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Three-dimensional structure of Conrad and Moho discontinuities in Egypt

Mohamed F. Abdelwahed [a,c,*], Sami El-Khrepy [b,c], Atef Qaddah [a]

[a] Geological Hazards Research Unit, King Abdulaziz University, 21589 Jeddah, Saudi Arabia
[b] Graduate Studies and Scientific Research, King Saud University, Saudi Arabia
[c] National Research Institute of Astronomy and Geophysics, NRIAG, 11421 Cairo, Egypt

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ABSTRACT

The three-dimensional structures of Conrad and Moho discontinuities beneath Egypt are investigated by local earthquake travel time inversion. A number of 2513 events with 24,696 arrival time data recorded by the Egyptian National Seismic Network (ENSN) are used. The station corrections of P- and S-waves and the hypocentral parameters are simultaneously estimated with the Conrad and Moho depths. The results of this study show that the discontinuities form patterns of shallow and deep structures getting shallow toward the northern and eastern coast, and deeper toward western Desert and northeastern Sinai. The Conrad and Moho discontinuities are located within the depth range 9–17 km and 27–41 km, respectively. The depth ranges of Conrad and Moho discontinuities are respectively: 15–16 km and 31–33 km in greater Cairo and Dahshour; 15–18 km and 32–35 km in Sinai; 16–17 and 33–35 km along the Nile River; 9 and 30 km near the Red Sea coast; 15 and 39 km toward the western desert. The comprehensive comparison with previous crustal studies suggests that the main patterns of Moho undulations and the range of Moho depths are in good agreement with the previous crustal models in Egypt, as well as with the Bouguer gravity anomalies that well explain the Nile River sediments, Red Sea mountain belts and Western Desert depression and Oasis. The model of the Moho and Conrad discontinuities improves knowledge of the three dimensional structure of the crust beneath Egypt in wide areas where geophysical data is sparse.

1. Introduction

The Earth's crust, the outer shell of our planet is a thin inhomogeneous skin, complex in structure when compared with the Earth's deep interior, in which the Conrad and Moho are the most dominant discontinuities. The Conrad is the discontinuity separating the upper (granitic) and lower (basaltic) crust. The Conrad discontinuity has been identified on most continents (Europe, North America, Australia, and Asia), but is not present worldwide (Nelson et al., 1985; Merriam, 2006). The nature of the Conrad discontinuity is debatable but presumably indicates a change in rock type, density and compositional phase (Wever, 1989). Whatever the changes, the discontinuity is reflected as a prominent P-wave velocity (Vp) change from 6.1 to 6.7 km/s on seismogram (Merriam, 2006). The Moho discontinuity, first identified in 1909 by Mohorovičić, separates the Earth's crust from the underlying mantle. It represents a major change in seismic velocity, chemical composition, and rheology. The Moho is a distinct discontinuity at the base of the crust indicating a significant change in elastic parameters, resulting from a significant change in the rock types between crust and uppermost mantle. The Moho discontinuity lies at 5–10 km below the ocean floor; and 20–90 km beneath typical continents, with an average of 35 km (Wever, 1989).

The model of the crustal structure, particularly the Conrad and Moho depths, plays an important role in seismology as the starting point for a variety of studies. They can be used for improving the location of earthquakes, thus assisting in defining and mitigating seismic hazards; and global models of crustal velocity structure used to calculate travel time corrections of teleseismic arrivals, facilitating investigation of the interior of the Earth. In conjunction with earthquake data, models may be used as the starting point for crustal tomography, which in turn adds new information to the model, refining it and improving its resolution. In addition to applications in seismology, crustal models define variations in physical properties, which have applications in modeling of tectonic processes and the evolution of the continental lithosphere.

Previously, several studies have been carried out to evaluate the crustal structure in Egypt by using data observed from seismic explosion, deep seismic sounding, shallow refractions, and gravity

* Corresponding author. Address: Geological Hazards Research Unit, King Abdulaziz University, 80206, 21589 Jeddah, Saudi Arabia.
E-mail addresses: mfarouk40@yahoo.com, mfibrahim@kau.edu.sa (M.F. Abdelwahed).

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(e.g., Drake and Girdler, 1964; Tramontini and Davies, 1969; Tealeb, 1979; Makris et al., 1979, 1983, 1988, 1991; Rihm, 1984; Marzouk, 1988; Gaulier et al., 1988; Rihm et al., 1991; Shaaban et al., 1994; , El-Hadidy, 1995; Abd El-Hafiez, 1996; Dorre et al., 1997; Seber et al., 2000; Mohamed and Miyashita, 2001; El-Khrepy, 2001, 2008; Koulakov and Sobolev, 2006; Gharib, 2006; Salah, 2011). Dorre et al. (1997) constructed a crustal thickness map of Egypt by gravity study. Seber et al. (2000) combined refraction gravity with seismic profiles to construct a Moho map of the Middle East and Egypt. Gaulier et al. (1988) estimated the crustal structure of the northern Red Sea and Gulf of Suez from fifteen wide angle profiles. Koulakov and Sobolev (2006) simultaneously inverted the P- and S-waves to constrain the Moho depth and three dimensional P- and S-wave structures of the crust and uppermost mantle in the Eastern Mediterranean and Middle East. Tealeb (1979) defined the basement and Conrad surfaces in northern Egypt by gravity density contrast study. Several deep seismic profiles were carried out along the Cairo–Suez road district (EL-Hadidy, 1995) and along the Red Sea and the Eastern Desert (Marzouk, 1988). In addition, other studies were carried out in different places: Rihm (1984) and Makris et al. (1988) in the northern Red Sea; Salah (2011) in greater Cairo; Hofstetter and Bock (2004) in Sinai; Gharib (2006) in upper Egypt; and wide spread studies conducted by Marzouk and Makris (1990), and Makris et al. (1979). In spite of these studies, the depth of Conrad and Moho discontinuities in Egypt are not well determined. In fact, there is a lack of travel time inversion studies that estimate the Conrad and Moho distribution in Egypt. Previously, travel time inversion studies were not possible due to the lack of real earthquake data. New stations of the Egyptian National Seismic Network (ENSN) have been installed in different parts of Egypt since 1998. Since then, the earthquake observation system in Egypt has been dramatically improved, which encouraged us to invert travel time data of local earthquakes for Conrad and Moho depth estimation. Worldwide, travel time inversion of local earthquakes have been widely used to study the crustal structure (Aki and Lee, 1976; Sato, 1979; Horiuchi et al., 1982a,b; Zhao et al., 1990a,b; Oda et al., 2005; Oda and Ushio, 2007; Bora and Baruah, 2012; and others). Horiuchi et al. (1982a,b) developed an efficient technique to estimate the crustal structure by expressing the Conrad and Moho discontinuities as a two-dimensional lateral depth distribution function using the travel time of the Conrad and Moho refracted phases P^* and Pn, respectively. The depth distribution of layer boundaries, station corrections and hypocentral parameters are determined simultaneously. Later, Zhao et al. (1990a,b, 1992) employed the first onset phase with an efficient ray tracing technique for a 3-D velocity structure. Nakajima et al. (2002) employed the Moho reflected phases (PmP) in conjunction with direct phases. Recently, Oda et al. (2005) and Oda and Ushio (2007) employed the Horiuchi et al. (1982a,b) method to estimate the Conrad and Moho depths in different parts in Japan. In the present study, we applied the technique of Horiuchi et al. (1982a,b) to estimate the 3-D structure of the Conrad and Moho discontinuities in Egypt by using the ENSN data. This study is considered the first attempt to use a large number of crustal phase travel times recorded by the ENSN data for Conrad and Moho depth estimation in Egypt. A short review of the previous seismological and seismic (refraction, wide-angle and near-vertical reflection, deep seismic sounding) studies that have been carried out in Egypt is provided as well, for comparison with the current results. This study is an attempt to improve our knowledge about the characteristics of the Earth's crust in Egypt and its relation with its seismic and tectonic settings.

2. Tectonic setting

Egypt is located in the northeastern corner of the African continent. It is bounded by three active tectonic margins: the African Eurasian plate margin; the Red Sea plate margin; and the Aqaba-Dead Sea fault (Fig. 1). This in its turn creates critical continental conditions that are responsible for the major seismic activities in Egypt since prehistoric time. The recent geodetic data and GPS measurements imply that the African plate is moving NW with respect to Eurasia with a velocity of 6 mm/year (McClusky et al., 2000) and the spreading rates along the Red Sea decrease from 14 mm/year at 15°N to 5.6 mm/year at 27°N. Along the southernmost segment of Aqaba-Dead Sea fault, motion is a left-lateral strike-slip of 5.6 mm/year (McClusky et al., 2003). This left-lateral motion shows a rate of about 2.8 mm/year at the northern segment of the Dead Sea with slight spreading of the Suez rift (Wdowinski et al., 2004). This yields some secondary deformation manifested by moderate earthquake activity along the northern Egyptian coast. Based on geophysical studies in the territory of Egypt, three major tectonic trends are recognized, namely the Red Sea trend oriented NW–SE, the Gulf of Aqaba trend oriented NE–SW and the Mediterranean trend oriented E–W (Yousef, 1968). Owing to these complex tectonics, the distribution of seismic activity in Egypt is observed in four narrow belts: Levant-Aqaba; Northern Red Sea-Gulf of Suez–Cairo–Alexandria; eastern Mediterranean-Cairo-Fayum; and the Mediterranean Coastal Dislocation (Sieberg et al., 1932; Ismail, 1960; Maamoun et al., 1984; Kebeasy, 1990; Abou Elenean, 1997). The interaction of the aforementioned tectonics creates continental conditions that are responsible for the major earthquake activity in Egypt. The African and Eurasian plates are converging northward across a wide zone in the northern Mediterranean Sea yielding some secondary deformation, which causes moderate earthquake activity along the northern Egyptian coast in a belt parallel to the Hellenic arc (Fig. 1). The Sinai triple junction (the intersection of the northern Red Sea rift, the Gulf of Suez rift, and the Gulf of Aqaba Dead Sea faults) is responsible for the high seismic activity in the eastern part of Egypt. The extension of this deformation zone westward follows the Suez–Cairo–Alexandria shear zone which is considered as the most active part of northern Egypt and probably extends northward toward the Mediterranean Sea (Kebeasy et al., 1981; Ben-Avraham et al., 1987). Significant seismic activity is also found along the entire Gulf of Suez and its extension on the northern part of the Eastern desert towards the Nile Delta along the E–W and WNW faults. This activity trend does not continue further towards the Mediterranean Sea and ceased closer to the west of Nile Valley at Dahshour area where the 12 October 1992 earthquake (ML5.9) took place. Further seismic activity is associated with the shear zones along the Red Sea coast southern of Egypt. For more detail see Abou Elenean (1997). For instance, the type of the crust beneath the eastern Mediterranean Sea varies from oceanic to continental types. Along the northern part of the Red Sea Egyptian coastline, the crust is oceanic (Makris and Rihm, 1991). Near the Red Sea, the crust is continental consisting of a sedimentary layer of 3 km with velocity of 3.5 km/s, overlying a 30 km thickness of crust having a moderate velocity changes from 6.0 to 6.35 km/s (Meshref, 1990). Near the Nile Valley, the crustal structure is rather heterogeneous and changes abruptly from area to another. Within the Nile Valley graben, loose water-saturated sediments are present having a rapid decrease in sediment thickness and water saturation in both directions away from the graben (El-Sayed and Wahlström, 1996; Badawy, 2005).