GROUND DEFORMATION STUDY OF KOS ISLAND (SE GREECE) BASED ON SQUEE-SAR^{TM} INTERFEROMETRIC TECHNIQUE

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ABSTRACT

The SE part of the Hellenic Volcanic Arc (HVA), including Kos, Yali and Nisyros islands, is geodynamically very active and of high tectonic unrest, where the largest volumes of volcanic products were emitted during the past 160,000 years. The SqueeSAR^{TM} Interferometric technique based on ENVISAT radar data has been applied in Kos to spatially and temporally study the ground deformation for the period 2003-2010. The observed LOS velocity field, with values ranging between -4 to +4 mm/yr, combined with small standard deviation velocity (<1.4 mm/yr) and acceleration (-0.5 to 1.5 mm/yr^2) values reveal an almost linear type of ground deformation. These small velocity values in conjunction with intermediate seismicity occurring only off-shore, indicate ground deformation of aseismic local character. The strongest subsidence is associated with local geothermal areas, as well as rural areas due to intense water pumping. Motions along the main faulting zones have also been clearly identified.

***Index Terms*—** Ground deformation, SqueeSAR technique, Hellenic Volcanic ARC, Kos Island.

1. BRIEF GEOTECTONIC SETTING

The HVA is a magmatic expression of the active northeastward-directed subduction of the African Plate beneath the Aegean Plate, which started around 5 Ma at the beginning of Pliocene [1]. The eastern sector of the HVA, which includes the islands of Kos (Fig. 1), Yali and Nisyros, is comprised of enormous quantities of volcanic materials. Although the Dodecanese Islands, the Bodrum Peninsula (Turkey, northeast of Kos) and Kos have been impacted by magmatic and volcanic activity over the past 10 million years [1], high geodynamic activity in the Kos-Yali-Nisyros Volcanic Field started in the Pliocene (ca. 2.6 to 2.8 Ma) with phreato-magmatic eruption of ignimbrites. Large remnants of these eruptives phases are present in the Kephalos Peninsula (western Kos) and in the islets of Pergussa and Pachia.

Approximately 160,000 years ago, ignimbrites were emplaced in the region of the NE-striking "Kos Horst-Graben System" in the largest eruption of the Eastern Mediterranean, emitting more than 100 km^3 of pyroclastic material (Kos Plateau Tuff). Ash, pumice and pyroclastic flows devastated an area of more than 3000 km^2 [2]. As a result, a present-day submarine caldera with a diameter of 15 to 20 km was formed, which is now covered up by several kilometers of volcano-sedimentary materials from younger eruptions.

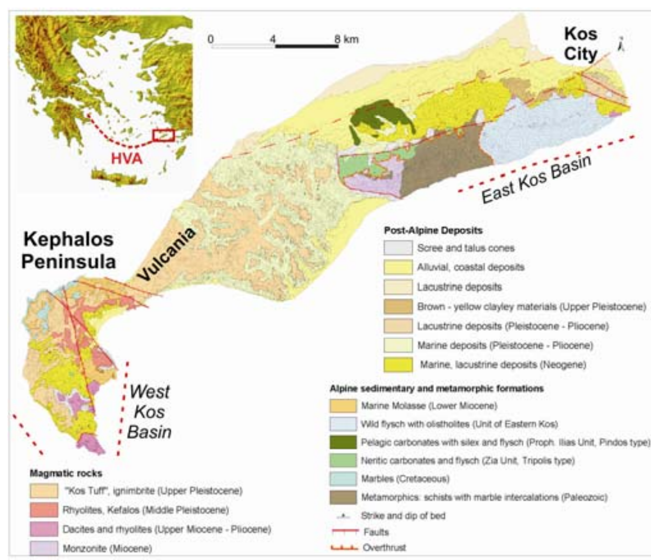

Fig. 1. Geological map of Kos Island [3]

The region around Kos Island (Fig.1) has active faulting and high seismicity. A major seismically active E-W fault defines the southern edge of the Bodrum peninsula, while the southeastern coastline of Kos and the northern margin of the East Kos basin are defined by a seismically active ENE-trending fault. Intense seismic activity occurred in the area during the period 1996-1997, causing strong deformation to the volcanic island of Nisyros which is located to the south of Kos [4]. Since 1999 the seismic activity of the area has dropped to pre-1996 background levels, with most of the earthquakes being located at great depths (>40 km), and the most significant events (M>4.5) occurring even deeper (>80 km) (Fig. 2). Kos Island itself is characterized by a complex geological structure, volcanism and superficial thermal manifestations [5], as being related to the extensional tectonics and the formation of the HVA.

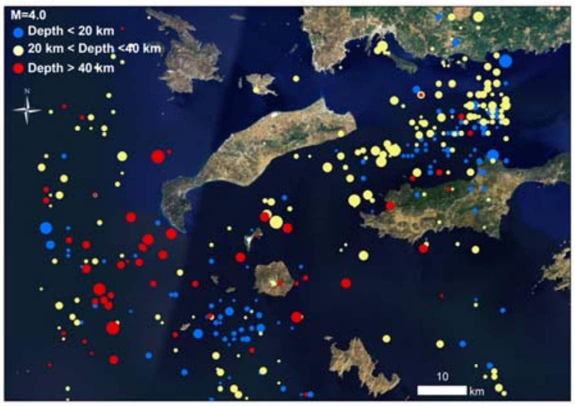

Fig. 2. Seismic activity in the broader area of Kos for the period 2003-2014 (M>3).

2. THE SQUEE-SAR^{TM} TECHNIQUE

Conventional Synthetic Aperture Radar (SAR) Interferometry (InSAR) is a proven processing technique for mapping ground deformation on a large spatial scale with short-term data sampling rates. Conventional InSAR uses the phase difference between two SAR acquisitions to obtain interferograms, but this processing technique has a drawback related to atmospheric noise that cannot be efficiently eliminated which results in unreliable interferograms of ground deformation. This deficiency has been dealt with by a specific analysis that considers phase changes in a series of SAR images acquired at different times over the same region. The result is a series of interferograms with respect to a “master” image, where small parts of the study area (pixels) exhibiting coherent phase behaviour may be identified, the so-called *permanent scatterers* (PS), introducing thus the PSInSAR^{TM} technique [6]. However, the PSInSAR technique was recently further advanced and replaced by the SqueeSAR^{TM} algorithm [7].

The SqueeSAR^{TM} is a second generation of the PSI technique, and involves searching targets from a radar imaging dataset in order to identify both consistent PS and homogeneous spatially **d**istributed **s**catterers (DS).. PS usually correspond to man-made objects (e.g., buildings and linear structures), while DS are typically associated with homogeneous ground surfaces, uncultivated, desert or debris covered areas, and scattered outcrops. All identified PS and DS are then jointly processed (taking into account their different statistical behaviors) by applying the SqueeSAR algorithm. Because of the higher density of identified measurement points (scatterers), and their wider spatial coverage, millimeter accuracy of ground displacement is achievable, together with reduced standard deviations, as compared to the PSInSAR^{TM} technique.

3. DEFORMATION OF KOS ISLAND

A total of 26 ascending and 22 descending orbital geometry ASAR scenes, acquired by ENVISAT satellites, were processed covering the period February 2003 to June 2010. More than 15,000 and 8,000 PS/DS in ascending (LOS angle 24.62^{o}) and descending (LOS angle 24.24^{o}) geometry, respectively, were identified within an areal extent of about 287 km^{2} (Fig. 3). The vertical component of ground deformation is about 93% of LOS, therefore this technique is more sensitive to the vertical deformation.

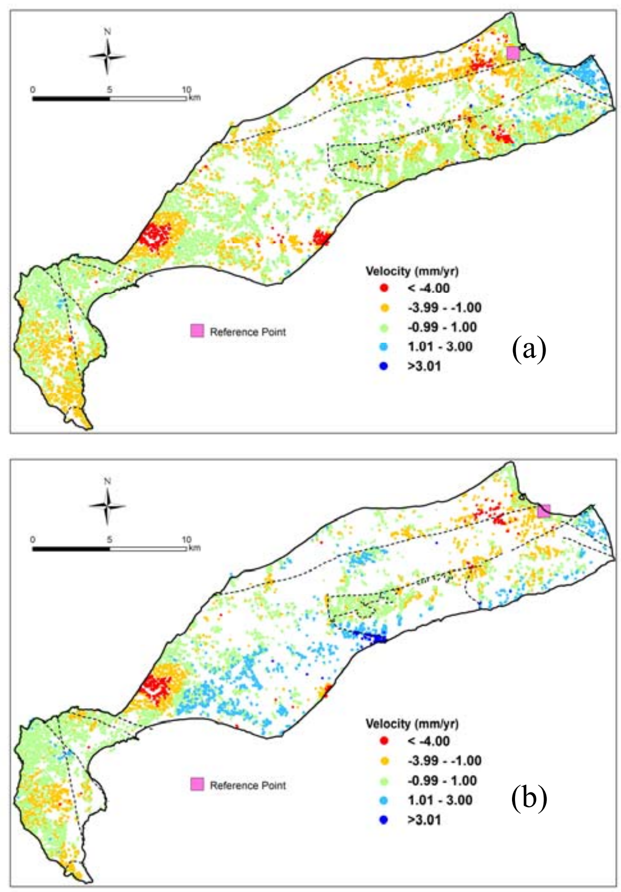

Fig. 3. LOS Velocity field (mm/yr) for **(a)** Ascending, and **(b)** Descending orbital satellite geometry (2003-2010).

The reference point for the interferometric analysis is located at the northeastern part of the island near a reference station for a GPS network that has been remeasured periodically since 1997. The GPS reference point has a horizontal motion to the SSE direction with respect to

ITRF2008 (V_{East}=9.1±2.4 mm/yr and V_{North}=-19.2±2.3 mm/yr), while the vertical component indicates small subsidence (V_{Up}=-3.9±2.8 mm/yr). The overall behavior of the reference station is consistent with the regional motion [8].

It is obvious that the SqueeSAR™ image of the ground velocity from the ascending data (Fig. 3a) has a significantly higher number of scatterers as compared to the descending one (Fig. 3b) because of the larger number of imaging acquisitions. Low velocities ranging from -1 to +1 mm/yr are observed on both images in the northeastern and southwestern parts of Kos. A more intense subsiding rate (about -3mm/yr) is observed in the northeastern part of the island, mainly in areas covered by alluvial and coastal deposits. However, a distinct difference between ascending and descending geometry is observed at the central part where small negative LOS values (about -1 mm/yr), indicate motion away from the satellite (ascending geometry), while positive values (1-3 mm/yr) are evident in the descending geometry (movement towards the satellite). The latter is an indication of an eastward horizontal component implicated in the data, evident in the descending orbital geometry. The highest subsiding rate (observed on both geometries) occurs in the northwestern part (east of Kephalos Peninsula) with values up to -5mm/yr. The PS/DS points in this area are associated with volcanic ash and ignibrites, where in addition a low gravity anomaly exists and a geothermal field is present [5]. Moreover, this area is on the downthrown side of the major WNW-ESE fault system (Vulcania Fault) that cross-cut the area on the west (Fig.1).

Faults that are located in the northeastern part of Kos play a key role in the evolution of the deformational pattern (subsidence to uplift), as noted by differential motions along local faults (Fig.1). Small patches of PS/DS showing high subsiding rates (<-4 mm/yr) are attributed to local morphological (steep slopes) and tectonic features, but also can be explained by human activity (water pumping for irrigation) near small villages, and touristic locations.

The *standard deviation* of the velocity field was also computed both for the descending and ascending images (Fig. 4) presenting values quite smaller than 1.5mm/yr. The standard deviation of velocity for the descending data (Fig. 4b) appear to have higher values than the ascending data (Fig. 4a), maybe due to the significantly smaller number of PS/DS points. Two parameters are generally affecting the calculation of the standard deviation: (i) *The distance of each PS/DS point from the reference point*. In fact, the displacement model is estimated on the phase-difference between the point under analysis and the reference point, in order to mitigate the effect of the atmospheric noise, which is strongly spatially correlated. The standard deviation of velocity increases moving away from the reference point. (ii) *The deviation of motion from the linear model.* Since the standard deviation is associated with the average rate of deformation, if a PS/DS point exhibits a strong non-linear motion then it would result in a large residual with respect to the linear model, and thus in a high standard deviation value.

Considering the above, it is inferred that generally an almost *linear* deformation is taking place in KOS for the period 2003-2010, with small deviation from the linearity in the geothermal areas (Vulcania) of south central Kos, and the southern costal cliffs.

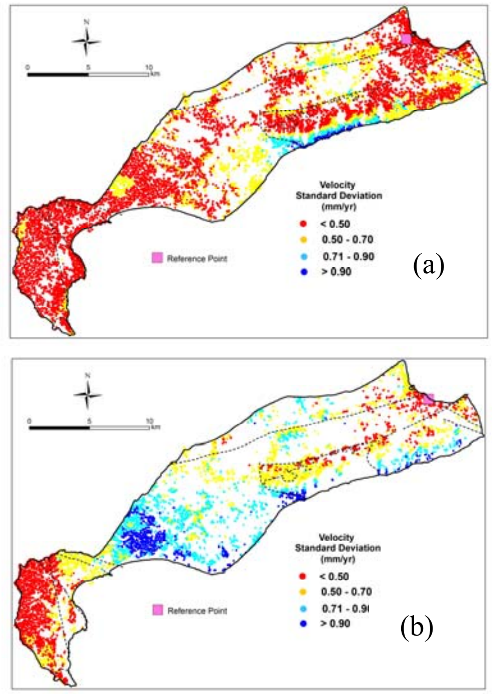

Fig. 4. Standard Deviation of PS/DS velocity deformation map deduced from **(a)** Ascending, and **(b)** Descending radar imaging.

The *acceleration field* was obtained by fitting a second order polynomial to the time series of each PS/DS point (Fig. 5). The acceleration field describes the rate of the velocity change of the PS/DS points; therefore the sign of the velocity (positive or negative) has to be taken into consideration. Considering PS/DS points with positive sign of velocity (i.e. uplift), positive acceleration is associated with an *increasing rate* of uplift, whereas a negative sign with a *decreasing rate*. For a negative sign of velocity (ie. subsidence), positive acceleration is associated with a *decreasing rate* of subsidence, whereas a negative sign indicates an *increasing rate*. Note that the small computed values of acceleration (-0.5 to +0.5 mm/yr^2) combined with the small values of standard deviation of velocity (<1.5mm/yr) confirm the *linear* type of ground deformation in large part of study area. Nevertheless, it is worthy pointing out some aspects relating to the *deformation rate* which is taking place in the island.

The most significant negative velocity values, indicating ground motion away from the satellite (i.e. subsidence) were basically observed in the SW part of Kos (close to Kephalos

Peninsula), where the geothermal field is located, characterized by a *increasing rate* of motion, while *decreasing rate* was noticed at its NE part, in the area around Kos City.

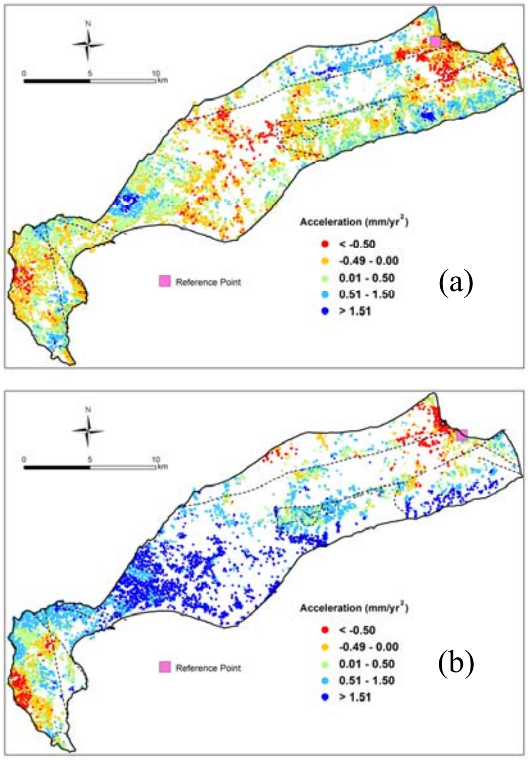

Fig. 5. Acceleration Field for **(a)** Ascending and **(b)** Descending acquisition geometry.

However, when looking at the descending data (Fig. 3b and 5b), an *increasing rate* of uplift was noticed in the south central part of Kos, while a *decreasing rate* was taking place at the same area when inspecting the ascending geometry (Fig. 3a and 5a). The latter proves that a significant eastward horizontal component involved in the data; since the descending data show higher velocity and acceleration values compared to the ascending geometry (east motion toward the descending satellite).

4. DISCUSSION - CONCLUSIONS

Reactivation of magmatic and volcanic activity in quiescent volcanic areas, as the broader area of Kos Island is presently characterized, can be noticed by an increase in the geodynamic activity as expressed through earthquake activity and ground deformation. In this respect, the Kos-Yali-Nisyros volcanic field represents a potentially severe risk hazard that requires continuous monitoring of surface deformation.

The SqueeSAR^{TM} velocity map of Kos Island for the period 2003-2010, using ascending and descending ENVISAT radar images, revealed an overall small rate of deformation (-3 to +3 mm/yr). Low velocity standard deviation (<1.5 mm/yr) and acceleration (-1 to +1.5 mm/yr^2) values have shown the almost linear character of the deformation.

Absence of significant seismic activity on-land, with the most intense seismicity taking place in depths larger than 40 km support the idea of the local aseismic character of the observed deformation. Discrepancies on the type of motion (uplift or subsidence) between ascending and descending data set could be justified by a significant E-W component of motion; mainly in the south-central part of Kos, where an eastward motion prevails. The most significant subsiding rates (<-3mm/yr) occurred in regions of alluvial and coastal deposits. The highest subsiding rate (<-4 mm/yr) is associated with the geothermal area (Vulcania) that is located in southwestern Kos, and which is controled by a major fault system on its west (Vulcania Fault).

5. REFERENCES

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