Final report for loan 869 - "Long-term investigation of Mt Etna's eruptive mechanism"

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Abstract
A 94-station dual-frequency GPS network on Mt Etna was occupied between 8th September and 14th October 2008, to measure deformation in association with the current series of eruptions, using 7 Leica system 530 sets. The 181-station precise levelling network was also occupied, using a Leica NA2000 digital level and invar staff, and we measured the 27 Dry Tilt stations on the flanks of the volcano using the same level and staff. The measurements were made at a critical time, beginning 4 months after the start of the longest Etna eruption since 1991-3. The results showed an interesting new type of deformation not seen since the whole-volcano network of GPS stations was set up in 1995. The summit movements were similar to previous eruptions in that there were horizontal movements of >1 metre at locations close to the emplaced subsurface dyke, with vectors normal to the dyke indicating fracture opening of more than 2 metres. But instead of the spreading of the flanks that has been the general rule accompanying such activity, this time the stations below 2000 metres altitude generally showed random small horizontal movements of less than 2 cm since October 2007, i.e. there was no evidence of gravitational spreading. The implication is that contrary to previous recent eruptions, this event was not driven by flank spreading opening fissures to passive lava escape, but by magmatic pressure alone.

Background
The overall aim of the project is to determine how Mt Etna volcano functions, and what controls the times, frequencies and intensities of eruptions. There are at least two ways of investigating volcano functioning: one is the geological approach, involving the gathering of evidence from the mineralogy and petrology of rocks and their disposition within extinct volcanoes, and this has usually been the main preoccupation of volcanologists, particularly in the UK. Another is the geophysical approach, involving continuing measurement of the ongoing changes within an active volcano, and study of the activity of the volcano itself. This kind of study is less common, is much more time-consuming to carry out, and does not yield results quickly. The applicant began a longitudinal study of the ground deformation of Mt Etna in 1975, and has carried out 69 series of measurements on the original network and its extensions since then. This study forms part of a number of inter-related investigations into the deformation and eruptive activity of frequently-erupting volcanoes. The aim is to apply analogue and numerical models to the observed horizontal and vertical deformation, in order to detect changes in the volcano's magmatic plumbing system and thereby to elucidate its eruptive mechanism, with the ultimate aim of facilitating the prediction of eruptions.

The P.I. began ground deformation measurements (precise levelling and Dry Tilt) in 1975, and three-dimensional measurements in the 1980s (trilateration with total stations, and later the first rudimentary GPS survey in 1989). The present whole-volcano GPS network measures 37 km E-W by 34 km N-S, and was set up in 1995, since when it has been totally or partially occupied 15 times, and the number of stations has risen from 56 to 94. The location of the network is shown in Fig. 1.

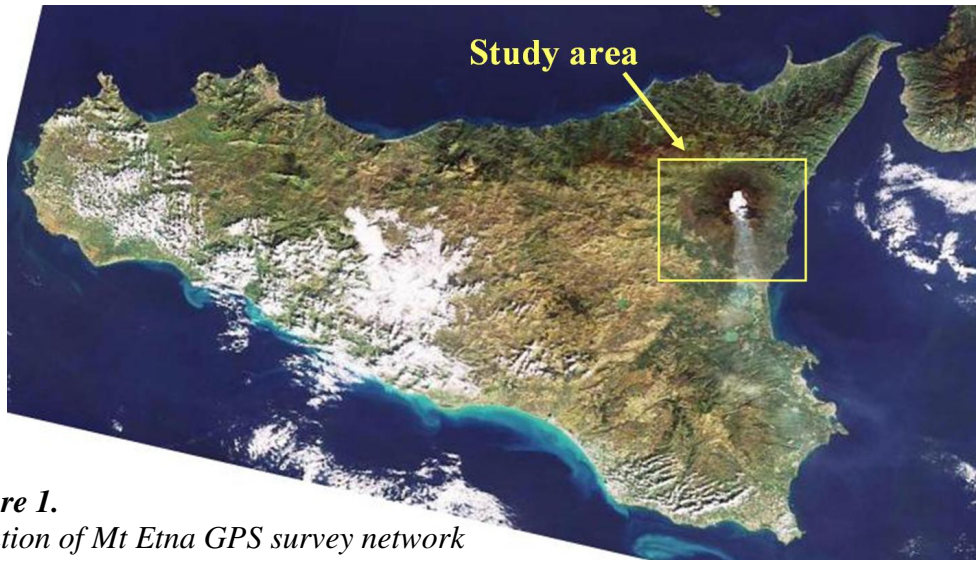

Figure 1.
Location of Mt Etna GPS survey network

Personnel
The measurements were carried out by the following student volunteers:

Andrew Bell, School of GeoSciences, University of Edinburgh
Katie Jill Gladstein, University of Vermont, U.S.A.
Melanie Hinrichs, Open University.
John B.Murray, Open University.
Andrew Pitty, University College London.
Saskia van Manen, Open University & Alaska Volcano Observatory, Fairbanks.
Joline Whalen, University of Liverpool.
Melanie Zacheis, University of Portsmouth.

Survey procedure
Where travel time and distance allowed, the 7 Leica 530 kits were simultaneously deployed to 7 stations in the network for periods of up to 12 hours, enabling 21 lines to be measured at one time. In the summit region, where stations were close together and shorter occupation times possible, five or six instruments were set up as first or second-order stations and one or two kits were carried to successive third order stations (up to 7 in one day). 60% of the points were repeat measured, four were measured more than ten times and a further 19 stations more than twice. A list of number of times occupied and length of each occupation is shown in fig. 2.

Data quality
The overall the data quality is excellent (see fig. 3) and there were very few problems encountered. However, some of the stations down the Valle del Bove were particularly difficult of access, since the active lavas were flowing down these slopes throughout the mission, and two stations (installed in July and September 1987) were unfortunately lost under these new flows. The route to the remaining stations in this valley involved crossing steep, hot and unstable Aa flows, some a few days old, with frequent avalanches of molten lava clasts from flow fronts running down the steep eastern slopes of the summit cones above. There are no paths or vehicle tracks in the Valle del Bove, and in the best of circumstances the measurement of these stations requires a 10 hour hike over difficult and at times dangerous ground, and can only be attempted in good conditions.

Stn	9. Sep.	10.Sep	11.Sep	12.Sep	13.Sep	14.Sep	15.Sep	16.Sep	17.Sep	18.Sep	19.Sep	20.Sep	21.Sep	22.Sep	23.Sep	24.Sep	25.Sep	26.Sep	27.Sep	28.Sep	29.Sep	30.Sep	1.Oct	2.Oct	3.Oct	4.Oct	5.Oct	7.Oct	9.Oct	10.Oct	11.Oct	12.Oct	No. days	Total Hours
1		00:37:30																					00:23:55										2	1.02
2																		02:01:35															1	2.03
3	03:43:15	03:14:30	08:54:05	10:18:10	09:06:30	09:06:05	08:53:50	03:17:40	11:26:10	03:44:35	10:21:25	07:37:35	03:07:35	07:53:10	10:50:20	08:54:45	08:37:45	03:15:10	03:46:45	07:52:10			06:16:20	08:22:05	08:02:30	07:27:15	10:13:00	03:47:15	08:21:40	10:18:25	03:08:45	10:16:00	30	268.65
4																						00:36:15											1	0.60
5																												00:33:05					1	0.65
6										00:18:45																							1	0.31
7					04:33:25																						00:26:40						2	5.00
8										00:22:00																							1	0.37
9																												00:20:25					1	0.34
10				00:38:15																										00:47:10			2	1.42
11															00:51:20																		1	0.86
12																		00:23:15															1	0.39
13	02:43:45		04:46:45		06:25:05		08:10:10			08:56:35		06:44:30		07:04:10											08:13:25		03:32:45						9	62.62
14											00:13:55														00:21:45								2	0.69
15																00:34:50																	1	0.58
16																00:43:45																	1	0.83
17																00:20:40																	1	0.34
18									02:57:45																	02:27:50							2	5.43
19																								00:21:10									1	0.35
20												04:39:45		02:28:00																		00:41:00	3	7.81
21			05:58:20	08:29:45	05:48:35					06:44:05	08:51:45				03:28:10				08:23:50				04:13:35	07:12:55	05:37:45		05:46:05		07:11:45	03:10:20			13	32.35
22			00:17:20																									00:15:15					2	0.54
23											00:22:25																						1	0.37
24		00:23:30																					01:10:10										2	1.66
25				00:19:45																										02:47:50			2	3.13
26								04:59:50									05:58:00																2	10.96
27		07:56:15	06:30:45	03:01:15	04:51:50					06:37:15	08:24:45								07:47:50	00:46:55					05:52:00		06:35:25	08:17:25					11	72.69
28				00:20:30																									00:22:30				2	0.72
29																		07:03:10			05:28:15											00:27:00	3	12.37
30					00:21:35																						00:23:15						2	0.75
31		00:26:05																															1	0.43
32							00:58:50							01:20:30				03:43:20															3	6.04
33																								00:30:20									1	0.51
34							02:17:35					00:47:40												01:51:55					00:20:45				4	5.30
35		00:22:40					00:58:15																										2	1.35
36				05:30:20																										00:20:45			2	5.85
37		00:30:20																															1	0.51
38																	00:13:55																1	0.33
39											00:13:55														00:21:35								2	0.69
40							00:22:25		01:25:15									02:02:30								03:53:20							4	7.73
41								02:10:20																							01:17:00		2	3.46
42						07:23:05		07:20:55			05:44:45				02:56:15		02:15:10																5	25.67
43							00:35:55																										1	0.60
44																			00:20:05														1	0.33
45																		00:30:10															1	0.50
46									05:50:55							02:18:55																	2	8.16
47				00:21:35																										00:22:50			2	0.74
48		06:43:50	05:23:30	06:36:05	06:23:50		04:50:30												02:08:45			05:39:30	03:35:05	06:42:40				07:28:40	06:41:20	08:11:15			12	70.42
49																												00:23:20					1	0.39
50												02:08:25		03:40:30				00:13:15															3	6.14
51									07:48:05																								1	7.80
52																					00:53:25												1	0.99
53						08:16:45											03:02:45														07:59:55		3	19.32
54																												00:35:30					1	0.59
55												01:35:20																					1	1.59
56															00:42:50																		1	0.71
57						00:27:15																									00:25:05		2	0.87
58																												00:23:25					1	0.39
59						00:18:45											00:53:00														04:01:45		3	5.23
60																									00:31:35								1	0.53
61						05:13:00											00:32:05														06:52:05		3	12.62
62											00:21:10																						1	0.35
63																								00:20:20						01:22:40			2	1.72
64																												00:36:05					1	0.60
65						00:41:35											00:53:50																2	1.69
66	07:17:35								10:58:25							08:45:45					03:22:05												4	36.40
67																	00:32:10																1	0.54
68																	00:36:45																1	0.61
69	03:32:55																															10:00:00	2	13.55
70	03:33:15																															#####	1	0.15
71	00:34:55									04:18:10																							2	4.88
72		00:21:25																					00:24:55										2	0.77
73							05:22:35	01:01:40				03:33:50		00:20:50				05:11:00				08:45:25											6	24.36
74																			00:13:15			00:32:40											2	0.77
75			00:47:00																									00:20:40					2	1.13
76		00:26:35																															1	0.44
77		00:21:35																				00:34:05											2	0.93
78		00:23:20																															1	0.39
79					00:20:55																						00:32:40						2	0.89
80	02:41:05								07:08:00																								2	3.82
81											00:20:05														00:28:30								2	0.81
82		05:47:05																											06:04:25	07:43:30			3	19.68
83									01:00:25						01:07:40			00:36:15								05:00:05							4	7.74
84							00:20:20																						00:23:15				2	0.73
85					00:21:30														00:30:00								00:21:15						3	1.21
86																												00:23:40					1	0.39
87						02:36:00		03:39:15							06:41:55		06:15:35														03:18:25		5	22.52
88		00:20:45																					01:40:40										2	2.02
89						04:02:15		05:57:25			05:43:05				06:46:00		04:32:25														06:20:35		6	33.46
90																												00:34:40					1	0.58
91											02:08:30																						1	2.14
92	00:34:55																																1	0.58
93		05:08:40		05:31:45			00:13:55															05:40:55	01:57:15	05:47:05				06:18:35					7	30.74
94	02:36:20													04:14:30							08:20:25												3	15.19

Figure 2: *List of GPS station occupation times (days:hours:minutes) in September and October 2008. Stations are numbered down the left column, and dates across the top. The last two columns on the right give the number of occupations for each station and the total number of hours it was occupied.*

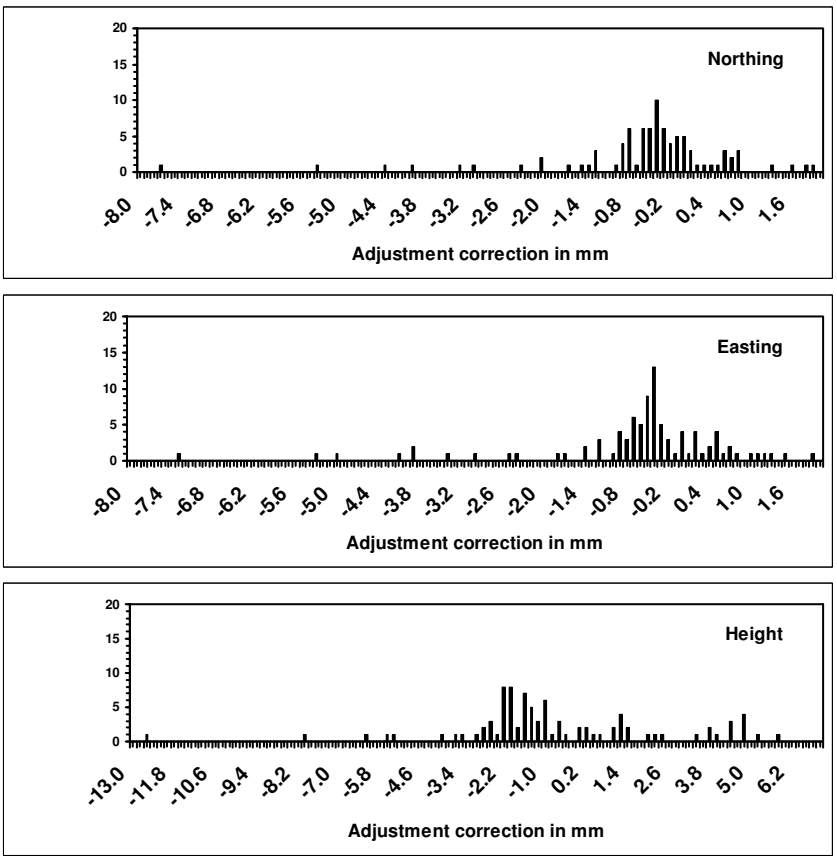

Figure 3. *Histograms of residuals to network adjustment. The vertical axis is the number of stations with the correction value after network adjustment.*

Processing & modelling

Processing was carried out using Leica GeoOffice software. The data were post-processed using data recorded at permanent GPS stations at Noto (southern Sicily), Cagliari (Sardinia) and Matera (southern Italy) from the internet. The data quality of the fully adjusted network is shown in Fig. 3 in the form of histograms of the station residuals after network adjustment. These histograms do not include the Italian permanent GPS stations.

The volcano was in eruption throughout the period of measurements, but the corrections after adjustment are generally small, suggesting that no significant deformation occurred during the 34 days between the first and last measurement.

Preliminary findings

A map of changes since 2007 is shown in fig. 4, with arrows denoting amount and direction of horizontal displacement compared to the base station at Centuripe, off the volcano to the southwest. In the vast majority of cases the uncertainty in vector direction and amount is small compared to the large movements observed (greater than one metre in some cases). The results of earlier GPS measurements since 1995 have shown continuous spreading of the edifice up to 2006, particularly the unbuttressed eastern flank, which has moved an average of around 4 cm per year to the ESE (Borgia et al 2000). This movement is illustrated by the easterly movement of the station in the town of Milo, 10 km east of the summit, compared to the station near the town of Centuripe, which is used as a reference and lies 19 km west of the summit, on the sedimentary basement a few kilometres outside the foot of the

volcanic edifice. A fairly constant easterly rate of movement is maintained 1995-2006 apart from the 2002-3 eruption, when the town moved 29 cm eastwards. However, the eastward movement 2006-7 and 2007-8 was 15 mm and 1 mm respectively, i.e., the movement has effectively come to a halt.

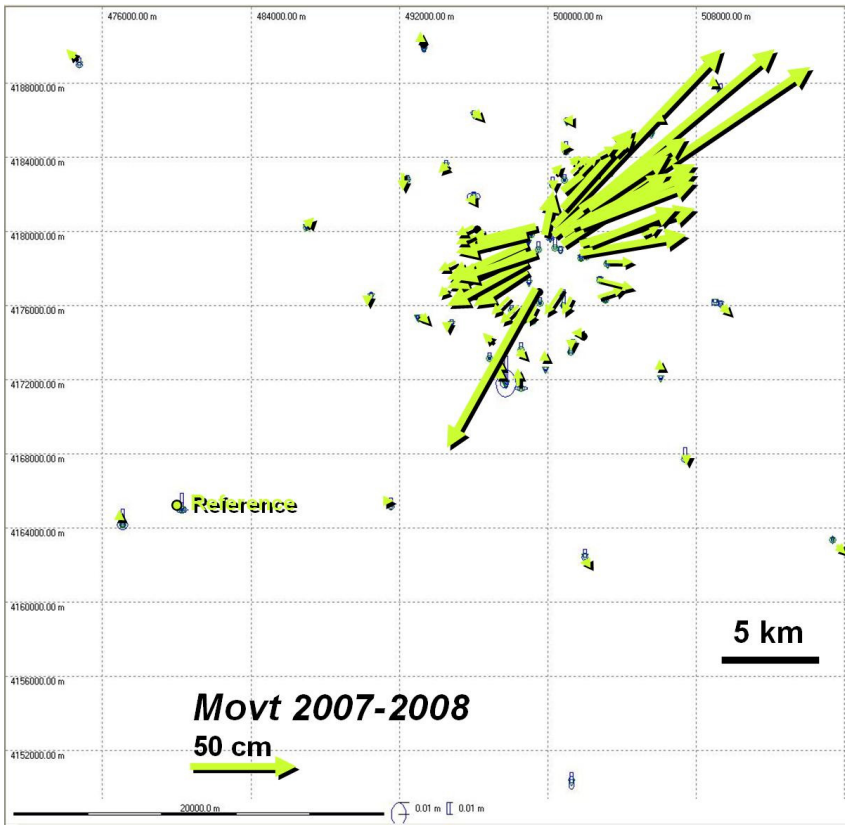

Figure 4. *Horizontal movements 2007-2008, with confidence ellipses. For this analysis, the off-volcano station at Centuripe was assumed to be stable (lower left).*

This was a particularly unexpected development, since the vectors of horizontal movement 2007-2008 over the upper parts of the volcanic edifice showed large horizontal movements of around 50 cm in most areas, as shown in Fig. 2. The disposition of these vectors indicates the presence of a dyke injected NW-SE between the summit and the eruption site. The results from the precise levelling traverse that runs around the summit and down the northern flanks to 2300 metres altitude (not shown) indicate that the dyke extends northwards from the summit to a distance of about 2 km, but did not reach the surface.

A striking feature of fig. 2 is that unlike previous years, the lower flanks do not show distinct signs of radial outward spreading. The movements are nearly all less than 2 cm, and the vectors exhibit an almost random disposition, many vectors pointing tangentially or towards the summit, as well as away from it.

Interpretation to date

The 2007-8 movements are a departure from previous behaviour, which could have been interpreted as gravitational spreading of the volcano driving eruptive activity, in accordance with earlier geological evidence for spreading at Mt Etna (Borgia et al 1992). On this previous model, the dilation of the lower flanks, stretching as far as

the sea in the case of at least one station, eventually causes the volcano to split and lava to escape from the flanks (Merle et al 1996). This is supported by the fact that between 1995 and 2006, expansion across eruptive fissures in the upper reaches of the volcano was roughly proportional to movement on the flanks at places such as Milo. The 2007-8 data suggests the opposite: that it is magma injection at the summit that drives spreading (Neri et al. 2009).

Conclusions and recommendations

The ground deformation of large volcanoes with steep slopes and large topographic differences can only really be studied by the use of dual-frequency GPS and other precise ground surveying techniques. The method of satellite radar interferometry, which showed such promise in the 1990s, and is still an extremely useful tool for volcanoes of low relief (such as some Hawaiian and Icelandic volcanoes), is subject to systematic topographic and unknown atmospheric errors. In addition, vegetation causes incoherence so that many areas of the volcano are inaccessible to this technique, which in any case can only yield movement in the ground-satellite vector, so that horizontal and vertical movement is indistinguishable.

Whilst rapid kinematic GPS surveys are useful during an eruption or when large movements are taking place in small areas, the small movements shown over a long period within such a large network as this require a well-coordinated campaign of multiple static observations.

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