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STUDY OF THE GEODYNAMICS IN WESTERN GREECE BASED ON JOINT SEISMOLOGICAL AND GPS DATA

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Abstract

Earthquake and CGPS recordings have been used to study the geodynamic regime in western Greece. The study area includes Aitoloakarnania, western Corinth Gulf, Patras Gulf, NW Peloponnesus and the area of the central Ionian Islands (Zakynthos, Cephalonia, Ithaki, Lefkas). This region was activated during the last decade with the occurrence of several moderate to strong events, providing a large amount of new information of enhanced quality due to the recently developed Hellenic Unified Seismological Network (HUSN). On the other hand, the currently established CGPS network in western Greece allowed the coupling of its recordings with the seismological data. A new catalogue of seismic phase data was compiled, including seismic activity with M≥2.0, recorded by the HUSN. Additionally, available phase data recorded by local networks in the frame of aftershock sequences monitoring and temporary microearthquake campaigns were employed. To achieve improved hypocentral locations the concept of double differences was applied and ~10000 out of ~12000 events were relocated. A catalogue of 1130 available focal mechanisms concerning 850 events was constructed, from which 710 events were relocated. A damped iterative technique was used to invert the focal mechanisms, in order to obtain the regional stress field parameters. The CGPS databank of daily recordings was processed and provided time dependent ground deformation at 11 stations. The combination of the above procedures allowed the detection and investigation of several seismogenic and aseismic zones across the study area, enlightening up to a degree the complex style of its crustal deformation with the elaboration of a geodynamic model. In the context of a future detailed survey, a strategy for collecting complementary data at specific sites in the area is proposed.

Introduction

The geodynamic regime of western Greece is investigated using combined seismological and CGPS data. The study area comprises of Aitoloakarnania, south Ionian Islands (Lefkada, Cephalonia, Zakynthos), western Corinth gulf, Patras gulf and NW Peloponnesus (Figure 1). The study area is characterized by the highest seismicity rates in the Mediterranean region, since it is dominated by a complex seismotectonic regime. Recently, this area undergone tectonic instability due to the occurrence of several earthquakes. Seismic activity started along the northwestern Hellenic trench and moved towards the east, to eastern Akarnania, NW Peloponnesus and western Corinth Gulf. Those earthquakes in conjunction with the recently deployed Hellenic Unified Seismological Network provided a large amount of new information for the area of W. Greece. The motivation for the current research was to combine selected available quality seismological and space geodesy data with modern analyses in order to give insight to styles of deformation in local and regional scale.

Locations and focal mechanisms from locally and regionally recorded earthquakes were employed in order to cover the under study area. The data used are from McKenzie (1972); Ritsema (1974); Papazachos (1975); Delibasis and Karydis (1977); McKenzie (1978); Anderson and Jackson (1987); Hatzfeld et al. (1990); Taymaz et al. (1990); Kiratzi and Langston (1991); Hatzfeld et al., (1995); Baker et al. (1997); Melis and Tselentis (1998); Liotier (1989); Haslinger et al., (1999); Louvari et al. (1999); Louvari (2000); Kaviris, (2003); Kaviris et al., (2007); Papadimitriou et al., (2011); Tiberi et al., (2000); Papazachos and Papazachou (2003); Kiratzi et al. (2008); Evengelidis et al., (2008); Agalos et al., (2007); Moshou et al., (2007); Konstantinou et al. (2010); Kassaras et al., (in press). Locations and fault plane solutions were also obtained by the Athenet network of the Seismological Laboratory of the University of Athens, the Geodynamic Institute of the National Observatory of Athens (GI-NOA), the Global Centroid-Moment-Tensor (CMT) Project, the Swiss Seismological Service (SED) at the ETH Zurich, the European-Mediterranean Regional Centroid Moment Tensors (Pondrelli et al., 2006), the "Earthquake Mechanisms of the Mediterranean Area" (EMMA) database (Vannucci and Gasperini, 2004). Five recent aftershock sequences were also incorporated into our dataset, namely: the 2003 Lefkas sequence, the 2006 Zakynthos sequence, the 2007 Trichonis Lake earthquake swarm, the 2008 NW Peloponnese (Andravida) earthquake sequence and the 2010 Nafpactos earthquake sequence.

Seismotectonic map of W. Greece

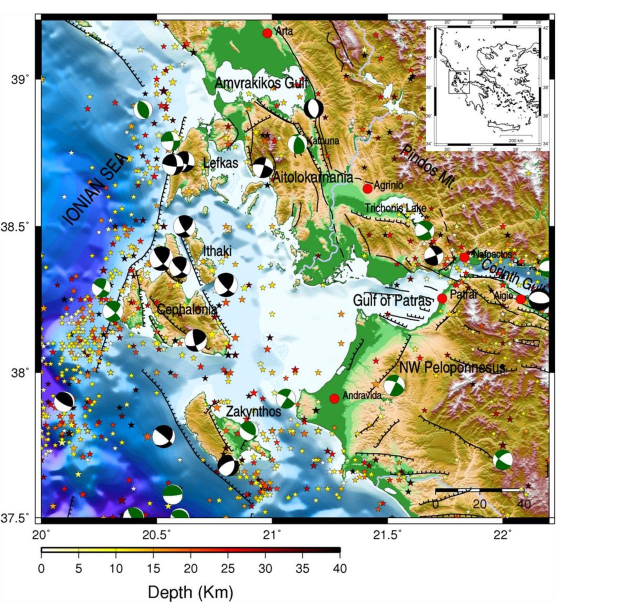


Figure 1. *Relief map of western Greece with the main tectonic features, observed (continuous lines) or inferred (dashed lines) and toponymes. Stars denote epicenters of shallow (H<40 km, Ms≥4.0) earthquakes. Beachballs are available fault plane solutions for events with M≥5.8. Black and green compressive quadrants denote earthquakes prior and after 1964, respectively. Top right embedded figure denotes the location of the study area within Greece.*

Hypocentral relocation

Precise earthquake hypocenter parameters are required to study in detail structure properties and processes that trigger seismic activity. The accuracy of hypocenter locations and their uncertainties depend on several factors, including the number and quality of available seismic phases, the accuracy with which arrival times are measured, the network geometry, the knowledge of the velocity structure and the linear approximation to a set of non-linear equations, which is assumed in the inversion.

The compiled seismic phase catalogue comprising of ~12000 events, with average horizontal and vertical spatial errors of ~2 and ~6 km, respectively was relocated using HypoDD (Waldhauser and Ellsworth, 2000). HypoDD is an algorithm that minimizes residuals between observed and calculated travel time differences (double-differences) for pairs of neighboring earthquakes at each station that recorded both events. In this way, errors caused by unmodeled velocity structure are minimized without the use of station corrections. A minimum 1-D layered velocity model was used to predict travel time differences and partial derivatives.

Iterative inter-event distance variations and misfit weighting were applied to the catalogue data, in order to optimize their quality during relocation. Throughout the relocation procedure the main factors that have been taken into account were the size of the dominant clusters, the network coverage of the area, and the occurrence of an aftershock sequence that could reduce the maximum input separation distance. About 10000 hypocenters were finally relocated. Relative spatial horizontal and vertical errors were improved leading to a denser spatial clustering of the earthquakes with respect to the initial locations (Figure 2).

Locations with Hypoinverse | **Relocations with HypoDD** | **Selected relocations with HypoDD**

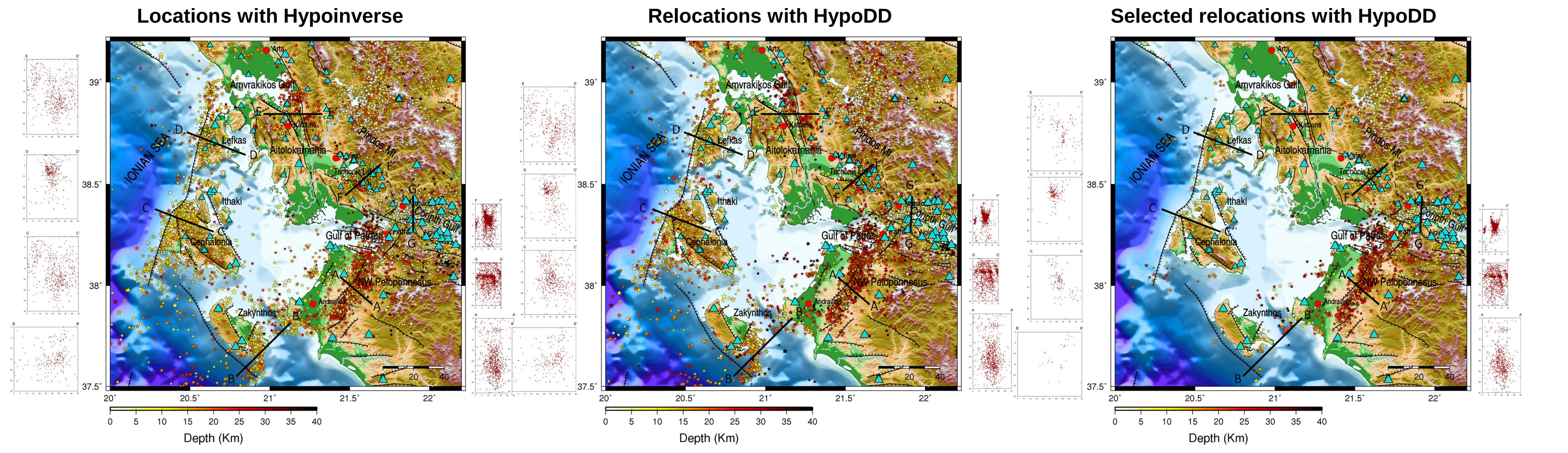


Figure 2. *Map of spatial distribution of located with Hypoinverse (left) and relocated with HypoDD (middle and right) crustal earthquakes in western Greece, included in the catalogue compiled in this study. Cyan triangles denote seismological stations used. Larger triangles are permanent stations and smaller are temporary stations. Black lines indicate the positions of cross sections AA'-GG', plotted side of the maps. Selected relocations are events with ERH, ERZ <5 km. Evident is that the quality of hypocentral locations and relocations is directly proportional to the number and epicentral coverage of the recording stations.*

The main comments on seismicity distribution are summarized below:

- Seismicity clearly defines a crustal block with almost absent internal seismic deformation, including Zakynthos, Cephalonia, Lefkada, NW Peloponnesus, Patras Gulf and Aitoloakarnania. This block has been activated within the last decade, with several strong and moderate earthquakes, providing new data of enhanced quality which were incorporated in the study.
- The majority of relocated seismicity is shallower than 40 km. A few earthquakes east of south Zakynthos are located deeper, implying for the active character of the Hellenic subduction in the area.
- In the area of central Ionian Islands, the hypocentral locations of this study (Figure 2) appear shifted by about 10 km towards the east with respect to the ISC locations (Figure 1).
- Relocated seismicity with HypoDD (Figure 2b, 2c) appears more concentrated with respect to the initial locations determined with Hypoinverse (Figure 2a).
- Cross-sections performed locally, perpendicular to main tectonic features, reveal the degree of relocation efficiency. It is clearly proved that the latter is directly depended on the stations density. Best hypocentral solutions and dense event clustering are observed in areas covered by dense networks, i.e. Nafpactos, Trichonida, Lefkada and Cephalonia. Relocation yielded poor results in the area of Zakynthos and partly NW Peloponnesus, due to the sparsely distributed stations of the regional seismological network.
- In the area of north Aitoloakarnania, even though data from two microseismic campaigns with a total duration of 5 months were employed (1989, 1995), the number of hypocentral solutions does not allow detailed analysis, due to the low seismicity rate, or the small size of earthquakes. Hence, the installation of a local dense network is perquisite, in order to provide additional enhanced quality data for this key area.

All focal mechanisms (located + relocated) | **Only relocated focal mechanisms**

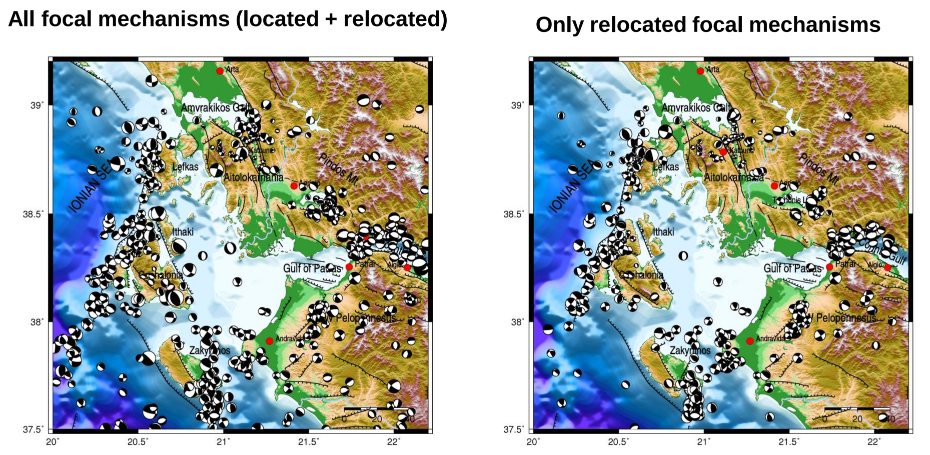


Figure 3. *Left: map of all available focal mechanisms of crustal earthquakes in western Greece containing the initial catalogue hypocentral solutions and those obtained by HypoDD. Right: map containing only the focal mechanisms for which hypocentral locations were obtained by the double difference relocation (HypoDD). Black and white quadrants represent compression and dilatation, respectively. The size of the beachballs is proportional to the earthquakes magnitude.*

Focal mechanisms

1130 fault plane solutions concerning about 850 earthquakes with 1.6≤M≤7.4 were considered in our study (Figure 3). Among those, 710 were relocated with HypoDD with 1.6≤M≤6.5 (Figure 3). Fault plane solutions of larger magnitude events are mainly moment tensor and teleseismic body wave modeling solutions, while for smaller events, focal mechanisms (M≤3.5) are determined by P-wave first motion polarities. Sources for the compiled fault plane solutions catalogue are listed above. In Figure 4a, P- and T-axes orientation is presented for all available mechanisms. In figure 4b and 4c, prevailing P- versus T- axes orientation is plotted employing all and relocated events with HypoDD.

Focal mechanisms all types of faulting in the study area. Normal, reverse and strike-slip. Strike-slip faulting dominates along the Cephalonia-Lefkas transform fault zone, in NW Peloponnesus along the recently activated (2008) Andravida fault zone and in NE Aitoloakarnania, along the Katouna fault zone. Reverse faulting is mainly observed in the area of south Zakynthos Island. SW-NE compressional tectonics dominates in the area of central Ionian Islands and SW-NE and N-S extensional tectonics in the area of east Aitoloakarnania and western Corinth gulf, respectively, as both beachball diagrams and P- and T-axes distribution indicate (Figures 3 and 4).

Regional stress tensor inversion

In order to produce a regional scale model of stress orientation, a stress tensor inversion method was applied to the focal mechanisms. The method used is SATSI (Spatial And Temporal Stress Inversion), developed by Hardebeck and Michael (2006), which is a modified version of Michael's code (Michael, 1987). The procedure includes division of the study area into small subareas, and employment of a damped inversion method to simultaneously invert for stress in all subareas while minimizing the difference in stress between adjacent subareas. Stress orientation uncertainty is estimated using bootstrap resampling of the entire data (Hardebeck and Michael, 2006).

Damped iterative inversion of the focal mechanisms was performed at equally gridded subareas of 0.25°×0.025° dimensions. The damping parameter was set considering the "knee" of the trade-off curves of the model length toward the data misfit function. The confidence degree of the focal mechanisms was set 80%, while the confidence region of the stress model was defined by the 95% of solutions closest to the preferred solution (2σ). The number of bootstrap solutions was set to 1000 (Hardebeck and Michael, 2006). Stress parameters were determined for 39 nodes. Nodes with less than 10 events were not used to smooth gaps in the seismicity only when compatible with adjacent areas, while nodes with less than 6 events were not considered. The results of the inversion procedure are presented in Figure 5 and briefly discussed below.

σ_1 stress component

Principal compressional component σ_1 appears homogeneous, especially when only relocated events are considered. In the area of central Ionian Islands σ_1 strikes WSW-ENE, compatible with ground deformation derived from GPS observations (Ganas et al., 2012; this study). In this area σ_1 is the prevailing horizontal component, as the inverted stress tensor magnitude indicates. Towards the east, the orientation of σ_1 gradually changes to WNW-ESE, while the magnitude decreases, as the inverted stress tensor indicates. The area where the compressional stress field appears rotated by 90º towards SE is along the Trichonis-Patra shear zone.

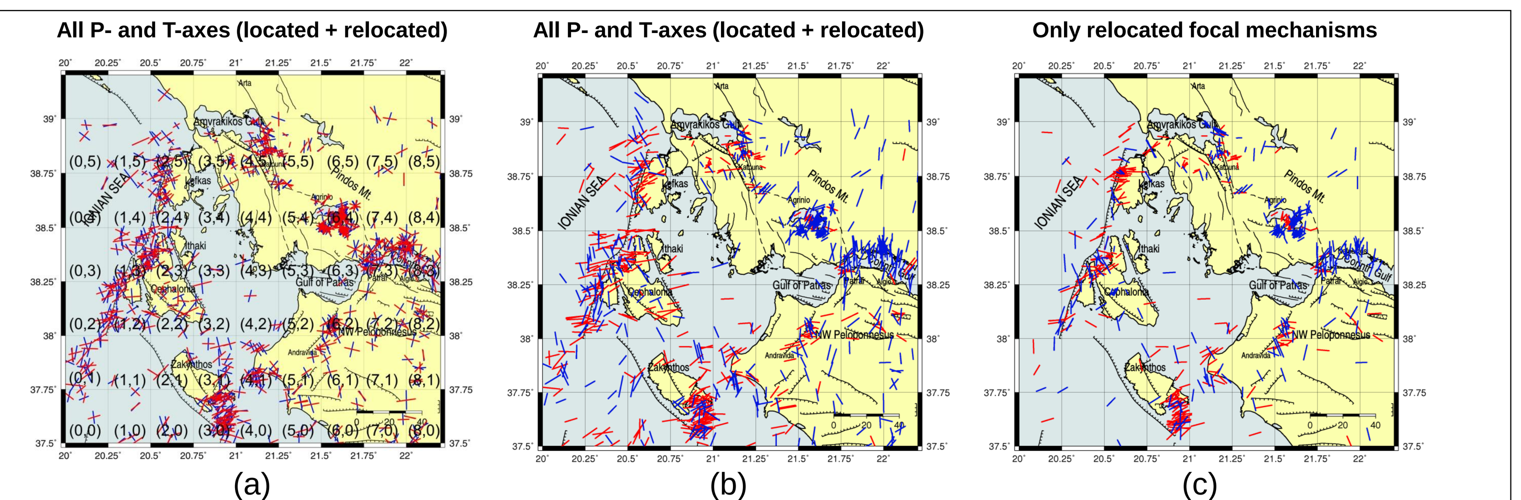
σ_3 stress component

Principal extensional component σ_3 appears homogeneous east of the central Ionian Islands (on mainland), showing an almost N-S orientation. In this area, σ_3 is the prevailing horizontal stress component. An abrupt change of σ_3 orientation in the area of Trichonis has been explained as a local isostatic effect (Kassaras et al., in press). In the area of central Ionian Islands two patterns are seen. South of Cephalonia, σ_3 is directing NNE-SSW and towards north Cephalonia and Lefkas, σ_3 is striking NNW-SSE. This variation could be explained by a change of the geometry along the Cephalonia-Lefkas transform fault, or/and some interaction of the southern tip of the above structure with the wedge of the African lithosphere north of Zakynthos Island.

σ_2 stress component

The orientation of the intermediate component σ_2 follows quite similar pattern with σ_1. Its NW-SE orientation in the west, gradually changes to E-W, with the boundary of the ~60º variation towards the NE being intergraded along the Trichonis-Patra shear zone. In the area of central Ionian Islands and south of Amvrakikos gulf σ_2 strikes parallel to the Hellenic Trench. Similar pattern was observed by Hatzfeld et al. (1990) in the area south of Zakynthos. This pattern is now observed northernwards. On mainland, σ_2 (except the area of Trichonis lake) is striking parallel to the long axes of basins in the area (i.e. Patras gulf, Trichonis Lake, Corinth Gulf). Furthermore, it is perpendicular to the Cephalonia-Lefkas transform fault.

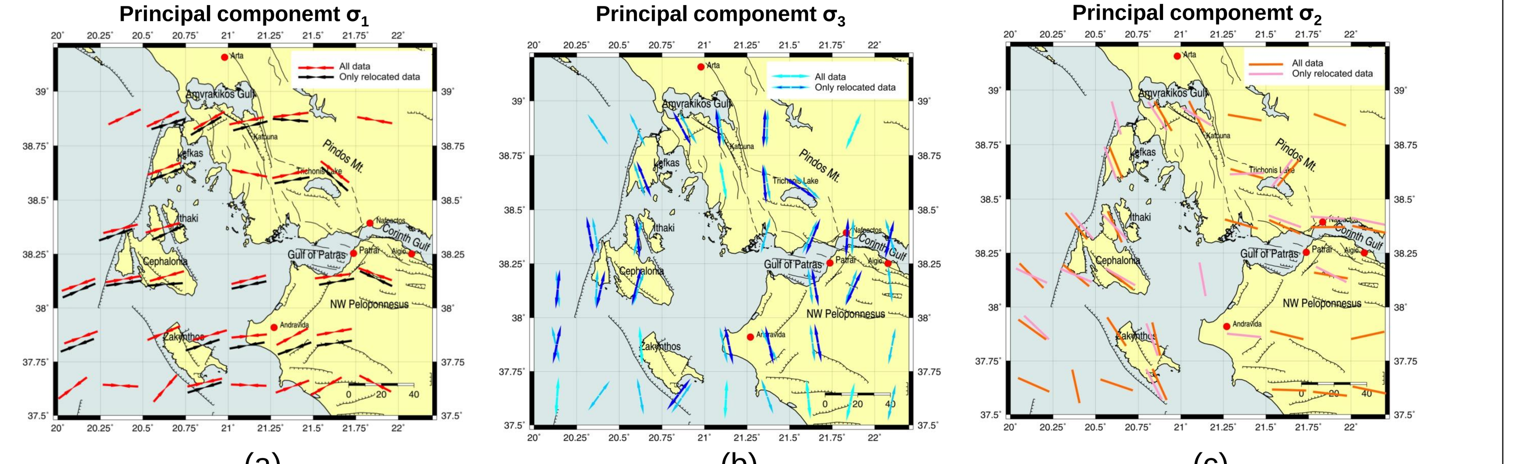
All P- and T-axes (located + relocated) | **All P- and T-axes (located + relocated)** | **Only relocated focal mechanisms**



(a) (b) (c)

Figure 4. *(a) Azimuthal distribution of P- (red) and T-axes (blue) for all available fault plane solutions. Pairs of numbers at the bottom of each rectangle indicate the coordinates of the grid points at which the study area was subdivided for the stress field inversion (b) Azimuthal distribution of prevailing P- (red) and T-axes (blue) of all available focal mechanisms of crustal earthquakes in western Greece containing the initial catalogue hypocentral solutions and those obtained by HypoDD (c) the same as (4b) but only for the focal mechanisms for which hypocentral locations were obtained by the double difference relocation (HypoDD). The size of the axes is proportional to the earthquakes' magnitude.*

Principal component σ_1 | **Principal component σ_3** | **Principal component σ_2**



(a) (b) (c)

Figure 5. *(a) Azimuthal distribution of* $\boldsymbol{\sigma_1}$ *stress tensor component for nodes shown in Figure 4a (b) Azimuthal distribution of* $\boldsymbol{\sigma_3}$ *stress tensor component for nodes shown in Figure 4a (c) Azimuthal distribution of* $\boldsymbol{\sigma_2}$ *stress tensor component for nodes shown in Figure 4a. Only components dipping <65º are presented in the maps and only solutions with number of available focal mechanisms >6 for each node are presented.*

Table 1. CGPS velocities

Station Name	ITRF2005 Vn (mm/yr)	ITRF2005 Ve (mm/yr)	ITRF2005 Vu (mm/yr)	Stable Europe Vn (mm/yr)	Stable Europe Ve (mm/yr)	Stable Europe Vhor (mm/yr)	Stable Europe Azimuth (degrees)
PONT	7.06	20.54	-1.77	-4.74	-3.06	5.64	212.87
SPAN	3.58	21.32	-0.16	-8.22	-2.28	8.53	195.48
VLSM	3.40	17.70	1.20	-8.40	-5.90	10.26	215.08
KIPO	9.17	15.86	-2.98	-2.63	-7.74	8.17	251.22
ZAKY	2.88	14.32	-0.85	-8.92	-9.28	12.87	226.11
ARTA	10.76	18.46	-6.12	-1.04	-5.14	5.24	258.59
KARP	11.46	18.23	-8.43	-0.35	-5.37	5.39	266.33
AGRI	8.61	13.89	-4.37	-3.19	-9.71	10.22	251.79
PATR	-9.33	7.30	-5.43	-21.13	-16.30	26.69	217.65
RLSO	-5.80	8.60	6.00	-17.60	-15.00	23.12	220.44
PYRG	-9.62	3.26	-4.75	-21.42	-20.34	29.54	223.52

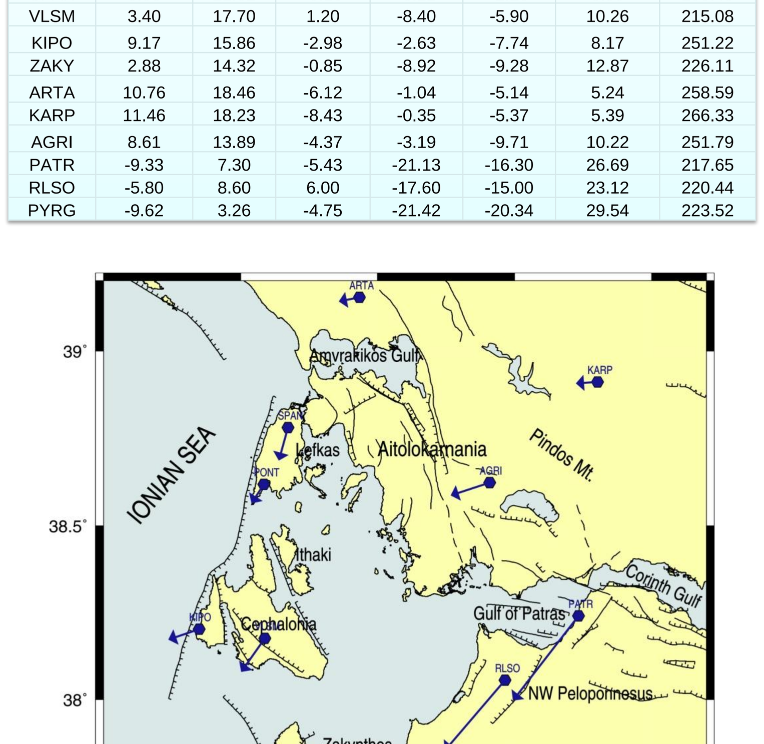


Figure 6. *Map showing the distribution of surface horizontal displacement velocity in the study area (blue vectors) measured at CGPS stations (blue hexagons) relative to stable Europe. Vector length is proportional to the velocity magnitude.*

CGPS Measurements

Data from Continuous GPS stations installed in the broader area have been employed. Analysis of all the available, since 2006, CGPS observations was performed using the automated mode of the Bernese Software v.5.0 (Dach et al., 2007). The result was the estimation of the daily horizontal and vertical surface ground position of each CGPS station with respect to the international reference frame ITRF2005. Daily solutions were used to produce the time dependent ground displacement and to estimate the ground deformation velocity of each station relative both to ITRF2005 and stable Europe (Table 1). In Figure 6, horizontal velocity vectors are presented with respect to stable Europe, considering standard errors at a rate of 10^{-1} mm/yr. In the vertical scale, the higher uncertainties (up to 1 mm/yr), along with the short duration of operation of most CGPS stations, have radically affected the estimation of vertical ground velocity.

Ground velocity, as seen in Figure 6, reaches maximum values south of the Patras Gulf (23.10 mm/yr at RLSO and 26.70 mm/yr at PATR, respectively). Velocity decrease is observed at Central Ionian Islands (Zakynthos, Cephalonia, Lefkas), ranging from 12.87 mm/yr (ZAKY) to the south, to 10.26 - 8.17 mm/yr (VLSM-KIPO) and 8.53 - 5.64 mm/yr (SPAN-PONT) to the north. It should be noted that the expected northward decrease of ground deformation velocity is not observed in Lefkas, as the northern part (SPAN) seems to be displaced SW with a higher velocity than the southern part (PONT), revealing a N-S crustal shortening on the island at a rate of 2-3 mm/yr, as already inferred by Ganas et al. (2012). Velocity also decreases gradually northwards at Aitoloakarnania, as observed at AGRI (10.22 mm/yr), KARP (5.39 mm/yr) and ARTA (5.24 mm/yr). Moreover, strain orientation appears rotated towards the NW by ~30º with respect to the Central Ionian Islands and NW Peloponnesus.
Observations on the velocity field variations, are summarized as following:

- N-S extensional ground deformation prevails in south Aitoloakarnania and NW Peloponnesus. This is consistent with the opening of Patras Gulf at the same direction.
- WSW-ENE compression dominates offshore Cephalonia, Zakynthos and Patras.
- NNE-SSW crustal compression in Lefkas and uplift of its northern part with respect to the southern is inferred by vertical velocities measured at SPAN and PONT stations.
- NNE-SSW crustal extension between south Lefkas and Cephalonia, or uplift of the eastern part of Cephalonia is inferred by the vertical velocity measured at VLSM station.
- Regional horizontal velocity gradually decreases northwards.
- Uplift is detected south of Patras Gulf (NW Peloponnesus) relative to Aitoloakarnania.
- Overall subsidence characterizes the Central Ionian Islands, with the exception of the eastern part of Cephalonia (VLSM).
- Additional CGPS observations over a larger time span should be incorporated in the analysis in order to determine velocities more precisely.

Conclusions

Joint seismological data were used to study the geodynamic regime in western Greece. For this purpose the following tasks were performed:

1. A phase data catalogue was compiled, comprising of more than ~12000 events recorded by local and regional permanent or temporary seismological networks. Relocation with HypoDD provided improved hypocentral solutions for ~10000 events.
2. A focal mechanisms catalogue was compiled, comprising of 1130 fault plane solutions, concerning about 850 earthquakes with 1.6≤M≤7.4 in the study area. The double difference relocation yielded a catalogue with 710 fault plane solutions for an equal number of events with 1.6≤M≤6.5. Damped iterative inversion of the focal mechanisms provided a regional scale model of stress orientation in the study area.
3. Data from 11 Continuous GPS stations installed in the broader area were used. Estimation of the daily horizontal and vertical surface ground position of each station with respect to the international reference frame ITRF2005 and stable Europe was carried out. Daily solutions were combined to produce the annual displacement at each station.

The main results of the study on the stress field and kinematics of western Greece are outlined in Figure 7. The overall pattern shows that the study area is a single block surrounded by rigid boundaries, namely the Hellenic Trench, the Cephalonia Transform Fault, the Andravida Fault Zone, the Tripolis-Pindos transition boundary and Amvrakikos Gulf. The latter zone has to be further investigated with the implementation of new data.

In order for enlightening to be given at several issues deduced by this study, we would like to notify the need for:

1. Installation of a dense temporary seismological network in the area of north Peloponnesus, Aitoloakarnania and around Amvrakikos Gulf, in order to detect small earthquakes, probably occurring in this area, or to establish that it is almost aseismic.
2. A GPS campaign in the above area, in conjunction with the seismological experiment.
3. The installation of CGPS stations in north Peloponnese, north of the Andravida-Nisi fault zone, a key area, in order to detect the northernmost tip of the African subduction.

In conclusion, dense seismological networks are "sine qua non". Our involvement and experience on implementing hypocentral solutions using both regional and local phase and waveform data, clearly proves that despite the existing state of the art relocation techniques (which are several), only local dense networks are capable to provide adequate data for thorough seismotectonic analyses, which are essential in current Geodynamics.

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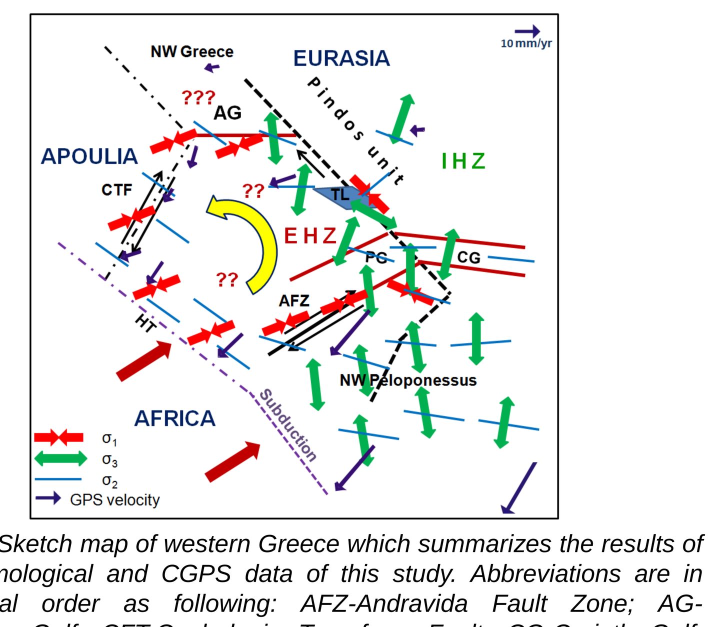

Figure 7. *Sketch map of western Greece which summarizes the results of joint seismological and CGPS data of this study. Abbreviations are in alphabetical order as following: AFZ-Andravida Fault Zone; AG-Amvrakikos Gulf; CFT-Cephalonia Transform Fault; CG-Corinth Gulf; EHZ-External Hellenides Zone; HT-Hellenic Trench; IHZ-Internal Hellenides Zone; PG-Patras Gulf; TL-Trichonis Lake.*

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