SECOND EUROPEAN CONFERENCE ON EARTHQUAKE ENGINEERING
AND SEISMOLOGY, ISTANBUL AUG. 25-29, 2014

THE 2013 EARTHQUAKE SWARM IN HELIKE, GREECE: A DETAILED SEISMOTECTONIC STUDY

Vasilis KAPETANIDIS[1], Anne DESCHAMPS[2], Panayotis PAPADIMITRIOU[3], Emanuela MATRULLO[4], Andreas KARAKONSTANTIS[5], George BOZIONELOS[6], Anna SERPETSIDAKI[7], George KAVIRIS[8], Helene LYON-CAEN[9], Nicholas VOULGARIS[10], Pascal BERNARD[11], Efthimios SOKOS[12], Kostas MAKROPOULOS[13]

The Corinth Rift in Central Greece has been studied extensively during the past decades, as it is one of the most seismically active regions in Europe. It is characterized by normal faulting in an approximate WSW-ENE direction with an extension rate increasing from east (~6 mm/yr) to west (~14 mm/yr) (Billiris et al., 1991; Briole et al., 2000). The western Corinth gulf has been the site of significant earthquakes in the past, the most recent being the Ms=6.2 earthquake which struck the city of Aigion on 15 June, 1995 (Bernard et al., 2006). The Corinth Rift Laboratory (CRL) local seismological network has been operating since 2000 in the region, recording thousands of earthquakes per year, with magnitudes as low as M≈1 (Lyon-Caen et al., 2004; Lambotte et al., 2014). Real-time telemetry has been established in the recent years enabling the automatic detection and location of current seismicity (http://crlab.eu).

On 21 May 2013, an earthquake swarm was initiated with a series of small earthquakes in the region of river Selinountas, below the West Helike fault (Bernard et al., 2006). In the next days the seismic activity became more intense, with outbursts following several stronger events of magnitude between 3.3 and 3.7. The largest ones have occurred during 22-31 May in the central part of the swarm's epicentral region. The seismicity migrated towards the East during June and then activated the western part, starting on July 15th. Previous results from instrumental data indicate that approximately the same region had been activated during July-August 1991 (Rigo et al., 1996). The availability of the dense permanent seismological network permits a detailed analysis of this crisis and a better understanding of the earlier events.

More than 1500 events have been detected and manually analysed during the period between 21 May and 31 August 2013, using over 15 local stations in epicentral distances up to 30km, including stations of the CRLNET, the Hellenic Unified Seismological Network (HUSN) and a temporary

[1] PhD Student, Department of Geophysics-Geothermics, University of Athens, Greece, vkapetan@geol.uoa.gr
[2] Directeur de recherche, Géoazur,Université de Nice Sophia Antipolis/ CNRS, Sophia Antipolis, France, deschamps@geoazur.unice.fr
[3] Ass. Professor, Department of Geophysics-Geothermics, University of Athens, Greece, ppapadim@geol.uoa.gr
[4] Post-Doc, Laboratoire de Géologie, ENS/CNRS, Paris, France, matrullo@ens.fr
[5] PhD Student, Department of Geophysics-Geothermics, University of Athens, Greece, akarakon@geol.uoa.gr
[6] PhD Student, Department of Geophysics-Geothermics, University of Athens, Greece, gbozionelos@geol.uoa.gr
[7] Researcher, Seismological Laboratory, University of Patras, Greece, annaserp@geology.upatras.gr
[8] Lecturer, Department of Geophysics-Geothermics, University of Athens, Greece, gkaviris@geol.uoa.gr
[9] Directeur de recherche, Laboratoire de Géologie, ENS/CNRS, Paris, France, lyoncaen@ens.fr
[10] Ass. Professor, Department of Geophysics-Geothermics, University of Athens, Greece, voulgaris@geol.uoa.gr
[11] Physicien, Institut de Physique du Globe de Paris, France, bernard@ipgp.fr
[12] Ass. Professor, Seismological Laboratory, University of Patras, Greece, esokos@upatras.gr
[13] Em. Professor, Department of Geophysics-Geothermics, University of Athens, Greece, kmacrop@geol.uoa.gr

station at Helike (HELI) which was installed on the 23th of May. A local velocity model was determined by applying a mean travel-time residuals and location uncertainties minimization technique (Kissling et al., 1994; Papadimitriou et al., 2010), which yielded better constrained hypocentral locations. A comparison of initial locations derived by the algorithm HYPOINVERSE (Klein, 1989) reveals that the focal depths range is similar with both models; however, the dispersion and location/RMS errors with the old one are larger. The differences of hypocentral locations between the two results become less evident once station corrections are applied.

Following, multiplet analysis was carried out by constructing a combined cross-correlation matrix based on full waveform recordings from two local stations, namely LAKA and TEME. Similarity-based clustering was performed using the nearest neighbour method on the contents of the matrix, which resulted in several distinct multiplets for different parts of the earthquake swarm. In order to minimize location uncertainties and provide a sharper image of the spatial distribution, a high-resolution relocation procedure was performed using the double-difference algorithm HYPODD (Waldhauser and Ellsworth, 2000), by incorporating both catalogue and cross-correlation differential travel-time data (Kapetanidis and Papadimitriou, 2011). The relocation separated the initial seismic cloud to several smaller densely concentrated spatial clusters of strongly correlated events. The hypocenters are constrained in a volume which extents ~7km EW and ~2km NS, while the focal depths range between 8km and 10km. The spatial distribution reveals a complex geometry which cannot easily be related to the superficial traces of known faults.

Waveform modeling with ISOLA code (Sokos and Zahradnik, 2008) was used to calculate the moment tensor solution for 16 of the largest events. Azimuths and angles of emergence from the relocated foci were used for the determination of focal mechanisms by first-motion polarities to enlarge the focal solution dataset to over 100 events. The solutions are mainly in agreement with the regional NNE-SSW extension. Selected mechanisms of events belonging to common spatial groups were considered for the calculation of composite mechanisms in order to characterize different parts of the fault surface geometry.

Moment magnitudes were calculated by spectral analysis of both P- and S-waves. The associated Gutenberg-Richter law suggests a b-value of ~1.1 between the completeness value of 1.5 and 3.5, but with a deficit in the larger magnitude events that can be interpreted as a variation of the b-value between smaller magnitudes (1.5 to 2.8) and larger ones (2.8 to 3.7).

The spatio-temporal analysis reveals the complex history of the seismic swarm and, in association with the distribution of multiplets, can aid in better understanding the fault geometry at depth. The swarm occurred at a place where the NNE-dipping Pyrgaki normal fault, outcropping ~8km to the south, and the NW-dipping Kerinitis fault probably meet and seems to have activated both faults at depth, at the root of the Pyrgaki fault, where it intersects with the microseismic layer documented more to the north, near the rift axis (Lambotte et al., 2014). The clear eastward migration of the epicenters during June implies triggering by fluids. The situation appears differentiated in the second part of the swarm, after July 15th, which illuminates almost uniformly one or two parallel structures west of the initiating point of the activity. The hypocenters are distributed in a curved fault surface or a junction of two neighbouring normal faults, with the central-eastern part dipping NNE, while the westernmost part, which was mostly activated after July 15th, apparently dips NW. Evidence for earthquakes occurring on the detachment zone at a depth of ~9km has also been found in a series of mechanisms with a sub-horizontal nodal plane, dipping slightly towards the North.

ACKNOWLEDGMENTS

The present study was co-funded through the FP7-ENV-2011 / Collaborative Project “REAKT: Strategies and tools for Real Time EArthquake RisK ReducTion”.

REFERENCES

Bernard P, Lyon-Caen H, Briole P, Deschamps A, Boudin F, Makropoulos K, Papadimitriou P, Lemeille F, Patau G, Billiris H, Paradissis D, Papazissi K, Castarede H, Charade O, Nercessian A, Avallone A,

Pacchiani F, Zahradnik J, Sacks S and Linde A (2006) "Seismicity, deformation and seismic hazard in the western rift of Corinth: New insights from the Corinth Rift Laboratory (CRL)", *Tectonophysics* 426:7-30

Billiris H, Paradissis D, Veis G, England P, Featherstone W, Parsons B, Cross P, Rands P, Rayson M, Sellers P, Ashkenazi V, Davison M, Jackson J, Ambraseys N (1991) "Geodetic determination of tectonic deformation in central Greece from 1900 to 1988", *Nature,* 350:124-129

Briole P, Rigo A, Lyon-Caen H, Ruegg JC, Papazissi K, Mitsakaki C, Balodimou A, Veis G, Hatzfeld D, Deschamps A (2000) "Active Deformation of the Corinth Rift, Greece: Results from Repeated GPS Surveys between 1990 and 1995", *Journal of Geophysical Research*, 105(B11):25605–25625

Kapetanidis V and Papadimitriou P (2011) "Estimation of arrival-times in intense seismic sequences using a Master-Events methodology based on waveform similarity", *Geophysical Journal International*, 187:889-917

Kissling E, Ellsworth WL, Eberhart-Phillips D, Kradolfer U (1994) "Initial reference models in local earthquake tomography", *Journal of Geophysical Research*, 99:19635-19646

Klein FW (1989) HYPOINVERSE, a program for VAX computers to solve for earthquake locations and magnitudes, U.S. Geological Survey Open–File Report, 89–314

Lambotte S, Lyon-Caen H, Bernard P, Deschamps A, Patau G, Nercessian A, Pacchiani F, Bourouis S, Drilleau M and Adamova P (2014) "Reassessment of the rifting process in the Western Corinth rift from relocated seismicity", *Geophysical Journal International* (*in press*)

Lyon-Caen H, Papadimitriou P, Deschamps A, Bernard P, Makropoulos K, Pacchiani F and Patau G (2004) "First results of the CRLN seismic network in the Western Corinth Rift: Evidence for old-fault reactivation", *Comptes Rendus Géoscience*, 336:343-351

Papadimitriou P, Kaviris G, Karakonstantis A and Makropoulos K. (2010) "The Cornet seismological network: 10 years of operation, recorded seismicity and significant applications", *Annales Géologiques des Pays Hélléniques*, 45:193-208

Rigo A, Lyon-Caen H, Armijo R, Deschamps A, Hatzfeld D, Makropoulos K, Papadimitriou P and Kassaras I (1996) "A microseismic study in the western part of the Gulf of Corinth (Greece): implications for large-scale normal faulting mechanisms", *Geophysical Journal International*, 126:663-688

Sokos E and Zahradník J (2008) "ISOLA a Fortran Code and a Matlab GUI to Perform Multiple-point Source Inversion of Seismic Data", *Computers & Geosciences,* Vol 34, Issue 8:967-977

Waldhauser, F and Ellsworth, WL (2000) "A double-difference earthquake location algorithm: Method and application to the northern Hayward Fault, California", *Bulletin of the Seismological Society of America*, 90:1353–1368