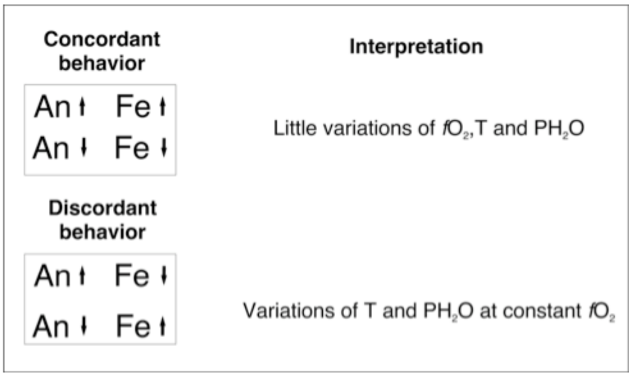
Chapter 4

INTERPRETATION OF OBSERVED TEXTURES

4.1 General Considerations

Processes able to modify physical and chemical parameters of the volcanic system are multiple and, at times, combined (e.g., convection, ascent-related pressure decrease, input of differing magma, loss or influx of volatiles). The An content in plagioclase changes as a response to all these phenomena, thus additional discriminating parameters must be considered. An attempt may be made by taking into account the concentrations of minor elements (e.g., Fe, Mg) in the envelopes with differing An contents: as an example, their concentrations should remain constant if An varies, due to changes in T and/or H_2O content, in a melt unmodified in composition. Conversely, An changes combined with variable concentrations in these elements would reflect chemical perturbations of the magmatic system. However, given the rather high detection limit for Mg and its low contents, only Fe has been considered. As shown by Ginibre et al. (2002a), Fe content of plagioclase chiefly depends on its concentration in the host melt, although other authors highlighted its dependence also on fO_2, T and An content (e.g., Phinney, 1992; Bindeman et al., 1998; Wilke and Behrens, 1999; Humphreys et al., 2006, 2009). However, data provided by Bindeman et al. (1998) predict that the effects of temperature on Fe partitioning between plagioclase and andesitic melt are relatively small, with FeO content in plagioclase increasing by only 0.1 wt.% for an increase in temperature from 850° to 1050 °C. It is worth noting that Etnean lavas are erupted at relatively constant temperature, which varies within a restricted range of values (i.e., 1050–1080 °C; e.g., Tanguy and Clocchiatti, 1984). Thus, we may expect that, in our case, temperature does not significantly affect the Fe partitioning in plagioclase, which should be more sensitive to fO_2 variations. Based on these experimental data, Fe partitioning between



Concordant behavior	Interpretation
An ↑ Fe ↑ An ↓ Fe ↓	Little variations of fO_2,T and PH_2O
Discordant behavior	
An ↑ Fe ↓ An ↓ Fe ↑	Variations of T and PH_2O at constant fO_2

Fig. 4.1 Schematic table of concordant and discordant behavior of An and Fe and its possible interpretations.

plagioclase and melt is positively correlated with fO_2 and negatively with An content. This would imply that FeO and An contents should be strongly discordant under constant fO_2, whereas they become concordant as the fO_2 modifications of the system are highly marked. (Fig. 4.1)

Water in magmas is found either as molecular H_2O or by reacting with oxygen to form hydroxyl groups (e.g., Silver and Stolper, 1989). Given the positive linear dependence between water activity and oxygen fugacity, changes in the water content dissolved in the melt (in the form of a mixture of molecular H_2O, hydroxyl groups and oxygen ions) will affect fO_2 (e.g., Moore et al., 1998). Variations of fO_2 in the Etnean system may therefore be related to two possible factors:

1) At shallow depth, when the melt becomes H_2O-saturated, fO_2 may be affected by changing the water content dissolved in the melt and by the crystallization of Fe–Ti oxides;
2) At greater depth, below the water saturation level, changes in fO_2 may chiefly be due to Fe–Ti oxide crystallization.

Such crystals appear early on the liquidus of Etnean magmas and crystallize even during syn-eruptive conditions, severely depleting the residual melt of oxygen ions.

4.1.2 Interpretation of the oscillatory zoning pattern

Several experimental and theoretical studies have demonstrated the primary role played by kinetics on oscillatory zoning in plagioclase (e.g., Lofgren, 1974a,b; Kirkpatrick et al., 1979; Haase et al., 1980; Lofgren, 1980; Allegre et al., 1981; Lasaga, 1982: Loomis, 1982; Ortoleva, 1990; Cashman, 1990; L'Heureux and Fowler, 1994; Wang and Wu, 1995; L'Heureux and Fowler, 1996a,b). Two main types of oscillatory zoning, that is small- and large-scale oscillations (cf. Pearce and Kolisnik, 1990), can be frequently observed in plagioclases of Mount Etna. These two pattern types may be ascribed to two contrasting mechanisms, respectively:

1) Kinetic effects and;
2) Minor changes in bulk chemistry or physical parameters of the system (e.g., melt temperature and/or composition).

The dynamics of crystal growth rate in the first instance are ruled by the plagioclase oversaturation of the melt in relation to undercooling at the crystal–melt interface, in a way that when the system is sufficiently undercooled, at high crystal growth rate the element diffusion kinetics are too slow to re-establish the melt composition at the crystal interface (cf.

Pearce, 1994). This leads to the formation of a chemical boundary (where the plagioclase saturation differs from that of the bulk melt), which finally affects the composition of the growing crystal. Most of the kinetic models are based on this interface vs. diffusion kinetics “antagonism” (cf. Pearce, 1994). Several models could be considered for explaining patterns consistent with our LAHF zoning (Fig. 3.1 a–b). As noted by Ginibre et al. (2002b), some kinetic models are poorly consistent with the observed LAHF patterns, chiefly because of the large amplitudes and low frequencies of variation obtained experimentally and theoretically (Haase et al., 1980; Lasaga, 1982; Ortoleva, 1990; L'Heureux and Fowler, 1994; Pearce, 1994; Wang and Wu, 1995; L'Heureux and Fowler, 1996a,b). Conversely, other models (Allegre et al., 1981; Anderson, 1984) are able to produce oscillations resembling those of the LAHF oscillatory zoning.

The model of Allegre et al. (1981) assumes a delayed growth rate response to changes in concentrations of the melt next to the crystal interface, possibly due to small perturbation of the system. The model of Anderson (1984) proposes that cyclic falls of the chemical boundary next to the crystal–melt interface (e.g., due to shear pulses related to tidal effects on pressure) allow an easier access of oversaturated melt to the crystal surface, affecting the composition of the growing plagioclase layer. Yet neither of these two kinetic models can be unquestioningly accepted. In accordance with the above discussions, the slight concordant or discordant An and FeO variations observed in LAHF oscillatory zoning patterns for Etnean plagioclases may be interpreted as due to small variations in volatile contents and fO_2 (cf. Table 3.1). Models applied to LAHF never imply dissolution because the melt is always saturated in plagioclase. Our observations show, however, some HALF-zoned plagioclases with envelopes characterized by irregular edges, angular unconformities and complex dissolution– regrowth patterns (Fig. 3.1). As a result, HALF patterns should be not considered as due to growth-related variations, but require models that also account for minor dissolution events. Repeated new magma recharges may result in increased temperature and compositional changes of the system. As an alternative, magma chambers can be zoned with regard to P, T, water content, and their bulk composition, and cyclic crystal movements across different zones can produce recurring changes in their growth conditions. Small, repeated replenishments of less evolved, hotter magmas appear inadequate, considering the perfectly cyclic pattern of oscillations and their almost constant amplitude. Therefore, convective movements in a magma chamber may be the most likely mechanism accounting for the HALF oscillatory zoning patterns and the slight concordant or discordant behavior of An and FeO in these crystals (cf. Table 3.1). Convection in an open, steadily degassing conduit might locally originate perturbations in a compositionally zoned system and consequently small changes of magma composition and/or fO_2 (cf. Singer et al., 1995). HALF zoning patterns like those found in plagioclases certainly grown in such a dynamic open-conduit system at Mt. Etna (i.e., those in lavas of the 2004–05 eruption; Corsaro et al., 2009) may support this inference.

4.1.2 Interpretation of dissolutions, resorptions and other textures

Most of the phenocrysts record LAHF or HALF patterns only in some envelopes. Perturbations of a regular oscillatory zoning, and development in turn of other textural–compositional changes, may be governed by several factors: sudden pressure drop, input of compositionally differing magma, loss or influx of volatiles (chiefly H_2O). Some of the possible interpretations will be discussed below. Strongly dissolved or resorbed ovoidal cores (Type 2; Fig. 3.2 a), rare in historic lavas, are frequently found in recent ones (Table 3.1). Compositional variations associated with this texture may include:

i) Relatively constant An content within and outside the core, especially in the crystals of historic and 2004–05 lavas or;

ii) Very high An content in the core followed by An decrease in the outer envelopes in crystals of recent lavas.

In instance i), An and FeO display substantially discordant behavior throughout the compositional profile, even outside the ovoidal core. In ii), an abrupt decrease in An and subordinately FeO marks the edge of the ovoidal core. The fairly discordant behavior of An and FeO in the cores may be interpreted as being due to small H_2O content variations and minor changes of fO_2. The important compositional changes beyond the ovoidal core should reflect major perturbations in the physical and chemical parameters of the system. Certainly, the ovoidal core testifies to a strongly destabilizing episode when part of the crystal was dissolved or resorbed, leading to an information gap about the nature of this event. I suggest that such a texture might be acquired by pressure decrease at fast ascent rates under H_2O-undersaturated conditions (cf. Table 3.1). In such circumstances, PH_2O of the system consequently increases, strongly reducing the stability of plagioclase that is then readily dissolved (cf. Nelson and Montana, 1992; Blundy and Cashman, 2001, 2005). Moreover, the higher the H_2O content dissolved in the magma, the greater the crystal dissolution at comparable ascent rates. If H_2O-saturation is reached, and water is lost from the system, a more sodic plagioclase begins to grow again (instance ii); conversely, if magma does not attain H_2O-saturation, water remains dissolved in the melt and, after re-equilibration, the composition of the growing plagioclase is not significantly modified (instance i).

The development of patchy textures at the core of plagioclase is still a matter of debate, mostly over whether it is a feature acquired during the growth or a consequence of dissolution (cf. Anderson, 1984; Kuritani, 1999; Hammouda and Pichavant, 2000). Humphreys et al. (2006), and similarly Ginibre and Wörner (2007), proposed that patchy "zoning" might be viewed as the combination of dissolution and re-growth events, where An-poor irregular patches represent earlier crystallized relics that are in turn overgrown by An-rich zones precipitating during dissolution (cf. Fig. 3.2b). According to several experimental results (Sisson and Grove, 1993; Hammer and Rutherford, 2002, and references therein), at a given temperature, decreasing pressure under H_2O-undersaturated conditions in a basaltic system reduces the plagioclase stability field and shifts its composition toward the more anorthitic. Conversely, H_2O exsolution from the melt (e.g., due to ascent-related pressure decrease) markedly increases the stability of plagioclase, leading to crystallization of a more sodic crystal (cf. Nelson and Montana, 1992; Blundy and Cashman, 2001, 2005). On the basis of such indications, we suggest, in accordance with Humphreys et al. (2006) and Ginibre and Wörner (2007), that the discordant An–FeO behavior observed in the patchy cores (Type 3) in historic lavas could be consistent with ascent-related pressure decrease under H_2O-undersaturated conditions and possible changes of fO_2 (cf. Table 3.1). This causes dissolution of the pre-existing An-poor plagioclase (remaining as irregular patches) and growth of An enriched plagioclase from the melt surrounding the dissolved crystal remnants. The kinetics of such a process (plagioclase must have enough time to dissolve and precipitate) implies that magma ascent would not have been continuous, and considerably slower than for the ovoidal core texture discussed above, which may be exclusively accounted for by dissolution or resorption of the crystal (cf. Table 3.1). Furthermore, patchy cores of the Etnean plagioclases from historic eruptions exhibit a sharp An and FeO decrease at their edges; like the ovoidal cores (considered under instance ii), this might indicate that water was lost from the system, as H_2O-saturation was finally reached, entailing the crystallization of a more sodic mantle.

Coarse sieve-textures (Type 4; Fig. 3.2c) occur at the core of plagioclases in both the historic and recent lavas, and are frequently superimposed on patchy textures or LAHF/HALF oscillatory patterns in crystals of the historic products. This texture could be acquired under conditions similar to those discussed for the Type 2 and 3 textures. Indeed, decompression under H_2O-undersaturated conditions is able to destabilize plagioclase, and to produce different textures depending on ascent rates. Given their textural features, patchy and ovoidal cores can be viewed as end-members representing, respectively, extremely low or high ascent rates. Coarse sieve textures an incipient resorption of the crystal developing neither rounding or patchy cores–could then develop during steps of decompression at ascent rates intermediate between those of texture types 2 and 3, along with very minor changes of fO_2 and H_2O contents (cf. Table 3.1). Several authors have interpreted sieve-textures associated with an abrupt An increase as clear evidence for inputs of less differentiated magma (e.g., Tsuchiyama, 1985; Pearce et al., 1987; Landi et al., 2004, and references therein). According to their inferences, sieve-textures observed at the crystal rim (Type 5; Fig. 3.2d), associated with marked increases in An and FeO, may be consistent with the input of more primitive magmas and their consequent mixing with the resident magma (cf. Table 3.1). These sieve-textured envelopes are sometimes less developed and associated with significant An and slight FeO increases (Fig. 3.5d). Such behavior might be interpreted as due to the input of H_2O-rich magmas with compositions similar to those of the resident ones ("cryptic mixing"; cf. Humphreys et al., 2006).

The sharp decrease in An and FeO contents associated with thin stripes of melt inclusions (Type 6), polygonal in section and distributed along well-defined crystallographic directions (Fig. 3.2e), may certainly be considered a fast-growth feature, and therefore not ascribable to dissolution/resorption events. Similarly, some phenocrysts show a drop in both An and FeO, associated with markedly sieve-textured envelopes parallel to the crystal faces, thus implying the absence of dissolution/resorption phenomena. Experimental results by Tsuchiyama (1985) show that a similar texture can be formed by interaction between the crystal and a more primitive melt below its liquidus. However, in our case, the lack of any evidence of interaction with a less evolved magma (i.e., An–FeO enrichments) leads us to interpret this texture as a growth feature analogous to that of Type 6, characterized by a denser arrangement of melt inclusions (e.g., crystal PP02-P4). These textures have been observed especially next to crystal rims, consequently indicating that they were acquired during the late growth stages in the shallow, likely H_2O-saturated, levels of the feeding system. In agreement with experimental results, similar textures have been recognized as a response to fast volatile loss in open-conduit systems, which induces strong undercooling and suddenly expands the plagioclase stability field (cf. Table 1; Kirkpatrick, 1977; Kirkpatrick et al., 1979; Lofgren, 1980; Helz, 1987). As a consequence, this results in the rapid crystallization of a more sodic envelope that can enclose portions of the host melt.

Several authors interpreted swallow-tailed plagioclase phenocrysts (Type 7) as a suddenly quenched skeletal texture, related to a rapidly-increased growth rate in the final crystallization stages, dependent on a high degree of undercooling (Fig. 3f; cf. Kirkpatrick, 1977;

Kirkpatrick et al., 1979; Lofgren, 1980; Helz, 1987; Shelley, 1992). Contrary to Type 6 texture, the observed An decrease at practically constant FeO near the rims may be interpreted as being due to fast decompression at practically unvaried fO_2, not associated with significant degassing (FeO should also decrease in that case; cf. Table 3.1).

4.2 A model of magma dynamics in the Etnean feeding system

The systematic study of plagioclase textural and compositional features provides valuable information on the dynamics within the plumbing system and its relationships with volcano-tectonics.

Plagioclases with patchy cores are peculiar to historic lavas, which are also characterized by the almost complete absence of ovoidal cores. Conversely, recent products frequently display plagioclases with strongly dissolved/resorbed ovoidal cores and no patchy-core textures (Table 3.1). The stability of plagioclase is lowered as P_{tot} decreases under H_2O-undersaturated conditions in two ways (cf. Nelson and Montana, 1992; Blundy and Cashman, 2001, 2005):

i) At constant ascent rates, the higher the H_2O dissolved in the melt, the greater the destabilization;

ii) At constant H_2O contents, the higher the ascent rate the, the greater the plagioclase dissolution.

However, according to the discussion above (Section 4.1.2), since patchy cores need enough time for partial dissolution and re-growth, whereas ovoidal cores imply only dissolution/resorption, we believe that the combination of diverse ascent rates and H_2O contents can account for differences between plagioclases of historic and recent lavas (cf. Table 3.1). Historic magmas, has been considered to have lower volatile contents (~2.5 wt.%; cf. Métrich and Rutherford, 1998), may have ascended at slower rates than the recent ones, recognized as more volatile-rich (~4 wt.%; cf. Allard et al., 2006, and references therein). At a given H_2O content, intermediate ascent rates with respect to those inferred for patchy and ovoidal textures might develop coarse sieved crystals (Fig. 4.2; cf. Table 3.1). Our inferences are also in agreement with the higher An content observed in plagioclases from the recent activity, reflecting the more primitive character of these magmas compared to the historic ones (cf. Viccaro and Cristofolini, 2008 and references therein).

After nucleation, growth and development of their cores, plagioclases of both historic and recent lavas show evidence of continuing crystallization at shallower levels of the plumbing system following two main possible crystallization scenarios:

i) Within the steadily degassing open-conduit or;

ii) Within closed systems, not connected to the open-conduit system (Fig. 4.2).

Under condition (i), large plagioclase crystals with undisturbed HALF oscillatory zoning patterns are produced, reflecting crystal growth in an efficiently degassing environment, where convection currents carry crystals along modest physical–chemical gradients (Fig. 4.2, part A of the scheme; cf. Table 3.1). Fast upward migration of these already degassed magmas, shortly before the eruption and during the syn-eruptive phases, can produce strong undercooling, leading to the development of skeletal swallow-tailed textures (Table 3.1).

In instance (ii), crystallization in closed reservoirs chiefly produces LAHF oscillatory zoning patterns, evidence for a non-convective system where small variations in the physical–chemical parameters of the magma can be balanced by slight changes in growth kinetics at the crystal–melt interface (cf. Table 3.1). The textural analysis has highlighted that the LAHF core pattern may be interrupted by two other important textures:

a) Strongly resorbed, sieve-textured rims (Type 5) or;

b) Thin stripes of melt inclusions parallel to crystallographic directions or sieved rims parallel to the inner portion of the crystal (Type 6).

The occurrence of such textures especially at the outer crystal rims yields information on the possible mechanisms for triggering eruptions. As discussed above, the Type 5 texture (case a) is evidence for the input of a more primitive (possibly hotter) and undegassed magma and its mixing with the resident one (Fig. 4.2, part B of the scheme; Table 3.1). The width of the envelopes characterized by An and FeO increase, as well as sieve textures, may be assumed to depend on the time interval of the destabilization event caused by the mixing. The widths of these envelopes are generally in the order of 50 μm. Several authors have proposed plagioclase growth rates in volcanic systems, giving a wide range of values, especially as a function of cooling rates and undercooling degrees. For basaltic systems, growth rates of 10^{-10}–10^{-11} cm/s have been calculated on the basis of crystal size distribution (Marsh, 1988; Cashman and Marsh, 1988; Cashman, 1988, 1990, 1992). Armienti et al. (1994) calculated higher growth rates for plagioclase in Etnean hawaiites of the 1991–1993 eruption, providing a value of $\sim 7\times 10^{-9}$ cm/s. However, during mixing between an evolved, cooler magma and a more basic, hotter one, the plagioclase growth rate can increase by some orders of magnitude (up to 10^{-7} cm/s; Crisp et al., 1994). In our case, assuming the lowest possible value to be that calculated by Armienti et al. (1994), a 50 μm-thick envelope may develop in less than 3 months, whereas only ~5 days are required for the same envelope to grow at the highest rate suggested by Crisp et al. (1994).

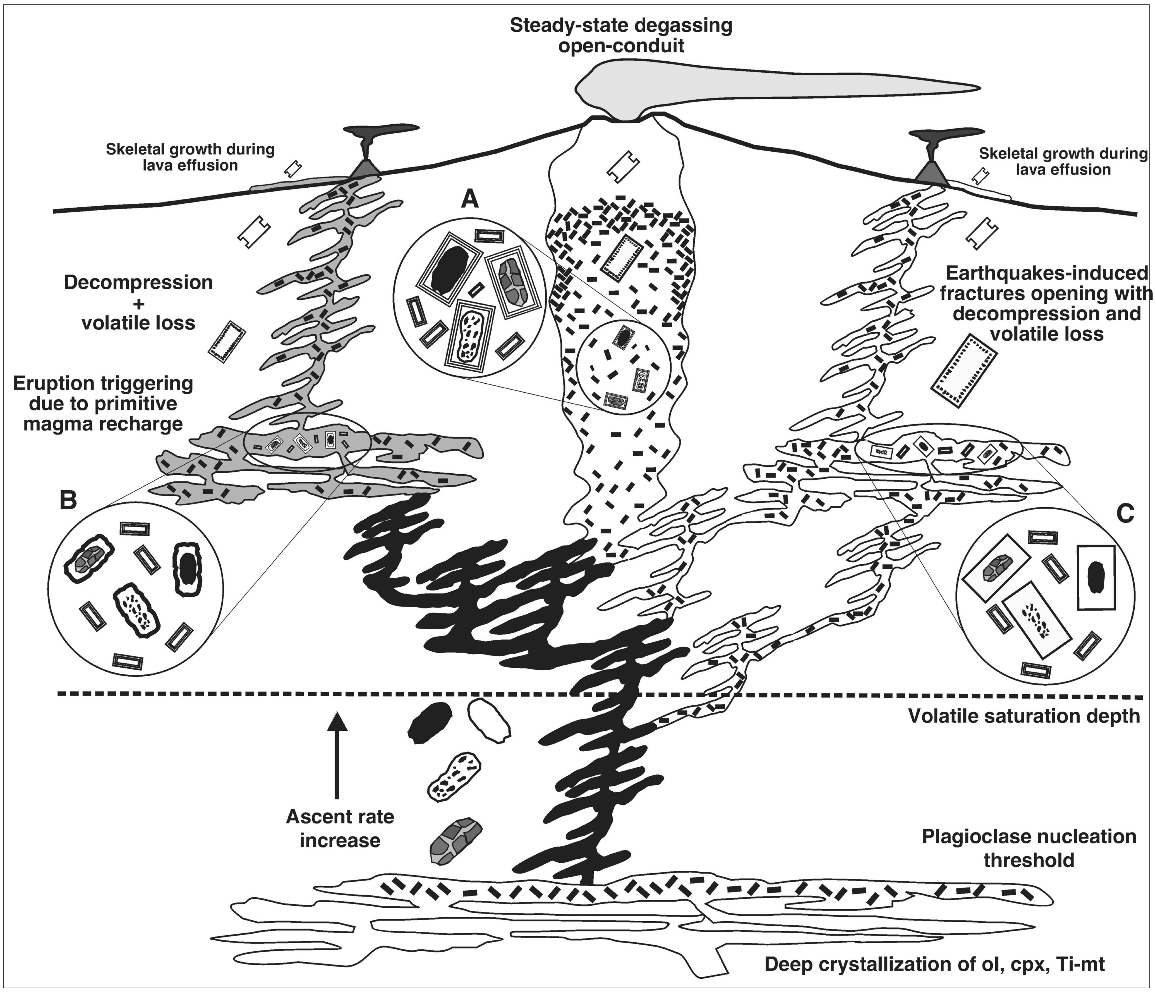


Fig. 4.2. Schematic representation of the ascent, storage and recharge history at various levels of the feeding system at Mt. Etna volcano. After plagioclase nucleation at depth (~10–15 km), different ascent rates toward the shallow levels of the feeding system may lead to three main types of textures, which indicate increasing ascent rate underH2O-undersaturated conditions: patchy, coarsely sieved, ovoidal. Above the volatile saturation depth (estimated on the basis of compositions and volatile contents as ~5–6 km for historic magmas and ~6–8 km for recent ones), three main instances for plagioclase crystallization occur, which may involve crystals showing patchy, coarsely sieved or ovoidal textures. a) Crystallization may continue in the open-conduit, producing envelopes characterized by HALF oscillatory zoning or totally oscillatory-zoned plagioclases. b) Crystallization may continue in enclosed reservoirs, culminating with an eruption triggered by recharge of a more primitive, volatile-rich magmas. LAHF oscillatory-zoned plagioclases may crystallize during residence in the chamber before mixing. During the ascent, volatile loss may produce Type 6 textures (stripes of regularly-shaped melt inclusions) or Type 7 skeletal textures (swallow-tailed) if already degassed magma undergoes a high degree of undercooling during syn- or post-eruptive phases. c) Similarly to the previous instance, crystallization continues in closed reservoirs developing LAHF oscillatory-zoned plagioclases during residence; the eruption triggering mechanism consists, in this case, of earthquake-induced fracture opening associated with consistent volatile loss, finally leading to development mainly of Type 6 textures or, during the final stages of the eruption, to Type 7 swallow-tailed crystals.

The occurrence of these textures suggests that recharging phases in systems not linked with the open-conduit can effectively trigger eruptions at Mt. Etna. Exceptionally, two of these sieve-textured envelopes occur along core–rim profiles, evidencing that at most two magma recharges in the shallow Etnean reservoirs can be recorded by plagioclase phenocrysts before being erupted.

Type 6 textures (case b of the latter instance) may also develop in systems not directly related to the steadily degassing open-conduit. No evidence that these textures are related to inputs of more primitive magma has been found, so that other mechanisms triggering the eruption must be invoked. Rapid pressure drop and massive volatile loss preceding the eruptive event may be related to sudden fracture opening (e.g., in response of seismic swarms; Fig. 4.1, part C of the scheme; cf. Table 3.1). The crystals analyzed generally exhibit only one inclusion-rich envelope, which suggests one significant event of pressure drop followed by eruption. However, rarely, some crystals show two inclusion-rich envelopes, suggesting that volumes of magma, not erupted as a consequence of an episode of fracture opening, can be recycled once before finally becoming involved in the eruption.