jaz Murian and Mashkel depressions, where recent field observations on their southern border demonstrate normal faults dipping north (Burg et al., 2013). This paper suggests an alternative view which is that some of the earthquakes on the north of the Makran accretionary wedge are related to the normal fault boundary of a pinched crustal wedge as demonstrated on the physical model of Chemenda et al. (1995). This may explain why most of the volume of the Makran accretionary prism is above sea level, which is dissimilar to other accretionary wedges over the world. If our interpretation is correct, it can be said that coeval normal faults parallel to thrusting can be developed in several tectonic settings independent of crustal thickness, elevation and scale, as seen in the cases of the Himalayas (Burg et al., 1984; Burchfiel and Royden, 1985), the Eldivan-Elmadağ pinched crustal wedge (Seyitoğlu et al., 2009) and the Makran accretionary wedge.

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