Inflation/Deflation Sequence on Nisyros Active Volcano (Greece) during 1995-2000 issued from SAR Differential Interferometry

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ABSTRACT

Nisyros is a poorly known Quaternary volcano, south-east of the Aegean volcanic arc. It is characterized by periods of intense seismic activity and paucity in eruptive episodes, sometimes accompanied by hydrothermal explosions. The most recent unrest episode lasted from 1995 to 1998, without eruption. Radar interferometry has been applied in order to study the evolution of the deformation from 1995 to 2000. Observations show a continuous uplift of 140mm during 1995-1997. At mid 1998, the movement trend changes into a slower surface deflation till 2000. Maximum crust deformation is constantly observed at the north-west part of the island, where most earthquake epicenters are located and in agreement to three GPS campaigns conducted between mid 1997 and mid 1998. We solve for the best-fit Mogi point source and best-fit Okada rectangular dislocation of the observed deformation field. Mogi model indicates a source at 5km depth beneath the north-west edge of the island, with a maximum deformation amplitude at surface of 0.14± 0.02m and a total volume change of 26± 4 x 10^6 m^3, during 1995-1997. The Okada model indicates a dike solution 2km long, 2.2km wide, with a 4m opening and a 30° dip. The upper center is at 6.4km depth and the volume change, also during 1995-1997, is 17.6 x 10^6 m^3. Each solution is discussed on the potential controlling mechanism resulting to the volcano's inflation/deflation sequence.

Keywords: Nisyros, Interferometry, InSAR, Volcanism, Aegean, ERS2, Remote Sensing, Modeling.

1. INTRODUCTION

Nisyros is a poorly known active Quaternary volcanic island in the south-east of the Aegean Volcanic arc. It is situated between 36°33' and 36°35' latitude and 27°7' and 27°13' longitude. The most recent long lasting episode of seismic unrest without eruption started in 1995, culminated in August 1997 and gradually declined to regular background levels by the end of 1998. The highest magnitude earthquakes recorded in August 1997, (Ms=5.3 and 5.2), were located approximately 5-8 km north-west offshore of Nisyros island [14].

Seismicity recorded by the permanent regional array during the period 1980-2002[14] showed that the earthquake depths in the area are shallow and the magnitudes vary between 4-5R.

Earthquake activity becomes important from mid 1995 till mid 1999 as shown in the diagram of cumulative events in time (figure 1). From September 1995 to June 1996 a continuous curve is observed. A break occurs between June 1996 and July 1996. From July 1996 till July 1997, the curve is continuous with a steeper slope, indicating an increase in seismicity rate. A second break is observed between July 1997 and August 1997. It is worth noting that the two major earthquakes occurred in August 1997 (Ml 5.3 and 5.2). From August 1997 to August 1998 the curve is continuous with

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a constant slope. In August 1998, the slope gradually changes and becomes smoother, with a third break between July 1999 and May 2000, probably indicating the beginning of a resting period, which lasts till 2002.

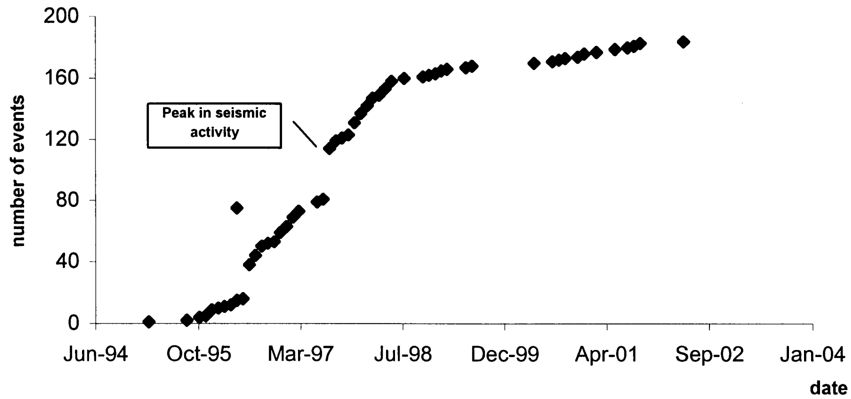

Figure 1. Cumulative number of seismic events from 1995 to 2002 recorded from the permanent regional array.

Moreover, the Institute for Geodynamics of the National Observatory of Athens conducted two seismic experiments with a local seismographic network in March and July 1997 [14]. The recorded seismicity patterns between the two seismic experiments varied both temporally and spatially. The first campaign recorded an intense seismic activity in a rather restricted zone north-west of Nisyros. During the second experiment, the epicentres were spread towards the central and southern part of the island [14].

Additionally to the seismic data, the Geology Department of the University of Athens[5] conducted a series of Global Positioning System (GPS) measurements data with three campaigns, in September 1997, December 1997 and in May 1998. A network of 15 geodetic stations was established at Nisyros with a mean distance of about 2km and 2 stations at Kos island on the north as a reference base to others. Data showed intense ground deformation, with the maximum deformation center at the north-west of island and not within the caldera, with a vertical uplift and a horizontal extension of the island reaching the 45 ± (5-10) mm at some stations. These observations referred to few specific points on the island. However, they provided the general movement trend and deformation pattern for the period around the main seismic activity (1997).

Radar interferometry (InSAR) was applied as a complement to the above existing in-situ observations.

2. InSAR DATA ANALYSIS

Differential radar interferometry has been proved extremely useful for measuring, monitoring and mapping active ground deformations [1,9,10,13].

In the present study, nine ERS2 SAR images in raw format were used, six in the ascending and three in the descending pass of the satellite sensor spanning the period June 1995 - September 2000. The data were processed with the DIAPASON (CNES) software using precise orbit data provided by the Delft Institute (NL).

The selection of interferometric pairs was based on their sensitivity to the topography expressed by the altitude of ambiguity (*ha*), which is the change in elevation resulting in the production of one topographic fringe (28mm). To avoid topographic effects, topographic fringe elimination was achieved by subtracting from the interferograms a synthetic fringe pattern produced by the DEM by employing the DEM-elimination (DEME) method introduced by [8]. The DEM was produced by digitizing 1:5000-scale topographic maps achieving a height accuracy of ±10m. The latter has been tested by a set of independent control points of known elevation in the island.

The quality of the DEM and the precise orbital data limited the possibility of deriving interferograms affected by orbital and topographic fringes. The validity of the observed fringes was also based on the systematic checks of the number and shape of the fringes between independent, ascending or descending, interferometric image pairs (Table 1).

Date Image 1	Date Image 2	*ha* (m)	Ascending/Descending pass	Number of fringes	Deformation in slant range (mm)
June 1995	May 1996	97	A	+3	+84
May 1996	June 1997	184	A	+2	+56
June 1995	June 1997	64	A	+5	+140
June 1995	June 1999	42	A	+3.5	+98
Sept. 1995	Oct. 1999	177	D	+3	+84
May 1996	June 1999	73	A	+3	+84
Aug. 1996	Oct. 1999	115	D	+2.5	+70
June 1997	June 1999	120	A	-1.5	-42
May 1998	Sept. 2000	148	A	-2.5	-70
Sept. 1995	Aug. 1996	70	D	+2	+56

Table 1: ERS2 image combinations used for interferometric processing. The altitudes of ambiguity are expressed in absolute values. The passes correspond to A=ascending pass of the satellite sensor, D=descending pass of the satellite sensor. One fringe corresponds to 28mm of ground deformation in slant range direction. Signs (+ / -) correspond to inflation / deflation respectively.

InSAR showed the existence of a clear deformation signal with a concentric pattern, centered at the north-west and covering the whole Nisyros island, though extending offshore to the north-west, during the whole period.

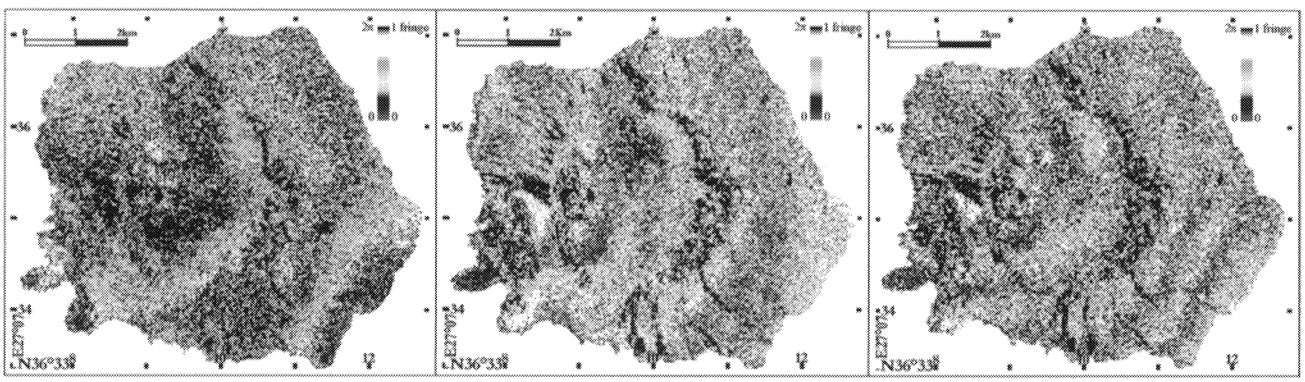

Figure 2: Differential interferograms of Nisyros spanning (a) June 1995-May 1996, (b) May 1996 – June 1997 and (c) June 1995 – June 1997 using image pairs acquired in the ascending pass of the satellite sensor.

During June 1995 – May 1996, a ground uplift of 84mm in the slant range direction is observed (3 fringes) and from May 1996 to June 1997, a further uplift movement of 56mm. As expected, the interferogram spanning the entire period June 1995 - June 1997 reveals five fringes that is an uplift of 140mm (Figure 2). However, for the period June 1995 – June 1999, the observed smaller surface uplift of 98mm (3.5 fringes) indicates a deflation movement that started after June 1997. This was confirmed by examining the independent interferogram of June 1997-June 1999. The latter shows 42mm of surface movement in the opposite direction (about 1.5 negative fringes). Moreover, the independent interferogram May 1998 - September 2000 shows 2.5 negative fringes (70mm), and confirms the deflation during that period [15]. Deformation during June 1997 – May 1998 was impossible to be directly calculated due to inadequate, in terms of altitude of ambiguity, interferometric pairs.

Descending pass interferograms, although less coherent, show a similar concentric pattern with the ascending ones and direction of the surface deformation.

interferometric observations as known ones [15]. A constraint was imposed that the difference between the estimated deformation rates and the interferometric observations should not exceed one fringe. Figure 3 illustrates the evolution of the surface deformation. Between 1995 and early 1998, a continuous inflation is evident. From May 1998 up to September 2000 a deflation seems to occur.

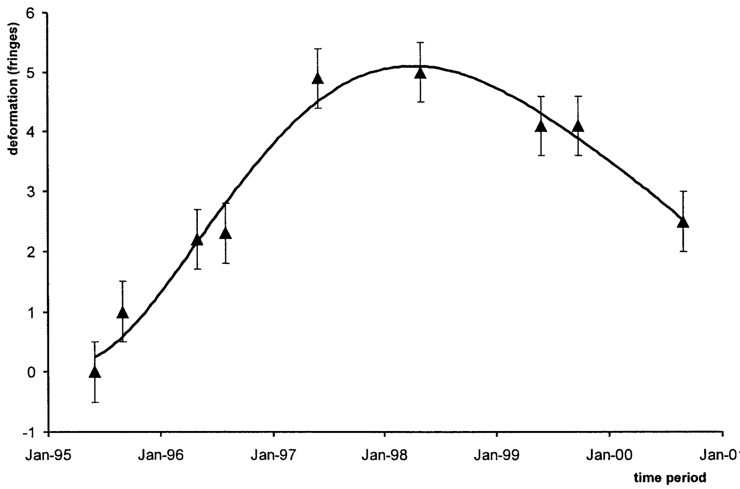

Figure 3. Deformation at Nisyros volcano from 1995 to 2000, inferred from InSAR analysis [15]. Each fringe corresponds to 28mm of deformation in slant range direction.

The existing GPS measurements[5] are consistent to the above observations. Uplift occurred from June 1997 till September 1997 though from September 1997 till May 1998 there was a decline in the deformation rate[5]. Consequently, the change from inflation to deflation most likely took place at mid 1998.

3. MODELING

An approximation in the interpretation of the deformation field observed by InSAR was intended by applying two different models corresponding to different possible mechanisms: a point-source deformation (Mogi model) and a rectangular dislocation in a half-space elastic medium (Okada model).

3.a. Point-source deformation

A simple model of point source inflation/deflation in an elastic medium was used, which was first introduced in volcanology by [11]. It does not take into account the possible complexity of the volcano's structure, in particular shallow discontinuities, faults and variable ground geology. However, it provides a useful first quantification of the deformation mechanism, especially depth and volume change involved in the process.
The fact that all interferograms reveal a rather constant in shape and location deformation field suggests that the depth of the deformation source remained stationary during 1995-2000. For this reason, the clearest interferograms, especially that of June 1995 - June 1997, was used as input to solve for the four model parameters: the horizontal coordinates and depth of the inflating center and the maximum amplitude of the deformation at the surface (Figure 4a). The best-fit solution was found for a point source with the characteristics presented in Table 2.

E (km) (UTM/Zone 35/ED50)	N (km) (UTM/Zone 35/ED50)	Depth (km)	Max. amplitude of deformation at surface (m)	Volume change at depth (m^3)
513.4	4050.6	5 ± 0.5	0.14 ± 0.02	26 ± 4 x 10^6

Table 2: Best-fit point source parameters. Volume change at depth was calculated for the period June1995-June1997.

Considering the model's characteristics and the fact that at mid 1998 inflation reversed to subsidence rather quickly, the deformation is most probably not directly linked to a usual mechanical effect of the injection of a magma body at depth. Although the injection of such a volume of new material could explain the inflation period 1995-1998, the deflation observed between 1998 and 2000 would imply the removal of the volume previously intruded.
Indeed, the features of earthquake activity in relation to the InSAR results and the characteristics of the hydrothermal field of Nisyros[7] favor the modeled inflation/deflation sequence. The process could correspond to a thermo-mechanical effect of magma intrusion at depth. The heating/cooling mechanisms and variation of the aquifers within the volcano could be the cause of the rather quick reversible ground deformation with variable rates and magnitudes inferred by InSAR. The less concentrated pattern of earthquake distribution is considered as most likely suggesting the transport of magmatic fluids from the north-west coast, where the maximum ground deformation occurs, towards the central south where very shallow aquifers heated by steam are located[14]. The magmatic fluids could form a shallow magmatic intrusion, and the seismic migration of hypocenters may indicate shallow magma transport. This activation of the hydrothermal feeding faults to the central south part of Nisyros is supported by field observations[14]. Indeed, the authors reported the ascent of steam from the very shallow aquifers and the intensification of the fumarolic activity, peaking up one day after the occurrence of the two strongest earthquakes. Moreover, [6] concluded that magma has intruded at very shallow depth below the caldera, explaining the very high temperature of 300°C observed in the aquifers at 1.5km depth below the caldera. Seismic events occur at shallow depths and delineate the circular geometry of the caldera.

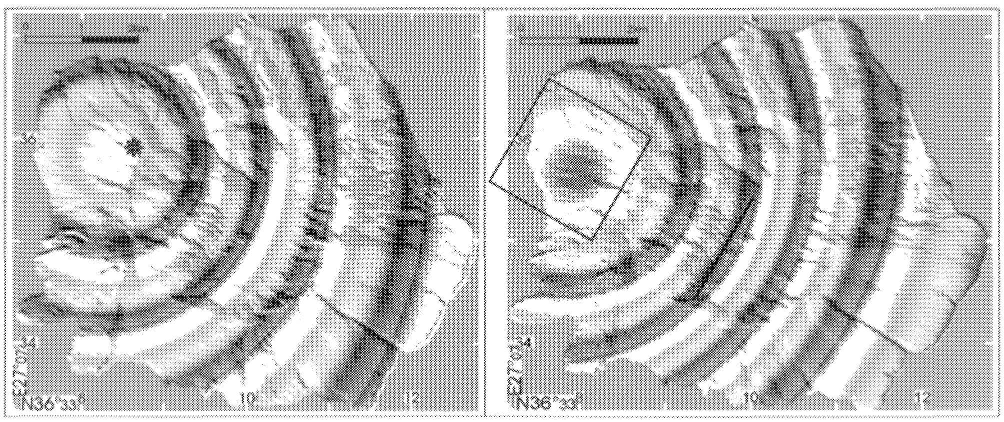

Figure 4. Modeled interferogram for the period June 1995-June 1997. On the left, simulated point-source deformation (described in Table 2).The star shows the location of the top of the point-source. On the right, simulated deformation from a simple rectangular dislocation dike source (described in Table 3). The rectangular shows the fault plane beneath the area of maximum deformation. The line represents the location of the upper edge of the dike in depth.

3.b. Rectangular dislocation

We also solved for a dike intrusion using an inversion model assuming a single rectangular dislocation surface in elastic half-space [12]. The interferogram spanning the period June 1995 - June 1997 was also used as main input. The inverse algorithm is developed by [2] using the least squares approach proposed by [16]. The resulting best-fit solution (Figure 4b) indicates a quasi rectangular dike (2km long and 2.2km height) at 6.4km depth striking to the SW (Table 3). The opening of the dike is 4m. The volume change for the period 1995-1997 is 17.6 x 10^6 m^3. The center of the upper edge of the dike is situated within the active caldera of the volcano.

E (km) (UTM/Zone 35/ED50)	N (km) (UTM/Zone 35/ED50)	Depth (km)	Azimuth	Dip	Length (km)	Width (km)	Opening (mm)	Volume (m^3)
514.8	4049.1	6.4	210	30°	2	2.2	4000	17.6 x 10^6

Table 3: Parameters calculated for the best-fit dike. Coordinates correspond to the upper edge center of the fault. Azimuth corresponds to strike angle considering north=0. Depth corresponds to the depth of the upper edge of the fault.

In autumn 1997, a series of active and seismic studies in Nisyros were conducted [6] concluding that the recorded seismic activity is partly controlled by tectonic processes and partly by volcanic intrusions and hydrothermalism. A dike source could reflect such a combination of tectonic and volcanic activity.
The observed non-continuous acceleration of the frequency of seismic events recorded from the regional array during 1995 - mid 1998 (Figure 1) could reflect a magma intrusion through opening and filling of the dike inducing inflation on the surface as observed by InSAR. As inflation changes to deflation rather quickly at mid 1998 till 2000, this could mean that the magma cooling in the dike occurs rather quickly assisted by the rapid heating of very shallow aquifers and the activation of hydrothermal feeding faults. This is supported by field observations [14] at the central south part of Nisyros where ascent of steam from the shallow aquifers and intensification of the fumarolic activity was reported.

4. DISCUSSION

Interferometric analysis has demonstrated significant ground deformations across the whole Nisyros island trending to the north-west during the period 1995-2000. Inflation lasted till mid 1998 and was then followed by deflation up to 2000. The interferometric results from ascending and descending passes have been crosschecked against each other. GPS measurements[5] agree with the InSAR observations concerning the location of the deformation center and the cease of the inflation.
The deformation observed during the 5-year period in the interferograms is rather smooth and suggests that the phenomena responsible for the deformation occurred at depth without involving direct deformation along existing shallow tectonic structures. However, a more refined study would detect the possible existence of local anomalies in the interferograms and the potential influence of active faulting. Indeed, InSAR observations as well as seismic data suggest that the controlling mechanism of the inflation/deflation sequence is rather complex. However, both modeled deformation sources are considered to be reasonable and provide good fit to the observed surface deformation pattern centered to the north-west. It is worth noting here that in the case of the dike solution, the shallow dip is rather unusual as dikes are generally sub-vertical. However, similar cases have been reported in bibliography[3]. This could probably imply a rotation in the local tectonic regime of the local extensional axis ($\sigma 3$) about both the vertical axis and the horizontral axis[3]. Indeed, in the case of Nisyros, an oblique direction of the maximum compressive axis was calculated from seismic events away from the maximum deformation area[14]. As in the regional compressive stress field the maximum compressive stress axis is vertical[14], such rotation would probably suggest the existence of a complex tectonic regime at Nisyros.

Still, the above results suggest that in any case the presently active north-west part of Nisyros volcanic complex is an area much smaller than the large ancient volcanic caldera [14,6] proposed by several volcanologists, and extends from Nisyros to the southern coast of Kos. It is the same area described as a tectonic block having suffered the maximum uplift in the geological history of the island[17].

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REFERENCES

1. F. Amelung, S. Jonsson, H. Zebker, and P. Segall, “Widespread uplift and “trapdoor” faulting on Galapagos volcanoes observed with radar interferometry”, *Nature*, **407**, pp. 993-996, 2000.

2. P. Briole, G. De Natale, R. Gaulon, F. Pingue, and R. Scarpa, “Inversion of geodetic data and seismicity associated with the Friuli earthquake sequence (1976-1977)”, *Geophys. J. Int.*, **134**, pp. 195-214, 1986.

3. S. Jonsson, H. Zebker, P. Cervelli, P. Segall, H. Garbeil, P. Mouginis-Mark, and S. Rowland, “A Shallow-Dipping Dike fed the 1995 Flank eruption at Fernandina Volcano, observed by Satellite Radar Interferometry”, *Geophys. Res. Letters*, **26**, 8, pp. 1077-1080, 1999.

4. H-G. Kahle, M. Cocard, P. Yannick, A. Geiger, R. Reilinger, A. Barka, and G. Veis, "GPS-derived strain rate field within the boundary zones of the Eurasian, African, and Arabic Plates", *J. of Geophys. Res.*, **105**, B10, pp. 23353-23370, 2000

5. E. Lagios, "Intense crustal deformation rates on Nissyros island (Greece), deduced from GPS studies, may foreshadow a forthcoming volcanic event", Earthquake Hazard and Seismic Risk Reduction, S. Balassanian et al. (Dorchert: Kluwer Academic Publishers), pp. 249-259, 2000.

6. J. Makris, and T. Chonia, T., Active and Passive Seismic Studies of Nisyros Volcano – East Agean Sea, Proc. 1999 CCSS Workshop on Active and Passive Seismic Techniques Reviewed, Comm. Dublin Inst. Advanced Studies, Series D, *Geophysical Bull.*, **49**, pp. 9-12., 2000.

7. L. Marini, C. Principe, G. Chiodini, R. Cioni, M. Fytikas, and G. Marinelli, "Hydrothermal eruptions of Nisyros (Dodecanese, Greece). Past events and present hazard", *J. of Volc. Geoth. Res.*, **56**, 71-94, 1993.

8. D. Massonnet, and K. Feigl, "Discrimination of geophysical phenomena in satellite radar interferograms", *Geophys. Res. Letters*, 22:12, 1537-1540, 1995.

9. D. Massonnet, P. Briole, and A. Arnaud, "Deflation of Mount Etna monitored by space borne radar interferometry", *Nature*, **375**, pp. 567-570, 1995.

10. D. Massonnet, and K. Feigl, "Radar interferometry and its applications to changes to the earth's surface", *Rev. of Geophys.*, **36**, 4, pp. 441-500, 1998.

11. K. Mogi, "Relations between the eruptions of various volcanoes and the deformation of the ground surfaces around them", *Bull. Earthquake Res. Inst. Univ. of Tokyo*, **36**, pp. 99-134, 1958.

12. Y. Okada, "Surface deformation due to shear and tensile faults in a half-space", *Bull. Seism. Soc. Am.*, **75**, pp. 1135-1154, 1985.

13. G. Peltzer and P. Rosen, Surface displacements of the 17 May 1993 Eureka Valley, California, earthquake observed by SAR interferometry, *Science*, **268**, pp. 1333-1336.

14. M. Sachpazi, C. Kontoes, N. Voulgaris, M. Laigle, G. Stavrakakis, O. Sykioti, J-C. Lepine, G. Vougioukalakis, J. Baskoutas, and J. Kalogeras, "Seismological and SAR signature of unrest at Nisyros caldera, Greece", *J. of Volc. Geoth. Res.*, **116**, 1-2, pp. 19-33, 2002.

15. O. Sykioti, C. Kontoes, P. Elias, P. Briole, M. Sachpazi, D. Paradissis and G. Kotsis, "Ground deformation at Nisyros volcano (Greece) detected by ERS2 SAR differential interferometry", *Int. J. of Rem. Sensing*, 2002, in press.

16. A. Tarantola, and B. Valette, "Generalized nonlinear inverse problem solved using the least squares criterion", *Rev. Geophys. Space Phys.*, **20**, pp. 219-232, 1982.

17. S.C. Stiros, "Fault patternof Nisyros Island volcano (Aegean Sea, Greece): Structural, coastal and archaeological evidence", W.J. McGuire, D.R Griffiths, P.L. Hancock, I.S. Stewart, *The Archaeology of Geological Catastrophes*, **171**, pp. 385-397, Geological Society, Special Publications, London, 2000.