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Geodetic evidence for low coupling on the Hellenic subduction plate interface

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ABSTRACT

We develop a block model for the Aegean and surrounding areas, constrained by Global Positioning System (GPS), in order to investigate the degree of coupling on the Hellenic subduction interface (i.e., the fraction of the motion across the plate boundary accommodated by elastic strain accumulation). We use previously published models, and seismicity to define the geometry of the interface separating the down-going Nubian slab from the overriding Aegean. This model provides a good fit to the GPS observations; for the ∼200,000 km^2 Aegean block the wrms of the residual velocities is 1.4 mm/yr for 80 GPS velocity estimates, approximately the 95% level of the GPS velocity uncertainties. We investigate the degree of coupling on the seismically active plate interface, the Hellenic trench splay fault (believed to be the source of the 365 AD Great Crete Earthquake and Tsunami), and the Kephalonia transform fault by comparing the modeled GPS residual velocity field for a range of coupling values. The GPS observations are almost insensitive to coupling on the Kephalonia transform fault, because of the vertical dip of the fault that creates interseismic deformation only close to the fault where few GPS sites exist. The absence of resolvable shortening of the leading edge of the Aegean Plate precludes coupling of more than 0.2 (20% of the full Nubia–Aegean convergence rate) on the modeled plate interface. Because of the shallow dip of the plate interface and trench splay fault, and high rate of convergence, if these boundaries were fully coupled, high elastic strain rates would be expected to extend well into the overriding Aegean plate. Based on our preferred value for the degree of coupling (0.1), and assuming characteristic earthquake behavior, we estimate a recurrence time for great earthquakes with slip similar to that for the 365 Crete event of 5700–8300 yr, consistent with the absence of subsequent great earthquakes on this segment of the subduction zone.

1. Introduction

The Hellenic subduction zone is the fastest and most seismically active deformation zone of the Mediterranean region (Fig. 1). Although the Eurasia–Nubia convergence rate at the location of the Hellenic arc is on the order of ∼6 mm/yr (McClusky et al., 2003), the motion of the Aegean region southward relative to Eurasia leads to a convergence rate along the Arc of ∼35 mm/yr (Reilinger et al., 2006). This subduction zone is a key element in the active tectonics of the eastern Mediterranean and the broader zone of Nubia–Arabia–Eurasia plate interaction (e.g., McKenzie, 1972; Le Pichon and Angelier, 1981; Jolivet and Faccenna, 2000).

The tectonic evolution of the Aegean region is intimately related to northward subduction of the Neotethys. Presently, Mesozoic Mediterranean sea floor subducts northward beneath Crete and the Aegean Sea. Opening of the Aegean Sea initiated at least during Oligocene with the retreat of the African slab (Jolivet and Faccenna, 2000; Jolivet and Brun, 2010). The present day geodetically determined velocity field of the Aegean region suggests very low deformation of a broad area of the southern Aegean and Peloponnese that can be modeled as a single quasi-coherent plate (Fig. 1; McClusky et al., 2000; Nyst and Thatcher, 2004; Reilinger et al., 2006). This present day, low deformation contrasts with the overall extension that has collapsed an early Cenozoic mountain belt (Jolivet and Brun, 2010). Nevertheless, the flat Moho around 25–26 km depth (Tirel et al., 2004) and the 5–25 km depth range of the normal faulting earthquakes in the overriding Aegean Plate (Shaw and Jackson, 2010) are consistent with a region of thinned continental crust with an approximately normal elastic thickness.

Geodynamic models for the eastern Mediterranean region generally appeal to two first order processes; retreat of the subducting African plate along the Hellenic subduction zone, and the westward extrusion of the Anatolian Plate accommodated by

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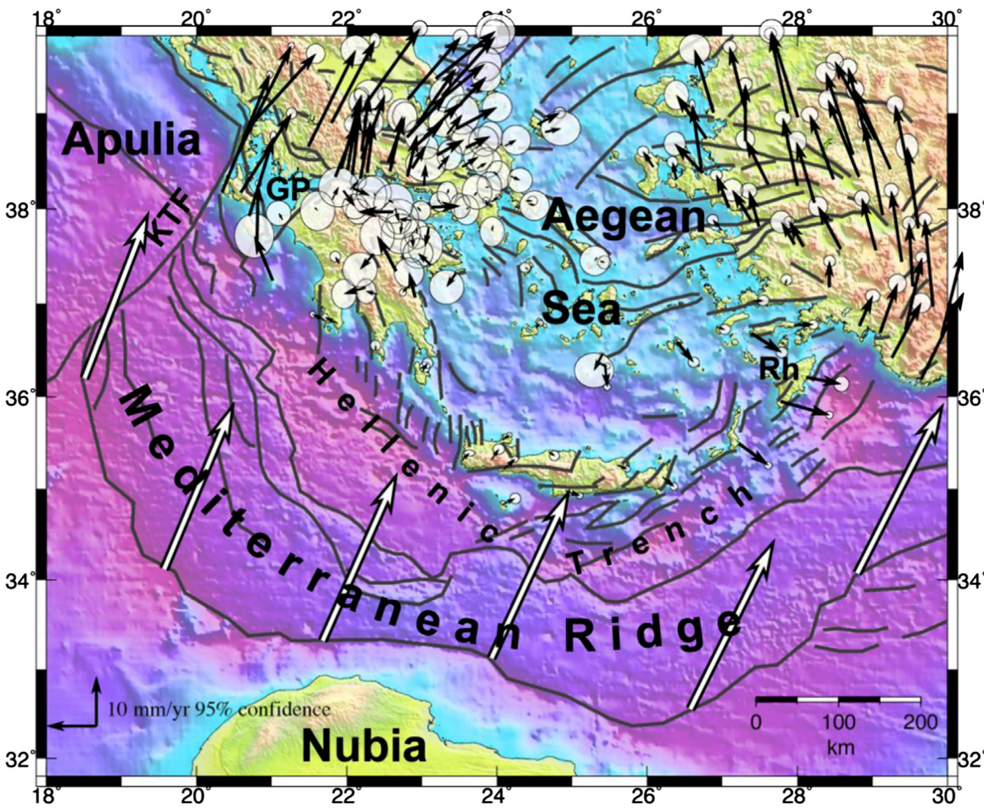

Fig. 1. GPS velocity field and 95% confidence ellipses with respect to the central Aegean (see Reilinger et al., 2010 for more details on stable Aegean reference frame). Velocities are from Nocquet's (2012) combination of Reilinger et al. (2006), Hollenstein et al. (2008), Aktug et al. (2009) and Floyd et al. (2010). To avoid clutter, sites with large uncertainties (>2 mm/yr) are not plotted. GP – Gulf of Patras; KTF – Kephalonia transform fault; Rh – Rhodes. White arrows depict the motion of Nubia relative to stable Aegean.

the North Anatolian fault (e.g., Le Pichon and Angelier, 1981; Şengör et al., 1985; Jackson, 1994; Flerit et al., 2004; Jolivet and Brun, 2010). Present-day kinematics emphasize the role of slab retreat based on the GPS velocity field that shows an increase in the rates of crustal motion towards the Hellenic trench from Arabia to the southern Aegean (McClusky et al., 2000; Reilinger et al., 2006; Le Pichon and Kreemer, 2010). Within this tectonic framework, the quasi-rigid behavior of the Aegean domain could be related to the westward propagation of the North Anatolian fault across the north Aegean (Armijo et al., 1999) that separates the southern Aegean region from Eurasia and allows its coherent translation towards the retreating subduction boundary (Reilinger et al., 2010).

The Hellenic slab is well imaged by seismic tomography (Wortel and Spakman, 2000; Piromallo and Morelli, 2003) with a length of more than 1500 km, attesting to the long period of Neotethys northward subduction. The seismogenic part of the Hellenic plate interface is primarily restricted to above 45 km depth (Shaw and Jackson, 2010). The precise location and geometry of the seismogenic part of the plate interface is key to further infer its coupling and associated seismic hazard. Several studies have focused on and contributed information on the location of the plate interface (Hatzfeld and Martin, 1992; Papazachos et al., 2000; Bohnhoff et al., 2001; Li et al., 2003; Meier et al., 2004; Kokinou et al., 2006; Ganas and Parsons, 2009; Pearce et al., 2012).

Although the Hellenic arc represents perhaps the most significant seismic and tsunamic hazard in the Mediterranean region (e.g., Shaw and Jackson, 2010), its kinematics and associated hazards remain uncertain and are actively being investigated. This is exemplified by recent geodetic and seismic studies of the degree of coupling along the Hellenic plate interface, a parameter needed to constrain estimates of earthquake repeat times. Aseismic slip on the plate interface was originally suggested by Jackson and McKenzie (1988) and further expounded by Shaw and Jackson (2010) based on the absence of sufficient subduction earthquakes to accommodate plate convergence. Based primarily on pre-2006 GPS velocities which showed low strain in the overriding Aegean plate, Reilinger et al. (2010) suggested a low coupling (i.e. less that 20%) on the Hellenic arc subduction thrust. But a similar study using a finite-element model to fit the earthquake activity and almost the same GPS data, but a more detailed geometry for the plate interface concluded that the interface is nearly fully coupled (Ganas and Parsons, 2009).

Since the initial geodetic studies that suggested quasi-rigid behavior of the Aegean domain, many GPS sites have been resurveyed, new studies including new GPS sites have been published (Hollenstein et al., 2008; Aktug et al., 2009; Floyd et al., 2010) and velocity uncertainties have improved. In this study we use the improved GPS velocity field and recent constraints on earthquake mechanics (Shaw and Jackson, 2010) to re-examine the degree of locking of the Hellenic plate interface, the Hellenic trench fault, and the Kephalonia transform fault (Fig. 1). We use all available seismic studies to better define the geometry of the seismogenic part of the plate interface. We then use a block modeling approach (McCaffrey, 2002; Meade and Hager, 2005), constrained by available GPS velocities combined by Nocquet (2012) and crustal seismicity to quantify the degree of coupling on the plate interface.

2. Geometry of the Hellenic arc plate interface

To model deformation of the overriding Aegean Plate due to strain accumulation on the plate interface, we estimate the geometry of the interface as shown in Fig. 2A from published seismic studies (Hatzfeld and Martin, 1992; Papazachos et al., 2000;