Chapter 7

DISCUSSION

The integrated analysis of textural and compositional features, whole rock petrology, volcanological observations and MELTS modelling, permit to make some important considerations on the volcano feeding system. In this chapter, the whole data set and observations will be applied at each individual eruptive event.

7.1 2001 eruptive event

Simultaneous eruptions from distinct vents are not rare in the historical records on Mount Etna. Typically adventives eruptions are cases in which magmas rise through the main conduit system to be drained along radial or rift structures only at a shallow level (Romano and Sturiale, 1982). The 2001 eruption, however, occurred within the same narrow sector on the southern flank of the volcano. Among various interpretations of the petrological features shown by the 2001 products, here is chosen the model presented by Viccaro et al., 2006; Ferlito et al., 2008; Ferlito et al., 2009, in which three distinct magmas have been recognized: i) the SE– PL magma that erupted from NNW–SSE trending fractures on the high southern flank (2650–3100 m a.s.l.) of the volcanic edifice; ii) the EC–L magma erupted at lower elevations (2100 m a.s.l.) on the same flank from N–S trending fractures; iii) the slightly different LC–L magma, erupted later from vents at intermediate elevation (2550 m a.s.l.) (Viccaro et al. 2006). SE–PL lavas are porphyritic (P.I. 30–40) with prevailing plagioclase, whereas EC–L and LC–L lavas are mesophyric (P.I. 10–20) with plagioclase and augite in similar amounts and up to 6 vol.% of Mg-hastingsite among the phenocrysts. (Metrich et al. 1998) suggests that high amount of H_2O dissolved in the melt increases the stability of olivine respect to pyroxenes and plagioclase that are the phenocrysts, which more determine the porphyritic index. The result is to different porphyritic index of the resulting magma, volatile loss induce highly porphyritic lava due to strong plagioclase nucleation; on the other hand, high water pressure generate oligophiric melts.

SE–PL features are consistent with those of the Etnean rocks of terminal and subterminal activity in the last few decades. The steady degassing conditions in an open and repeatedly filled conduit prevent the pressure to increase and allow the concentration of volatile components to rise above the saturation level.

In EC–L and LC–L volcanics the presence of Mg-hastingsite phenocrysts and their dehydration rims are related to decompression and consequent volatile loss immediately preceding and during the eruption. (Viccaro et al 2005)

7.1.1 Inferences from plagioclase features

Most of plagioclase in SE-PL lavas are euhedral and shows an oscillatory HALF pattern, that vary from An_{78} to An_{85} in composition. MELTS simulations model (Fig. 7.1) suggest a quite shallow crystallization from 1800-800 bars in a magma (7.5-2.8 km depth) with a maximum of 2.5 wt% H_2O dissolved. Oscillatory pattern reveals crystallization in a convective regime where heterogeneities in P-T and magma composition are the causes of the generation of angular unconformity and dissolutions edges. Sieve textures are frequently founded at the core, indicating that they underwent to rapid decompression.

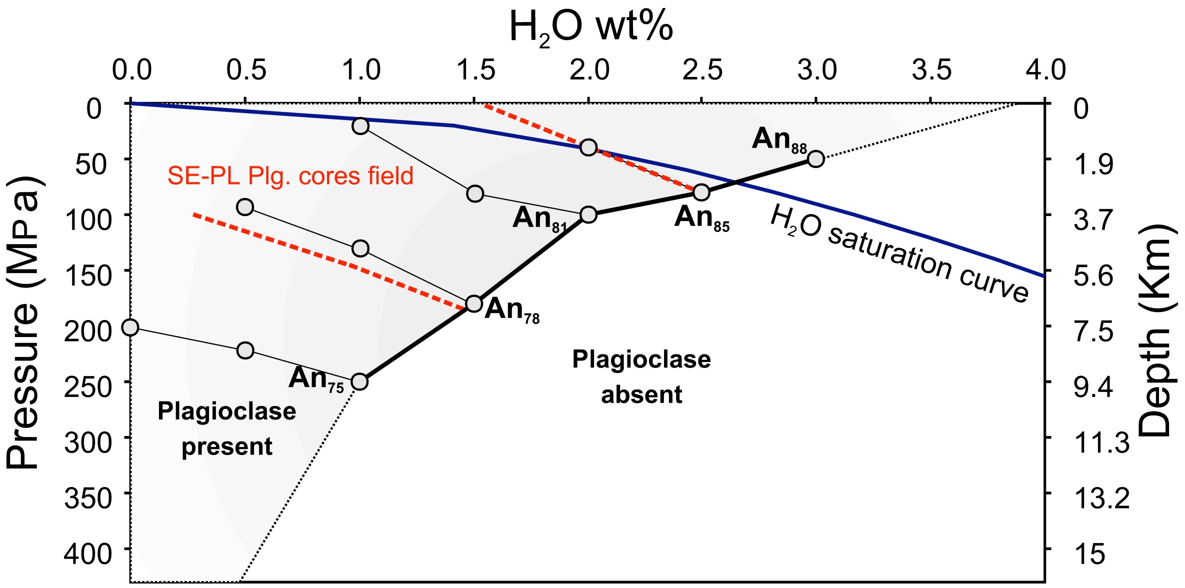

Fig. 7.1 MELTS simulation of plagioclase stability, red dotted line indicate the range of pressure of starting nucleation of phenocrysts in SE-PL magma.

Plagioclase in EC-L show a less calcic composition at the cores (An_{55} on average) characterized by oscillatory pattern (Type 1). Whole rock analysis and the occurrence of Mg-hastingsite phenocrysts in this lavas, indicate less basic composition crystallizing at T=980°C at $P=PH_2O=2000$ bars (Foden and Green, 1992; Holloway and Blank, 1994; Rutherford and Devine, 2003). Low magma temperature is consistent with low calcic compositions of plagioclases. Plagioclase cores are often sieve textured (Type 4) as a consequence of the decompression during ascent. Plagioclase rims are resorbed and dusty (Type 5) associated to a strong increment in An and FeO content. These rims strong indicate a change in the chemical and physical parameters of the magma, that is T or in magma composition (including H_2O), suggesting that a magma mixing occurred with a more femic, hotter and/or water rich magma.

Plagioclase in LC-L lavas are quite similar to those of EC-L, having the same range in composition (An_{65-55}) however, some differences occur. Some crystals show Type 3 patchy cores, similar to those observed in Pre-1971 lavas and tephra. At the rims LC-L crystals present the same resorbed dusty Type 5 rims, associated to An and FeO increase, observed in EC-L ones. However, the majorities of these crystals are ovoidal and present a glassy, opaque outermost edge indicating a non-equilibrium condition and consequently dissolution of the crystal in the melt. Dissolution of the outermost crystal edge is quite rare in plagioclase of Mount Etna and indicate a strong depression of liquidus of plagioclase, which can be induced by contact with a more basic melt, a rising of the whole temperature of the magma or by an increase in the dissolved water content. Major and trace element in whole rock as well as experimental petrology on dusty rims formation mechanisms (Tsuchiyama et al. 1985b), support the idea of the magma mixing with a more basic end member. However, glassy rounded edges occur after the An regrowth of dusty rims, indicating a second process which increased the water content in the melt and depress the liquidus of plagioclase. Amphibole destabilization is confirmed by its rounded shape and opaque rims, reflecting a rise of the whole temperature above Mg-hastingsite liquidus. Amphibole breakdown could have brought enough water to the melt, contributing to the destabilization of plagioclase phenocrysts.

7.1.2 General considerations on the feeding system of 2001 eruptive event

As suggested by Viccaro et al. (2005), mixing occurred between the Mg-hastingsite-bearing magma (C–L), residing in a closed batch, and an inferred deep basic end-member (DBM), whereas the SE–PL magma should have played no significant role in the mixing process, as suggested by the marked differences between the textures and mafic to salic phenocryst ratios of LC–L and SE–PL. However, some plagioclase with resorbed dusty rims (Type 5) and the alignment of data points of LC–L lavas toward the SE–PL field (Figs. 6 and 7 in Viccaro et al. 2005) suggests that a modest interaction might have occurred.

Mixing had to occur at the level of the C–L batch (~6 km), immediately before and/or during the start of C–L magma ascent. It may also be inferred that after the first seismic swarm (July 17th) DBM rose up, intersected the batch and uprise system of the C–L magma, and partially mixed with it. Mixing between ~980 °C) and the hotter DBM (T ~1150 °C) set off a limited heat transfer, (see appendix in Viccaro et al. 2005) resulting a T of the mixed magma of 1025°C. Part of the heat is used for endothermic reactions of plagioclase resorption observed at the Type 5 rims and enhancing amphibole dissolution. Water supply by DBM together with those due to amphibole breakdown, increased water pressure of the resulting magma from the mixing and depressed the plagioclase liquidus, promoting the dissolution.

The physical disturbance originated by DBM entering the C–L shallow reservoir probably contributed in easing the gas exsolution. The LC–L magma supplied a significant amount of gas, characterizing then the dynamics of the eruptive activity at the Laghetto vent, which was on the whole highly explosive.

7.2 Eruptive event of 2002/2003

A model of 2002/2003 eruptions has been presented by Ferlito et al. (2009), concentrated to the NERS and briefly summarized here.

a) As suggested by micro-seismicity precisely determined by Gambino (2006), the oligo-phyric magmas, both HK and LK, may have intruded some months before the event, within closed reservoirs of indeterminate depth below the NE Rift.

b) The seismic crisis below the summit craters started about 3 h before T1, accompanying the eruption on the southern flank along a N–S-oriented fracture (~2,750 m a.s.l.). Products of this very early phase have been collected and analyzed by Andronico et al. (2005), who reports HK magmas with oligo-phyric texture. They were successively covered by later products and are no longer accessible for sampling.

c) At T2, at the base of the NE crater (~2,950 m a.s.l.), HKO tephra were emitted during a short, Strombolian activity from a N10W-oriented fracture. These products, thug less basic, are very similar to the oligo-phyric products that first erupted on the southern fracture.

d) After a time gap of 4–5 h, at T3 from a N15E trending fracture (~2,500 m a.s.l.) a violent Strombolian eruption of LKO bombs and lapilli occurred from an isolated (and probably small) pocket of magma.

e) At T4, the fracturing continued downwards with N35E orientation (~2,300 m a.s.l.) and the Strombolian activity erupted HKO tephra, followed by three lava flows (Fig. 7c). Products erupted at T2 and T4 are chemically and texturally very similar but, since they have been emitted at different times, from two fractures with distinct orientations and separated by the fracture emitting the LKO magma, they may represent two distinct batches of a similar magma.

f) Finally, at T5 the fracturing was complete and the last segment of the NERS (~2,200 m a.s.l) oriented N45E was activated with the emission of both tephra and lava flows of HKP magma (Fig. 7d). The volume of this magma is far larger than the volume of magmas erupted by the other segments.

The products emitted at T5 and the lava flows of the almost contemporary at the southern fracture's present similar petrographical and geochemical features. The affinities between these two HK magmas, together with similar high explosivity levels and the presence of quartzarenite xenoliths exclusively found in the products emitted by these two fractures suggest a common provenance. To proof this idea a new data of chronologically controlled sampling and on textural and compositional features of plagioclase have been collected.

7.2.1 Inferences from plagioclase features of 2002/2003 event

Plagioclase embedded in LKO presents two textures type: Type 2, dissolved cores and Type 3, patchy cores (Fig. 6.13a,b). Dissolved cores are clear and bytownitic in composition (An_{82-88}). Patchy cores are labradoritic (An_{70-80}), chemical zoning inside this core, is quite concordant with FeO (Fig. 6.13b). Both crystals with dissolved (Type 2) and patchy (Type 3) cores are followed by a more sodic overgrowth with similar chemical composition. Rims are mostly oscillatory, with a LAHF zoning pattern (An_{60-70}). MELTS simulations indicate a nucleation pressure of 120-70 MPa corresponding to a depth of 4-2.2 Km (Fig. 7.2). Sr/Ba ratio at crystal cores indicate that dissolved cores are most easily in equilibrium with host basaltic magma, on the other hand, patchy cores have a Sr/Ba ration in the cores too low to be in equilibrium with the host magma, suggesting the they could be recycled, as also indicated by the common overgrowth.

HKP lavas represent the most voluminous magma erupted during the 2002/2003 event both on the northern and southern flanks. The study of the plagioclase textures and in situ geochemistry show that HKP lavas and tephra from both southern and northern flanks have similar dissolved and rounded An-rich cores varying from An_{75} to An_{84}, but texturally distinct rims.

The dissolution texture at the cores (Type 2) is associated to a significant decrease in An and subordinately FeO, at the edge of the ovoidal core. The important compositional changes beyond the ovoidal core reflect a major perturbation in the physical and chemical parameters of the system. Such texture and compositional variation might be acquired by pressure decrease during fast ascent under H_2O-undersaturated conditions. In such circumstances the plagioclase liquidus decreases and concomitantly the P_{H2O} of the system increases, strongly reducing the stability of plagioclase and promoting dissolution (cf. Nelson and Montana, 1992; Blundy and Cashman, 2001, 2005). When H_2O-saturation is reached, and water is exsolved from the magma, a more sodic plagioclase begins to grow. The absence of any interaction with a more basic magma is also confirmed by Sr/Ba ratio, which does not show any increase from core to rim. The occurrence of plagioclases with this texture and compositional variations in both NERS and SRS lavas, suggests that they were crystallized in magmas ascending under the same H_2O-undersaturated conditions. MELTS calculations on plagioclase stability indicate a range of crystallization depth from 250 to 80 Mpa (9.4 to 4 km), below the volatile saturation depth calculated with VolatileCalc. (Fig. 7.2)

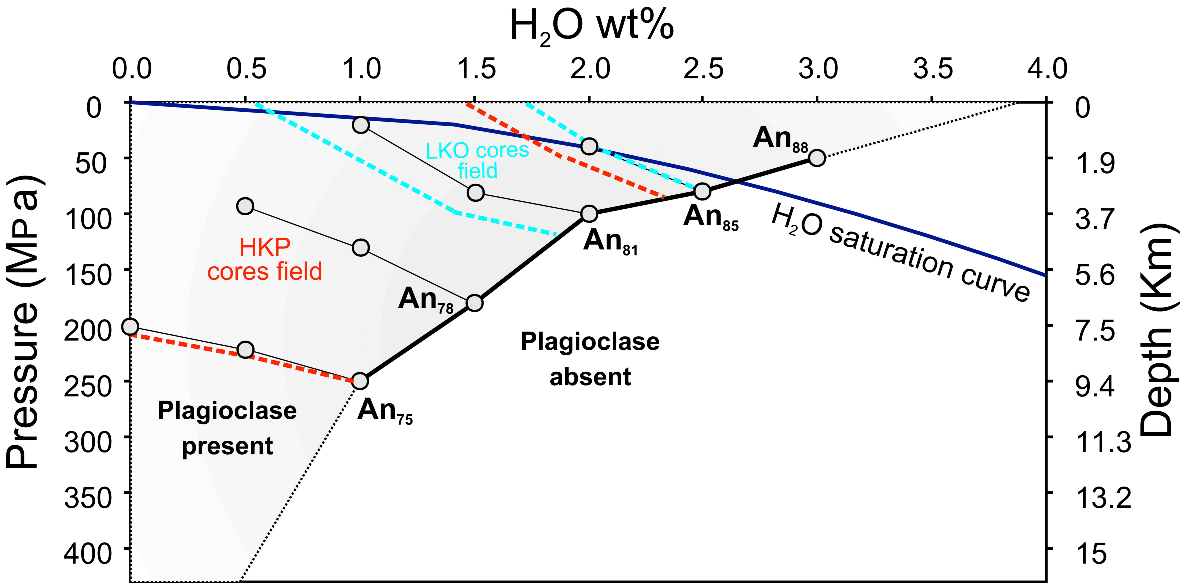

Fig. 7.2 MELTS simulations of 2002/2003 plagioclase nucleation.

The partially resorbed dusty rims, associated to an abrupt increase in An and FeO content, which characterize SRS outer rims emitted at T6 and T8 are interpreted as a clear evidence for an input of less differentiated magma, in accordance with several authors (e.g., Tsuchiyama, 1985; Pearce et al., 1987; Landi et al., 2004, and references therein). These textures at the rims testify the reaction between the pre-existing crystals and a melt, which can be hotter, more mafic or “simply” undegassed. Sr/Ba ratios confirm this idea, showing an increment associated to the resorbed rims. On the other hand, the oscillatory zonation of SRS plagioclase emitted in T5 and T7 can be accounted by kinetic processes at the crystal/melt interface in a convectively moving magma batch.

The stripes of melt inclusions, polygonal in sections and distributed along crystallographic directions and associated to a sharp decrease in An and FeO contents, found in plagioclase of HK NERS lavas, may be considered as a fast-growth feature induced by a rapid undercooling event and not referable to dissolution (Lofgren et al. 1980), An increase in the rate of crystal growth can be easily promoted by volatile loss and/or depressurization of the magma batch due to fracture opening. The presence of this texture in NERS HK lavas suggests that eruption was tectonically triggered by fracture migrations rather than by an input of a more primitive magma. The absence of new magma inputs is also testified by whole rock data, by trace element Sr/Ba determinations at crystals rim, and by the fact that the eruption on this side of the volcano ended after few days.

The observed plagioclase textures and compositional features suggest the following scenario:

1. Plagioclases begin to nucleate within a volume of HK magma and grow in water-undersaturated conditions. The decompression associated to the ascent of HK magma have induced dissolution;
2. At T1 the HK magma reached the surface on the SRS, along the pre-existing fractures opened during 2001 eruption;
3. Twelve hours later the HK magma reached the surface at NERS. This delay can be explained considering that the NERS system was closed and was reactivated by a seismic swarm with 300 instrumental earthquakes;
4. At the NERS fracturing, which induced decompression and volatile loss in the magma, triggered eruption. Volatile loss promotes a strong undercooling of the magma, enhances plagioclase growth, forming the observed melt inclusion alignments;
5. On the NERS at T5 eruption ceased, whereas on the SRS magma input occurred and reaction between resident plagioclase and new magma is recorded with the formation of the partially resorbed An-rich dusty rims.

7.2.3 General considerations on the feeding system of 2002/2003 eruption

The detailed petrological study of the products emitted at the SRS during the 2002/03 eruption of Mount Etna, allows some important considerations about the magma ascent dynamics and volcano feeding system. During the entire eruption, HKP magma fed the activity. This magma has petrographical features similar to those found in lavas and tephra emitted by the lower segment of the NERS. Geochemistry reveals that these HKP products are on the same liquid line of descent, in which the most evolved terms are those emitted on the NERS. However, time reconstruction reveals that two basic magma input occurred at T6 and T8 along the SRS, feeding the eruption for other two months; while on the NERS magma input did not occur and eruption stopped after few days. This is the first time that these input episodes are testified outlining the importance of time resolved sampling, when possible, during the eruption. Mass balance fractional crystallization model proves that the most evolved HKP lavas emitted on the NERS can be obtained by fractionation of about 13% of cumulitic gabbroic material (Ol, 12.5%; Cpx, 19.33%, Plg 62.13% and Mt, 6%) starting from the least differentiated HKP lavas emitted on the SRS.

These data seem to indicate a common depth for the origin of HKP magma for the southern and northern branches of the feeding system. On the other hand, Different kinematics of volatile release and frequency of magma input characterize the upper and shallower part of the system: on the South rift inputs are frequent, as indicated by the large frequency of eruptions in recent time, and magma mixing is probably the most efficient cause of eruption triggering; on the NE Rift, tectonics do not easily promote magma intrusions, causing formation of shallow magma batches and passive triggering due to seismic crisis seems to be the most efficient mechanism.

7.3 2004 Eruptive event

Corsaro et al. 2009 proposes to divide this eruptive event in three temporally distinct phases: phase 1, eruption before 24th September, Phase 2 (24 September to 15 October) and Phase 3 (post-15 October).

7.3.1 Phase 1 Eruption before 24th September

The eruption started with the opening of a fracture zone extending ESE that tapped a batch of magma stored at very shallow level since the 2002–2003 eccentric (EC) activity. The position of the uppermost eruptive vents at 2,920 m a.s.l. suggests that the top of the reservoir was probably located at about 300–400 m below the summit craters. The magma have been stored in this reservoir since the 2002–2003 EC eruption (Corsaro et al. 2009) degassed and evolved through closed-system fractional crystallization, because no input of new magma was detected by the petrological data. Corsaro et al. (2009) support the hypothesis that the 2004–2005 eruption was triggered by the movement of the east flank of the volcano, as suggested from the structural and geodetical data by Burton et al. (2005), Neri and Acocella (2006), and Bonaccorso et al. (2006). It is noteworthy that the trend of the 2004–2005 eruptive fractures matched well the ESE-WSW tensile stress indicated by ground deformation from 2003 to 2004 (Bonaccorso et al. 2006).

7.3.2 Phase 2 (24 September to 15 October)

Corsaro et al. 2009 observe a progressively change towards Central Conduit (CC) isotopic features (Figs. 4, 5, and 6 in Corsaro et al. 2009). The composition of lavas in phase 2 progressively changed with time and shifted towards CC magma The different geochemical features of phase 2 from phases 1 and 3 are also evident in Fig. 6.19-6.20, where phase 2 lavas significantly depart from the FC horizontal trend and point towards the 2001–2003 CC magma. This pattern precludes derivation of phase 2 magma from phase 1 magma through FC process and suggests its origin from a mixing between the phase 1 magma and a new magma, probably arriving from the central conduits. Model calculations show that the compositional variation of phase 2 lavas can be explained by progressive mixing from 10% to 50% of the 2002–2003 CC magma with phase 1 magma.

Petrological data from Corsaro et al. 2009 suggest that in phase 2 the eccentric (EC) magma mixed with the CC magma, which remained in a shallow part of the plumbing system during phase 1. It is expected that this mixing was induced by propagation of the ESE fracture zone inwards. Decreasing magma pressure in the reservoir of phase 1 magma, due to loss of magma by eruption, may have permitted successive intrusion of the CC magma from the central conduits (Fig. 8). The fact that the magma plumbing system was changed by the depressurization after 24 September may be verified by geophysical and geochemical observations such as a remarkable increase in the amplitude of tremor on 25 September (Di Grazia et al. 2006) and SO_2 flux peaked since 25 September (Burton et al. 2005; Fig. 9). The chemical variation of the phase 2 lavas is characterized by a rapid decrease of EC magma in the mixing and a progressive shifting towards CC magma composition. This is a good indication that the mixing is a syn-eruptive process, which occurred quickly and operated efficiently essentially in phase 2.

7.3.3. Phase 3 (post-15 October)

After 15 October till the end of the eruption, the contents of most incompatible elements and the Sr–Nd isotopic ratios (Figs. 4, 5, and 6 in Corsaro et al. 2009) remain fairly constant and are very close to the values of the CC magma. AS consequence, Corsaro et al. 2009 propose that the phase 3 eruption was fed by magma with very similar chemical and isotopic compositions to the CC-type magma. Homogeneous compositions was continuously erupted for the next 4 months confirming that the mixing process in phase 2 ended and eruption occurred stably in the central conduits system. Eruptions fed by magmas residing in the central conduits at Mt. Etna had not generally been preceded by significant deformation and volcano-tectonic earthquakes (Patanè et al. 2004, 2005). During phase 3 too, no significant changes in geophysical signals occurred, strengthening the idea that a CC-type magma was, at that time, feeding the activity. It is notable that the effusive eruptive style was unmodified by progressive eruption of CC magma occurring in phases 2 and 3. We might then argue that the new magma rising in the central conduits had already released most of volatile components during continuous degassing in the open conduits of the summit craters (Caltabiano et al. 2004). As a consequence, the abundance of volatile components was insufficient to make the eruptive style more explosive.

7.3.4 Inferences from plagioclase features of 2004/2005 event

Plagioclase in lavas emitted from the fracture at the base of South East Crater, ascribed to phase 1 in Corsaro et al. (2009) are Type 1, oscillatory zoned and Type 4, coarsely sieved cores. Oscillatory zoning indicates a "quite" convective regime and few coarsely sieved textured cores are consistent with a depth just below the volatile saturation level. This observations are confirmed by MELTS calculation on plagioclase stability, which indicates that cores crystallized in a pressure range from 80-60 MPa (4-2 Km), close to the saturation level (Fig. 7.3). Cores are always followed by a less calcic overgrowth, indicating a strong volatile loss due to saturation and exsolution in the melt before the eruption.

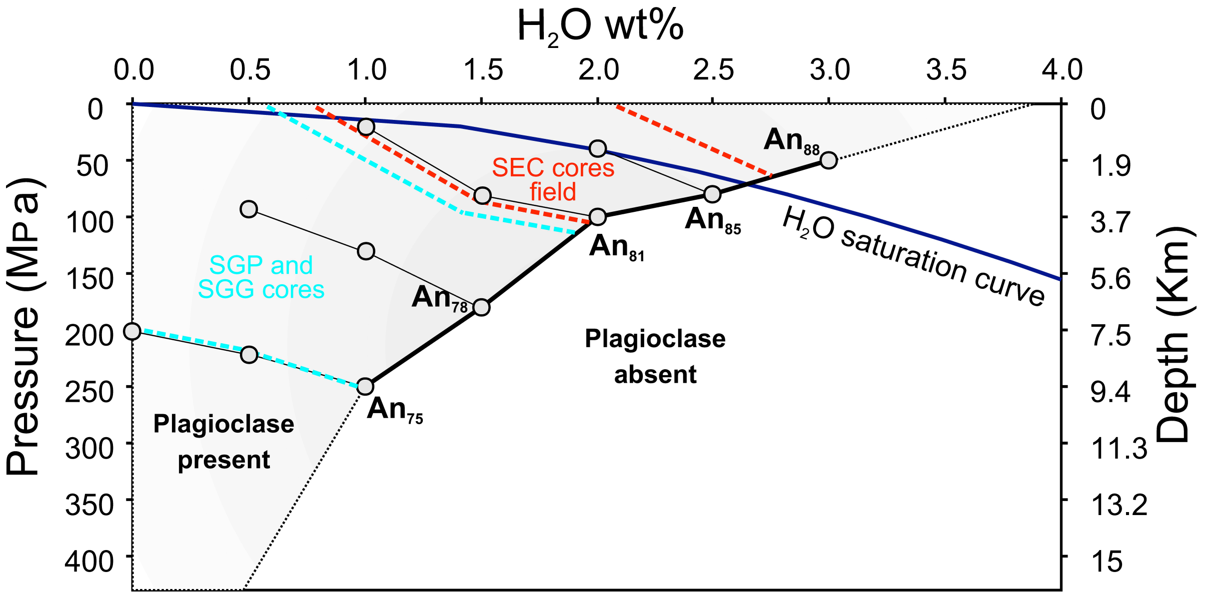

Fig. 7.3 MELTS simulation of plagioclase cores nucleation during 2004/2005 event.

Plagioclase erupted from the fracture at Serra Giannicola Piccola (SGP) and Serra Giannicola Grande (SGG), comparable to phase 2 and phase 3 in Corsaro et al. (2009) are

Type 4 coarsely sieved cores and Type 5, resorbed dusty rims. Coarsely sieved cores are more frequent respect to the plagioclase emitted during the first eruptive phase, indicating that fast decompression in a water under-saturated melt is constant during this phase. Compositions vary from An_{85} to An_{70}, averaging at about An_{80}. MELTS calculation set these cores at a depth of 120 MPa, but several crystals indicate an initial deeper nucleation ($P=\simeq 200$ MPa)(Fig. 7.3). This data indicate a deeper origin of this magma with respect to phase 1 plagioclases. Resorbed dusty rims, associated to an increment in An content suggests a reaction with a more mafic and volatile-rich magma, which mixed with the residing one.

7.3.5 General Considerations on feeding system of 2004/2005 event

Whole rock studies in Corsaro et al. (2009) and plagioclase features, suggest a similar scenario. The event involved first a resident magma batch, located at a shallow depth, inside the volcano edifices. Similarity between the outermost plagioclase rims of the latest period of 2002/2003 eruption, with those erupted in this first phase suggest a remobilization of a magma intruded in the previous eruptive event along the SRS fractures thus explaining the absence of precursor seismic activity. Plagioclase rims start to indicate a reaction with a more mafic incoming magma already in this first eruptive phase. On contrary mixing seems to be evident in whole rock, only after September 24th. After September 24th plagioclase core indicate a deeper origin and resorbed dusty rims are more frequent, indicating a more efficient mixing.

Petrological data confirm that 2004/2005 eruption was probably tectonically controlled in its first phase. Fracture opening due to regional movement simply reactivate a resident magma batch intruded along the South Rift System. Eruption continued due to the recall of a deepest more mafic and volatile rich magma, which alimented the event.

7.6 2006 Eruptive event

A magma input with more basic composition fed the November 16th explosive episode as suggested by Ferlito et al. 2010. Due to repeated rock failures on the eastern flank of the SEC cone were that, in only a few hours, its thickness was greatly reduced. The removal of a volume of volcanic material for a maximum thickness of 150 m decreased the confining pressure exerted by the lithostatic load on the dyke feeding the eruption at the summit of the SEC cone and at the hornito at 2,800 m (Vent E, fig.). The decompression can have been recalled a more basic and volatile rich magma and, therefore, more energetic (as also indicate by infrasonic data, Sciotto et al. 2009, Vergniolle and Caplan-Auerbach 2004). An hydromagmatic mixture with great quantities of juvenile and lithics tephra, together with steam due to vaporization of interbedded snow and pore water, was ejected from the entire length of the fracture to an estimated height of ~300 m. The eruptive curtain collapsed a few seconds later and produced a pyroclastic flow channeled into the gully which had been formed by repeated rock failures of the SEC eastern flank during the morning.

7.3.4 Inferences from plagioclase petrological features of 2006 event

MELTS simulations suggest that plagioclase emitted by fractures before November 16Th start to nucleate from 120 to 80 MPa, corresponding to a depth of 4-3 Km.

Plagioclase emitted before and during November 16th show strong resorbed dusty rims associated to an increment in anorthite and FeO content and MELTS simulation indicate a shallower depth of nucleation, from 120 to 40 MPa (Fig. 7.4) This shallow pressure, together with the calcic composition, suggests high water content dissolved in the melt, close to 3.4 wt%. At such depth water saturation is not reached and crystals can react with the more volatile-rich magma.

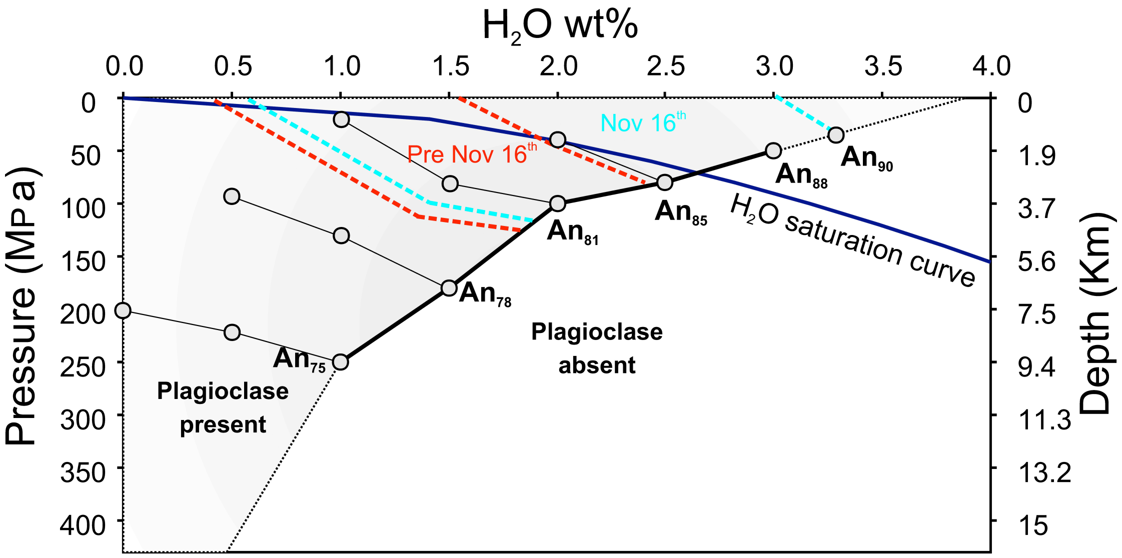

Fig. 7.3 MELTS simulation of plagioclase cores nucleation during 2006 event.

Plagioclases emitted after November 16th show a strong oscillatory pattern and sieve textured cores. Compositions indicate a shallower crystallization pressure <80 Mpa, corresponding to a depth <3.7 Km. This depth is close to the volatile saturation curve, a convective regime with repeated volatile loss and crystal sinking, should be the cause of the strong oscillation pattern.