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# A study of the crust stress field for the Aegean region (Greece)

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ABSTRACT

The in situ stress field may be assessed from data such as the fault plane solutions of the earthquakes occurring in the region and by estimation of a stress field compatible with the kinematic behavior of the crust. The regional kinematics may be derived from the velocity field estimated from GPS data and other geodetic observations.
In the present work an investigation of the stress field of the Aegean Sea is carried out following two approaches; both use the same tectonic characteristics for the Hellenic region and the same assumptions referring to the mechanical properties of the medium. In the first approach, the yearly rate of the in situ crustal stresses, based on a two-dimensional FE linear analysis, are evaluated solving for the inverse problem, given the GPS observed displacement field for the broader Aegean region. The results have been compared with published papers and with stresses obtained from available focal mechanism solutions.
In the second approach the borders of the probable lithospheric micro-plates and the active faults are considered as discontinuities in an elastic half-space representing the earth's crust. The Coulomb stress changes due to the tectonic slip are evaluated, providing an insight of the way these tectonic elements interact. Assuming succeeding activation of the tectonic structures of the region the accumulation of the Coulomb stress changes has been estimated. The accumulated Coulomb shear stress distribution provides a criterion for the selection of the more realistic boundary conditions for the FE modeling. In this respect, the two approaches complement each other and enrich the final picture discussed here.



## 1. Introduction

The Eastern Mediterranean is a region of great geotectonic interest, where intensive and repeated geological, geophysical, geodetic, and geomechanical studies have been carried out for several decades. The complicated tectonic behavior of this area appears to be governed by the collision of the Arabian and African plates with Eurasia. A key element needed for better understanding of the driving forces shaping the region is to estimate constraints on the active stress field associated with the tectonic motions.

The scope of the present work is to study the stress field in the Aegean region by following two distinctly different but complementary approaches and to compare and discuss the respective results. Both procedures acknowledge common assumptions regarding the mechanical behavior of the medium that is linear elasticity and frictional interaction of the fault surfaces, while they share a common tectonic setting and the same area of study.

First, we use kinematic information in the form of GPS average surface yearly displacements available for the region, in order to estimate the stress field by solving the inverse problem. Commercial finite element software developed for geotechnical purposes is used, since it allows for the fault segments to be embedded in the continuum as discontinuities where frictional slip may occur. These discontinuities are inserted in the model piecewise – in successive stages – until, in the final stage of the FE modeling, all documented active tectonic features have been included. The initial stage refers to an un-fractured continuum. The method allows the major tectonic features of the Hellenic region (e.g., the Hellenic arc, the Corinth rift, the north Aegean trough etc.) to evolve in the stress field. The features are delineated even in the initial stage, where none of these discontinuities have been introduced in the modeling yet.

Second, in order to study fault interactions and the respective stress changes, we evaluate the cumulative Coulomb stress changes assuming sequential activation of the main tectonic features of the Hellenic region. Due to the hypothesis that the medium behaves in a linear elastic manner, superposition is allowed and the final result is independent of the stress history (sequence of the activation of the tectonic elements) provided that the cumulative effect is sought. The Coulomb Stress software of the USGS is used in this case (http://www.coulombstress.org), with the underlying method being the boundary element method modified to calculate the Coulomb stress changes and to illustrate the

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results. Linear elasticity is a requirement in the case of the Coulomb software we used; thus our FE modeling was, also, restricted to the same condition, in order to be able to compare the results. Provided that the Coulomb stress changes are shear in character comparisons between the two approaches are feasible.

### 1.1. Tectonic setting

In the south Aegean, the convergence rate between Africa–Eurasia of less than 10 mm/yr (Becker and Meier, 2010; Shaw and Jackson, 2010) is significantly lower than the southwestern extension rate of about 35 mm/yr of the Aegean lithosphere, estimated from satellite geodetic observations (Reilinger et al., 2006, 2010) (Fig. 1a). The Hellenic subduction zone is an important element for the description of the eastern Mediterranean tectonics, although several aspects of its kinematics are still insufficiently understood. The knowledge that it is largely aseismic, in the sense that there is a marked deficit of earthquakes to account for the Africa–Aegean rapid convergence (Shaw and Jackson, 2010) is one of them. However, the south Aegean boundary, the Hellenic arc, is the most seismically active region of Europe, being fairly well delineated from the west, close to Zakynthos, to the south, beneath Crete and to the eastern termination near Rhodes (Fig. 1a). Several large earthquakes ($Ms > 6$) of intermediate depth have occurred along the Hellenic arc, while the historical record contains two earthquakes of $Mw > 8$ in the last 2000 yr (Becker and Meier, 2010; Papazachos et al., 1999; Shaw and Jackson, 2010) (Fig. 1b). When historical earthquakes from the last 100 years are used in order to estimate the cumulative seismic moment release rate for the region, the result amounts only to about 15% of the convergence rate of Nubia–Aegean. The contribution of the rare events of $Mw > 8$ only adds 5–10% more to the seismic moment estimations; the subduction zone is largely uncoupled (Shaw and Jackson, 2010).

The complicated tectonic history of the region involves subduction and continental collision, followed more recently by extension. It is assumed that the extension rate of the Aegean Sea (Fig. 1a) is mostly driven by the "roll-back" of the relatively thin subducting slab beneath the south Aegean, as it sinks into the mantle (Kahle et al., 2000; Le Pichon et al., 1995; Reilinger et al., 2010; Taymaz et al., 1991). The westward motion of Turkey with respect to Eurasia, with a rate of 20–25 mm/yr is mostly accommodated on the North and East Anatolian strike-slip fault systems. The seismically active regions of western Turkey, eastern and northern Greece and the north Aegean Sea are dominated by extension, while the region of the Aegean Sea is moving rapidly, at a rate of 35 mm/yr, in an approximately NNE–SSW direction with respect to Eurasia. Although a significant seismic activity has been observed around the edges of the Aegean Sea (Fig. 1b), the southern Aegean and Peloponnesus peninsula show little internal deformation, as the extensive GPS observations indicate and all the kinematic models for the region suggest (Reilinger et al., 2006, 2010; Shaw and Jackson, 2010).

Even though there is a general agreement about the large-scale tectonics of the region, the mechanical interpretations of the relations between the driving forces and the resultant relative motions differ to a significant extent. According to several researchers (Le Pichon et al., 1995; Nyst and Thatcher, 2004; Reilinger et al., 2006, 2010), deformation in the region occurs in the form of motion between rigid microplates with zones of diffuse deformation in the interior of the plates. Alternatively, the continental lithosphere is considered weak enough to deform in a distributed fashion under the forces acting on it. The relatively thin (~10 km depth) brittle crust is considered as moving, on the large scale, in a pattern reflecting the spatially smooth deformation of the underlying ductile parts of the lithosphere (Davies et al., 1997; Taymaz et al., 1991). More recently, an approach based on fracture mechanics and crack propagation considers that almost all deformation is concentrated along block boundaries, while faults evolve by propagation in a similar way that fractures occur in a brittle medium (Armijo et al., 2003; Flerit et al., 2004). This last approach is more closely related to the essence of our work since they use a continuum modeling approach where faults are modeled as dislocations embedded in the elastic medium. This is in agreement with the mechanical modeling we are attempting here, since we also consider linear elasticity and the faults as discontinuities under frictional slip embedded in the continuum.

### 1.2. Previous models for the Aegean region

The tectonic behavior of the region has been studied and described by a variety of both kinematic and dynamic models. The kinematics of deformation observed on the free surface of the Earth has been studied by block (or microplate) modeling; it emphasizes the role of discontinuous deformation in the upper elastic/brittle layer of the lithosphere. The dynamic modeling exploits continuum mechanics and attempts to combine both kinematics and dynamics based on the assumption that the ductile properties of the lithosphere control the deformation (Thatcher, 2009). The choice of the appropriate model for understanding continental deformation depends on whether the stresses driving this deformation are supported mostly in the brittle/elastic upper layer of the crust or the ductile lower region (Thatcher, 2009).

The surface motions, monitored by GPS observations, are often block-like; therefore, the block model has been applied extensively to model the kinematic behavior of a region quite successfully. A common technique in all kinematic studies is to use the geodetically derived velocity field (GPS or otherwise) as the primary data for the modeling. In the case of the dynamic modeling boundary conditions and elastic parameters are used as input and the model velocity field is compared to the geodetically observed one in order to improve the model in an iterative procedure. Our dynamic modeling is the first, as far as we know, to use as input kinematic information that is the available average yearly GPS velocity field for the Hellenic region, in order to calculate the in situ stresses. For comparison purposes a short description of previous similar studies is given below.

Previous dynamic modeling for the Aegean region includes Chianetti et al. (1997), who used a two-dimensional FE analysis with a two-layered model for the upper crust and the lower more ductile lithosphere. Their model included boundary conditions of 30 mm/yr northward motion for the Arabian plate, restriction of the westward motion of the extruding Anatolian plate in north Greece and a trench suction force of 40 MPa – as they call it – at the Hellenic trench (Chianetti et al., 1997); the resultant velocity field was comparable with the observed one from GPS observations. A more recent study of the broader Aegean–Anatolia region (Chianetti et al., 2001) used FE modeling including heterogeneity for both the crustal thickness and for the surface heat flow. Their predicted velocity field is an improvement to their previous modeling and satisfies to a better degree the complex pattern of the observed GPS velocities. Mantovani et al. (2000) also used plane stress and two-dimensional FE modeling for the Mediterranean region with boundary conditions representing the motions of Africa (Nubia) plate and Anatolia with respect to Eurasia. Their predicted velocity field

**Fig. 1.** a. Setting of the Aegean. Labels show places referred to in the text. Lines with teeth show the locations of reverse faults of the Hellenic Trench system. None of the trenches coincides with the true plate boundary. Blue line marked KFZ shows the Kefalonia right-lateral strike-slip fault zone. The major gulfs are shown by crossed lines: the Gulf of Evvia, is between Evvia and Central Greece; the Gulf of Corinth lies between the Peloponnese and central Greece. b General tectonic setting of the research area. The filled circles indicate relocated ISC seismicity from 1964 to 2006, and black stars indicate historic seismicity with $Mw \geq 7{:}0$ for the time period from 550 B.C. to 1999 A.D.
Panel a: after Floyd et al. (2010). Panel b: after Becker and Meier (2010).