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Effects of basement structural and stratigraphic heritages on volcano behaviour and implications for human activities (the UNESCO/IUGS/IGCP project 455)

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The UNESCO/IUGS/IGCP project 455 (2001-2005) is intended to contribute to the comprehension of volcano behaviour in different geodynamic settings from a poorly known perspective: the reciprocal influence exerted by volcanoes on their substrate and by the basement on the volcanoes. The main task is to assess the role of this influence in determining natural geological hazards such as eruptions, landslides and earthquakes. The geologic-tectonic control of the substrate on the volcanoes has been usually considered questionable or less important than the conditions of the deep magma source, whereas the control of volcanoes on their basement has even received very little attention. This project improves the comprehension of these phenomena by a strong interdisciplinary approach that ties data on the various geological conditions and heritages of the basement with the deformation processes and geological evolution of different volcanic edifices. We compiled stratigraphic, structural, geomorphological, geophysical, geotechnical, petrographic, geochemical and geochronological data. These data have been transferred to the laboratory-working groups, thus providing realistic numerical and physical simulation even of complex geological structures. Here we present a selection of the main results obtained for some of the studied key volcanoes: Alicudi (Italy) located in a low-tectonic rate setting, Stromboli (Italy) in extensional tectonic setting, Reventador (Ecuador) in compressional setting, and the Northern Volcanic Group of Kamchatka (Russia), Galeras (Colombia) and Mayon (Philippines) in a transtensional setting.

Introduction

The UNESCO/IUGS/IGCP project 455 “Effects of basement structural and stratigraphic heritages on volcano behaviour and implications for human activities” started in 2001 and will end in 2005. It is intended to contribute to the understanding of volcano behavior in

different geodynamic settings from a poorly known perspective: the reciprocal influence exerted by volcanoes on their substrate and by the substrate on volcanoes. This reciprocal influence is a recent discovery that sheds new light on the reconstruction of the evolution of volcanoes and on the understanding of the present behaviour of active volcanic cones and calderas. As an example, large volcanic cones can experience diffuse spreading or more localised rifting depending on the rheology of the underlying basement (Walker, 1992; Borgia, 1994). At the same time, the structure of the basement underlying volcanic systems can display peculiar structural and geological characteristics, which now can be reinterpreted taking into account also the volcanic history. In fact, the presence of volcanic masses can be so important to create perturbation of the regional tectonic stress field and induce variation in the geometry and kinematics of coeval faulting in the basement (e.g., Tibaldi and Ferrari, 1992; van Wyk de Vries and Merle, 1996).

Recognising and evaluating the role of this interplay between basement and volcanoes can also be important in the assessment of natural geological hazards such as landslides and related tsunamis, volcanic eruptions and earthquakes. For example, improved models on the relations between volcanoes and their basements can forecast the collapse of volcanoes (caldera and lateral collapses) and magma-feeding paths in volcanic cones (sub-volcanic intrusions and eruptions). These include chaotic effects arising from self-similar distribution of fracture systems and parasitic cones, as a function of the basement conditions. On the other side, the data of the basement will contribute to a better understanding of how basement structures react to the formation of volcanic cones and calderas. This theme is particularly important in order to improve the comprehension of the mechanics of basement earthquakes in volcanic regions. Above all, this will provide technical information usable for geothermal energy, and mineral and water exploration and exploitation.

In this paper we introduce the main themes and results of the project up to the present, as well as a selection of the main results obtained for some of the studied key volcanoes (Figure 1): Alicudi (Italy) located in a low-tectonic rate setting, Stromboli (Italy) in extensional tectonic setting, Reventador (Ecuador) in compressional setting, and the Northern Volcanic Group of Kamchatka (Russia), Galeras (Colombia) and Mayon (Philippines) in a transtensional setting.

General background

Influence of basement to volcanoes

Up to about twenty years ago, it was quite common to associate volcanism with extensional crustal deformations only, and some

Figure 1 Location of studied areas within this UNESCO-IUGS-IGCP Project 455 (boxes) and of key site examples described in the text.

workers still hold this view in volcanic arc zones (e.g. Hamilton, 1995). One of the first papers dealing with the influence of the regional basement stress field on the distribution of volcanic centres is from Nakamura and Uyeda (1980). From field data and earthquake focal mechanisms, they recognised the gradual rotation of the stress tensor moving from the subduction trench towards the continent. They hypothesised that magma can reach the surface when the greatest (σ_1) and intermediate (σ_2) principal stresses are on a vertical plane, corresponding to extensional and transcurrent deformations. These authors, however, have not been successful in finding examples of the association between volcanism and strike-slip faulting. Cas and Wright (1987) recall this possibility giving as an example the Sumatra volcanic arc (Hamilton, 1979). In those years, many researchers started to recognise the influence of transcurrent tectonics in guiding magma rising and location of volcanic centers (DeBoer et al., 1980; Bahar and Girod, 1983; Harmad and Moukaridi, 1986; Kozhurin, 1990; Tibaldi, 1992; Marinoni and Pasquarè, 1994; Lavenu and Cembrano, 1999; Tibaldi and Romero, 2000). Other authors even suggest that contractional deformations within continental magmatic arc favours volcanism (e.g. McNulty et al., 1998) and magma emplacement (e.g. Paterson and Miller, 1998). At the same time, many structural geologists discover that the emplacement of some plutons and smaller bodies occurred along regional strike-slip faults in a transcurrent tectonic crustal regime (e.g. Jacques and Reavy, 1994; Johnston, 1999; Olivier et al., 1999; Salvini and Storti, 1999), whereas other researchers still disregard this possibility (Schmidt and Paterson, 2000).

In extensional regimes, it is widely accepted that magma-feeding paths are linked with the regional stress field. In fact, this type of stress regime produces the brittle discontinuities perpendicular to the least principal stress (σ_3) through which the magma is transferred from below to the Earth surface, giving rise to the birth and growth of volcanoes. In some cases, the regional stress field can directly influence the entire volcanic edifice, giving rise to rift zones that crosscut the edifice itself. These rift zones can channel magma up to the summit zone of the cone, feeding dyke swarms with a preferred orientation. These dyke swarms, in turn, can displace the volcano flanks and even induce lateral collapse of the edifice (Elsworth and Voight, 1996; Tibaldi, 1996). Of course, other factors controlling the volcano evolution exist, such as a deep source of magma, but they have been more intensely studied when compared with the effects due to the basement heritage and behaviour.

Particularly intriguing is the fact that many volcano collapses have been triggered by magma inflation in the cone, which in turn, can be geometrically guided by fractures related to the basement

strain and stress field. Alternatively, or in a complementary way, collapse geometry can be controlled by rift zones on the volcano, by hydrothermal alteration along weakness zones, or by the topographic and geological characteristics under and around the cone (McGuire, 1996); all these features are related to the basement. The destructive power of volcano collapses was dramatically revealed by the 1980 flank failure of Mount St. Helens, in which 2.8 km³ of debris travelling at a speed of 35 ms⁻¹ was spread over an area of 60 km² (Voight et al., 1981). Collapse of volcanic cones is most commonly associated with stratovolcanoes (Ui, 1983). However, catastrophic failure of volcanoes is not limited to steep-sided volcanoes (Siebert, 1992). Massive slumps and debris avalanches are now widely recognised on gently-inclined subaerial and submarine volcano slopes in many basaltic volcanic islands. Examples of these are in the Hawaiian, Reunion, Tristan de Cunha, Canary, Marquesas, and Galapagos islands (Lenat et al., 1989; Chadwick et al., 1991; Holcomb and Searle, 1991; Borgia and Treves, 1992; Moore et al., 1994). Additionally, avalanches entering the sea have the potential to generate destructive tsunamis, which cause most of the fatalities resulting from volcanic flank collapse (Siebert, 1996).

Petrology and geochemistry of igneous rocks are important in recognising the evolution of volcanoes, which is one of the main tasks for evaluating the basement-volcanoes interplay. The types of magma emplacement are linked to the bulk magma compositions that, in turn, depend on pre-eruptive processes occurring mostly in the basement of volcanoes during the ascent of magma to the surface. The magma composition can firstly suggest the presence or the absence of a magma chamber, depending on the degree of magma evolution. In particular, the continuous eruption of primitive aphyric basaltic magmas can indicate the direct magma input from the source, whereas the emplacement of rhyolitic magmas clearly suggests the residence of magmas at shallow levels. Petrological and geochemical studies of volcanic rocks are also useful in recognising processes of magma evolution in open systems. Besides triggering, explosive magmatic eruptions, and episodes of magma mixing or mingling can lead to an increase in volume of the magma reservoirs, consequently changing the stress regime of the basement. Magma evolution by crustal contamination is one of the best examples of the crust-magma interaction process, with consequent increase of both magma chamber volume and contents of volatile elements in magmatic melts. The latter increase, in turn, can cause huge explosive eruptions, leading to the emptying of the magma chamber and the formation of surface collapses, which change the structural setting of the basement.

Petrological investigations on well-defined stratigraphic sequences of volcanic rocks also allow the estimation of the volume of magma chambers, the residence time of magma in the reservoir and the temperature and pressure of magma crystallisation. All these parameters are useful in order to understand the relationships between the behaviour of a volcano and the structural characteristics of its basement. The petrographic and geochemical studies of dyke swarms can also help in understanding their time relationships with sector or flank volcano collapses possibly linked to the emplacement of the dykes.

As a matter of fact, these data show that a link between the geology, structure and instability of volcanoes and the geological-structural characteristics of the substratum does exist. However, some fundamental problems are still pending such as: What is the shape, structure and location of volcanoes in relation to the geology and the regional stress regime? Are calderas also controlled by upper crustal structures generated in a compressional state of stress (transcurrent or reverse faulting?), and to what extent are calderas influenced by extension in divergent zones? Moreover, Siebert (1984) shows that lateral collapse of large volcanoes usually occurs along a direction perpendicular to the horizontal maximum principal stress and to the fracture used as magma path. Is this true also for collapsed volcanoes standing above strike-slip faults? What is the role and importance of the structural and lithological characteristics of the basement with respect to the structural behaviour of the volcano? The first to notice the basement influence was Van Bemmelen (1949), but this important controlling factor was not fully appreciated until 1990 (Borgia et al., 1990). In what proportion the behaviour of a volcano is sensitive to the relations between its dimension and the influence of the basement? Is the evolution of a small volcano more influenced by its basement compared to a bigger volcanic edifice? And, finally, can resurgent calderas develop lateral collapses and how much are these related to the basement conditions (Tibaldi and Vezzoli, 2004)?

Influence of volcanoes to the geological-structural evolution of the basement

Recent works on volcano-tectonics underscore the role of volcanoes, and more generally of magmatic processes, in modifying the regional tectonic stress field. Each magmatic or volcanic structure may be regarded as a perturbation introduced in the general stress field, which is unique in space and time. Among the first papers on this topic are the works of Johnson and Pollard (1973), those reported in Suppe's book (1985), and Woodcock and Underhill (1987). In the 1990's, some papers showed that the substratum of large volcanoes can undergo phases of deformation which can be directly linked to the surface build-up phases of the volcano or to the spreading phases of the edifice (Borgia et al., 1990; van Wyk de Vries and Borgia, 1996). The basement can be warped, faulted, or folded, its morphology can change and drainage systems can be diverted. All these factors control the sedimentary and geological processes on the basement.

The presence of large volcanoes can even affect the geometry and kinematics of regional tectonic faults, such as those discovered in the Asal Rift and other rifts (De Chabaliér, 1993; van Wyk de Vries and Merle, 1996), or in Ecuador where tens-of-kilometres-long faults disappear, or change strike and kinematics, in response to the presence of huge stratovolcanoes such as Cayambe, Cotopaxi, and Chimborazo (Tibaldi and Ferrari, 1992). In Colombia, a regional Tertiary tectonic fault crosses the basement under the Galeras Volcano, a large stratovolcano of Quaternary age. Northeast of this volcano, the same fault re-activated during the Quaternary and is known as Buesaco Fault (Tibaldi and Romero, 2000), whereas Quaternary fault motions disappear approaching the volcanic cone. These examples highlight various possible influences of the presence of volcanic cones on the deformation evolution of the substratum.

Active volcano-induced deformations in the basement can have a brittle (seismic) behaviour or a ductile (aseismic) creep. In both

cases, they can produce important economic damages to civil or industrial buildings and to strategic networks such as roads, pipelines, railways, etc., or even induce loss of human life. If these earthquakes represent the effect of stress accumulation induced by the presence of the volcanic edifice and related magmatic system, it would not be correct to use the classical recurrence-time theory of tectonic stress accumulation to evaluating the probability of future occurrence of seismic events of a certain magnitude. This clearly represents a formidable and recently recognised problem for the interpretation and classification of seismic activity in relation to seismic and volcanic hazards assessment. It should be wise to stress that only a very few papers exist on this.

Open questions thus regard the identification of the size, shape, and geological characteristics of volcanoes which can influence the geological-structural behaviour of the basement in extensional, contractional, and transcurrent settings; the establishment of how basements react to the volcano evolution; and how and to which extent this phenomenon can affect the assessment of seismic and volcanic hazards.

Methodology

New achievements on these topics will be reached only by a strong interdisciplinary approach that ties the various basement geological conditions and heritages with the deformation process and geological evolution of different volcanic edifices. Usually, researchers working on volcanoes do not focus on the possible influences of the basement on volcano evolution and vice-versa. On the contrary, this project stimulates this co-operation: the involved task forces provide a venue to link together similar research works on volcanoes and their basement. The task forces are focused on specific techniques of study, concentrated on stratigraphy, structural, geomorphology, geophysics, geotechnical engineering, petrology, geochemistry and geochronology. The basic idea is to carry on at the same time all these types of studies on a series of volcanoes or volcanic zones that have been selected based on their scientific/social relevance and location in different geodynamic settings.

As key volcanoes we selected: Ollague (Bolivia-Chile), Stromboli, Alicudi, Ischia and Mt. Etna (Italy), Reventador and Cotopaxi (Ecuador), Nevado de Toluca (Mexico), Mayon (Philippines), Galeras (Colombia) and Shiveluch (Russia) (Figure 1). As key volcanic areas we also selected: the southern Andes of Colombia, the north-western Argentina, the Northern Kamchatka volcanic group (Russia), and the south-western Luzon (Philippines). At a lesser extent, some investigations have also been performed in the Canary islands, Hawaii islands, Nicaragua, Romania, East Africa rift, New Zealand, North Victoria Land (Ross Sea Embayment) (Figure 1). These areas comprehend examples of both recent and active volcanism as well as older, deeply eroded volcanic complexes. They include circum-Pacific plate converging zones with crustal strike-slip, reverse, and normal faulting; oceanic and continental intra-plate volcanism of Atlantic and Asia; plate boundary complex conditions in the Mediterranean region.

Importance has also been given to techniques that have been rarely applied to volcanic edifices; we made systematic field geomechanical surveys on volcanoes in order to delineate in detail the fracture field of the rock succession. The geomechanical survey involves the systematic measurement of orientation, frequency, dilation amount, type, and mechanical characteristics of the fractures at representative sites on the volcano flanks. These data, integrated with lithological, structural and applied geomorphologic surveys, allowed the selection of rock sites to be sampled in order to perform geotechnical field and laboratory tests. Sampling has been carried out by portable drilling equipments. Specimens of rocks or volcanic loose deposits have been characterized by parameters such as density, porosity, shear strength, friction angle, cohesion, elastic modulus, etc.

As a further step of the study, all these field data have been transferred to the laboratory-working groups, thus providing a large

amount of ground truth. This is used to perform realistic numerical and physical simulation even of complex geological structures. A database with all the original data of each studied volcano is under preparation and will be made available on the web. This database will be particularly useful for comparing the various possible relationships between basement faults and lateral collapses, and to evaluate the sensitivity of volcano behaviour in relations with its dimension and basement geological and structural characteristics.

General results

The papers published from researches carried out in the first years of this project, focused on four main topics: a) the description of the basement geology and tectonics in key areas affected by volcanism, and how they influence the volcanic structures, evolution, flank failures etc., b) the characterization of petrography, structural geology and stratigraphy of the volcanoes, which can be used to analyze their influence to the processes in the basement, c) new types of approaches to the study of the relationship between basement and volcanic edifices; nominally numerical and analogue scaled modeling, and d) practical applications of the research to societal and economic aspects. Here we will briefly summarise these results.

a) With regard to the basement description, a clear and very important outcome of the project scientific results is the fact that more and more convincing evidence indicates that volcanism cannot be restricted to extensional basement tectonics, as previously widely considered (e.g. Hamilton, 1995). New evidence shows that volcanism is also associated with coeval tectonics of compressional type. For example, in Japan (Acocella et al., 2003a), in Chile and in Bolivia (Tibaldi et al., in prep.), and in southern Kamchatka, Russia (Kozhurin, 2004) volcanism is associated to reverse faulting in the basement. This is clearly in contrast with the accounts of previous authors, which did not consider the possibility of volcanism in a contraction deformation environment. In other cases, volcanism is associated to coeval transcurrent faulting, both transpressional, as for example in Colombia (Tibaldi and Romero, 2000), almost pure strike-slip in Philippines (Lagmay et al., 2003) or transtensional in New Zealand (Acocella et al., 2003b) and central Kamchatka (Tibaldi, 2004a). Of course, in many cases volcanism is also clearly related to extension, as for example in the eastern Aeolian Arc (Italy, Tibaldi et al., 2003), in the Aegean Arc (Greece), or in the Ethiopian Rift (Acocella et al., 2002). This however, does not seem to be the rule.

b) Concerning the petrographic, structural and geochemical characterization of the volcanoes, detailed data have been published, or are underway to be published, on the Ollague (Chile), Reventador (Ecuador), Concepción (Nicaragua, Borgia and Van Vyck De Vries, 2003), San Pedro (Mexico, Petrone et al., 2002), Mt. Etna (Italy, Billi et al., 2003; Calvari and Pinkerton, 2002; Calvari et al., 2004), Stromboli (Italy, Mattioli et al., 2003; Renzulli et al., 2003; Salvio-Mariani et al., 2002), and several volcanoes of Kamchatka (Gusev et al., 2003; Dirksen et al., 2002; Melekestsev, 2004; Melekestsev et al., in preparation; Ponomareva et al., 2002a,b, in press). Also two main new geological maps were produced from the efforts of IGCP 455 participants, namely the *Geologic map of Lanzarote and Isla Graciosa (Canary Islands)*, at a 1:50,000 scale covering 863 km², by Marinoni et al. (2004); and the *Geological Map of Stromboli*, scale 1:10,000 and 1:50,000, by Tibaldi and Pasquaré (2004). Two main scientific general results came out from these studies and were discussed in Tibaldi (2003) and Tibaldi (2004b): the structural and morphological evolution of a volcanic cone strongly influences the geometry (strike, dip, inclination) of dykes and the location and orientation of related fracture eruptions. This is because unbuttressed sectors of the volcano strongly influence the orientation of the least compressional stress, which in turn guides the orientation of the dyke. In particular, the development of sector collapse in a volcanic edifice can cause the relocation of dykes and, as a consequence, induce fracture eruptions. Moreover, the occurrence of a sector col-

lapse can produce major changes in the type of eruption mechanisms, as well as an increase in the eruption rate, the upwelling of more fluid magmas, and degradation of the geotechnical characteristics of the volcano deposits. Correspondingly, there is an increase in the probability of future occurrence of new sector collapses.

c) A strong increase in the number and importance of dedicated studies on new approaches to the study of the relationship between the basement and the volcanic edifice is one of the major accomplishments of this IGCP project. In particular, the original proposal of this project planned the enhancement of co-operation amongst field researchers in its third year activities. It also planned for inter-laboratory accessibility and development of theoretical models. This co-operation was enhanced by the application of laboratory model lists to fieldwork and by the participation of field geologists in laboratory work. In particular, three laboratories dedicated to analogue scaled modeling of volcanic behaviour and its relationships with basement morphology and tectonics have been constructed in the Philippines (University of Quezon City) and in Italy (University of Rome III and Milan). The teams of researchers of these three laboratories are working closely together and also are cooperating in the field with direct collection of data and with an active exchange of researchers and graduate students. Field researchers and laboratory modelists worked together on Mt. Etna and Stromboli (Italy), Nevado de Toluca (Mexico), and Mayon (Philippines) volcanoes. Collaboration is being planned for modeling volcanoes of the Kliuchevskoi volcanic group (Kamchatka, Russia) and Reventador volcano (Ecuador). Major scientific results published up to now, comprise the delineation of basement-volcano relationships in areas of caldera (e.g. Acocella et al., 2002) and along strike-slip faults (e.g. Lagmay, 2002). Another main result involves the application of conventional engineering methods for the evaluation of the instability of volcanic cones. These techniques are usually related to resolve engineering problems on non-volcanic environments. We have applied this methodology to study the probability of developing new lateral collapses along the northwestern flank of Stromboli (Italy, Apuani et al., 2003a, 2003b).

d) Research projects under this link have had practical applications for volcanic hazards assessment, geothermal energy exploitation and mineral exploration. In particular, the participants of this project, as a team, studied some major volcanic eruptions that occurred during the years 2002–03. Aspects of hazards related to the eruption of Mt. Etna (Italy) have been discussed in Calvari and Pinkerton (2002); Calvari et al. (2004); Duncan et al. (2002); Hunter et al. (2002). The persistent eruption of Kilauea Volcano, Hawaii, has been studied with new techniques related to detect the surface temperature of lavas by Pinkerton et al. (2002). Dirksen et al. (2002) studied the eruption of Chasha volcano (Russia) while Melekestsev et al. (2003) studied long-term forecasting of volcanic eruptions in Kamchatka. The Reventador (Ecuador) volcano, on January 2003 went into a volcanic crisis with emission of ashes, which reached the town of Quito. A team of IGCP 455 scientists has been working on this volcano in 2003 and 2004. Similarly, an eruption has been affecting the Stromboli volcano since December 2002 to April 2003. An eruption-related landslide occurred on January 2003 and produced a tsunami causing severe damage to the economy of the island and injuring two persons. Several teams have been working on Stromboli since the inception of this eruption.

Studies concerning the relationship between volcanoes and their basement and geothermal energy have been mostly conducted in the Philippines (e.g. Lagmay et al., 2003a, 2003b). Researchers from the University of the Philippines, with the participation of an Italian Ph.D. student from the University of Milan, made studies on such type of work. Structures in three of the several volcanic fields in the Philippines, namely the Tongonan, Tiwi, and Bulalo geothermal fields were investigated. Dynamic analysis of volcano structures was conducted in order to arrive at useful models for the economic development of geothermal prospects. Most of the work related to ore mineralization are still underway but some preliminary results on the mapping of sub-volcanic bodies in mineral-rich areas have

already been presented by von Quadt et al. (2002), Corazzato et al. (2002), and Cvetkovi et al. (2002a,b).

Selected examples of volcanoes

Alicudi and Stromboli (Italy)

Alicudi and Stromboli (Aeolian Arc, southern Tyrrhenian Sea, Italy, Figure 1) have an age < 100 ka B.P., lie above the same substratum, and have a similar size. The Alicudi Volcano is about 2.4 km high above the sea-floor. The evolution of the emergent part is characterised by several main episodes of cone growth in alternation with erosion periods and volcano-tectonic collapses. The oldest recognised rock unit represents the remnant of a deeply eroded stratocone of 90–87 ka (Gillot and Villari, 1980) of basaltic and basaltic-andesitic composition. The building of the younger Alicudi volcano, of basaltic to andesitic composition, started with lava flows and tephra erupted by a main summit centre located northwest of the present summit area. A period of instability of the volcanic cone reached its climax with a lateral collapse which slid the summit part of the cone southward (Figure 2A). It seems that the northwestern-most and highest part of the collapse rim could have coincided with the position of the former magma conduit, which acted as a weakness zone. A new cone was built up mainly inside the preceding collapse amphitheatre with some lava flowing towards east and south. The main summit eruptive centre was located in the same place as the present summit area of the island. Pyroclastic deposits are more abundant at the beginning and end of this eruptive period, which started around 55 ka ago (Gillot, 1987). A series of andesitic domes, epiclastic breccias and short lava flows were emplaced at the end of this period. Their present distribution along a semicircular zone suggests the presence of a developing horseshoe-shaped zone of weakness and the development of another large sector collapse. When this collapse developed, it gave rise to a new asymmetric depression open S- and SE-wards, reflecting another period of major instability of the volcanic cone. After the main volcano-tectonic deformations ceased, the last period of volcanic activity took place and lasted until around 28 ka ago (Gillot, 1987). The related deposits are represented by lava domes and flows outpoured mostly inside the sector collapse depression.

During these stages, dyking occurred with a radial pattern (Figure 2A). Average frequency is two dykes each 100 m with a low dispersion value suggesting a uniform radial frequency. Inclination is mainly subvertical going from 75°C to 90°C. Some dykes injected along normal fault planes, as evidenced by the pre-existence of normal dislocations of strata. Several dyke generations, also suggested by some crosscutting relationships, show the persistence of radial dyking planes which reflects the stability over time of the feeding system geometry. Also strike distribution of faults and joints shows a radial arrangement. Dip distribution is bimodal, reflecting the presence of conjugated brittle failure systems. Inclination ranges between 60°C and 90°C. Fault dislocation is of normal type, even if one should remember that the scarcity of tectoglyphs on the fault planes enabled only the gross vertical component of motions to be estimated. Net motions were detected on a few fault planes showing pitches > 45°C. Some slip planes paralleling the slopes are present. A few relatively recent dykes and fractures show a preferred N-S strike. Oceanographic studies by Calanchi et al. (1995) show that no large faults are present beneath Alicudi volcano and that the sea-floor deepens southwards with a low inclination.

The island of Stromboli represents the emerged part of a composite volcano which reaches an elevation of about 2.6 km above sea-floor, and whose growth was repeatedly interrupted by collapses of various types (Pasquarè et al., 1993; Tibaldi et al., 1994; Tibaldi, 1996, 2001) (Figure 2B). The rock composition spans from basaltic-andesite to shoshonite and to latite-trachyte (Hornig et al., 1993). The oldest dated rocks have an age of about 100 ka (Gillot and

Figure 2 Structural sketch map of Alicudi (A) and Stromboli (B) islands. Both are younger than 100 ka BP, are stratovolcanoes with dominant lavas and volcanic tephroclastic breccia, and lie on the same basement of southern Tyrrhenian Sea, Italy. (A) The structural history of Alicudi has been dominated by a radial pattern of hydraulic fracturing and dyking related to dissipation of overpressure in the main magma conduit. Two sector collapses occurred southwards. (B) At Stromboli systematic and enduring fracturing and dyking along a NE-SW-trending weakness zone passing through the cone summit, and eight collapses have dominated the structural history of the cone (collapses numbered from the oldest). This NE-SW zone is geometrically controlled by far field tectonic stresses revealed by basement faults discovered by geophysical studies and by seismicity distribution. Only two dyking phases have a different geometry, linked to magmatic system adjustment and slope gravity attraction respectively. The first was characterised by formation of a N-S dyke swarm linking the main magma conduit to another center located offshore. The other anomalous dyke geometry occurred after the oldest large sector collapse towards NW (< 13 ka BP) following the related amphitheatre.

Keller, 1993). Between 85.3 ± 2 ka and 64.3 ± 4.9 ka B.P. a summit caldera collapse was accompanied by tephra eruption. After a phase of cone growth, the SE flank of the edifice was affected by a relatively small flank collapse dated between 35 ± 6 ka and 26.2 ± 3.2 ka B.P. In the same time interval, another summit caldera collapse took place accompanied by pyroclastic deposits and followed by another phase of cone growth. A further summit collapse took place between 26.2 ± 3.2 ka and 21 ± 6 ka B.P. A new cone growth lasted until 13 ka B.P. This age marks an important transition in volcanic and collapse style. From this time, four lateral collapses developed, alternated by cone growth phases. They formed horseshoe-shaped amphitheatres open northwestwards.

The deformation system accompanying the various growth phases was strongly dominated by fracturing and dyking along a NE-trending weakness axial zone crossing the Stromboli volcano summit (Figure 2B). Inside this zone, single dykes strike between NNE and ENE. Some scattered dykes with the same orientation are also present outside the weakness zone. Some of them have planes parallel to the cone slopes. Relationships between the unconformity surfaces of the various growth phases and these dykes indicate that the NE-trending weakness zone endured for the volcano's entire history. Only two growth phases were accompanied by dyking with a different geometry. The first occurred before the oldest caldera collapse and was characterised by formation of a N-S dyke swarm ($64\text{--}36$ ka B.P.). This system linked the main Stromboli conduit to another main center located off-shore and revealed by marine geophysical data. The other anomalous dyke geometry occurred after the oldest large sector collapse towards NW dated at 13 ka. Since this time in fact, dykes have injected along the NE-trending weakness zone and also parallel to the amphitheatre walls of the 13 ka sector collapse. The same geometry characterises the fracture systems. These data suggest that dyking along the NE-trending weakness zone could have exerted a geometric control and a relevant push for lateral collapsing in the NW-SE perpendicular direction. This weakness zone orientation coincides with the strike of the regional faults which are very close to or under the edifice (Gabbianelli et al., 1993). More external dyking with respect to the weakness zone was extremely sensitive to the local σ_3 induced by unbuttressing, as revealed by injection planes paralleling the sector collapse escarpments. External dyking on Stromboli was also sensitive to the free surface as suggested by dyke planes parallel to the cone slopes (Tibaldi, 2003).

The data collected on these two volcanoes indicate that:

- 1) volcanism developed under a low tectonic state of stress at Alicudi, where fracturing and magma injection planes followed the dominance of hydraulic forces related to magma pressure;
- 2) at Stromboli volcanism developed in an extensional tectonic environment where NE-SE-striking fractures are related to a NW-SE-trending σ_3 ;
- 3) at Alicudi the gently-inclined substratum sloping southwards coincides with the trend of the sector collapses, suggesting that where tectonic forces are low, the substratum geometry can influence the orientation of flank failure;
- 4) at Stromboli the multiple sector collapses developed perpendicularly to the trend of dykes, which in turn are geometrically compatible with the tectonic trend.

El Reventador (Ecuador)

El Reventador volcano is located in the sub-Andean zone of Ecuador (Figure 1), a compressional belt that separates the Cordillera Real to the west from the lowlands of the Amazonian foreland to the east. J. H. Sinclair first recognized El Reventador as a volcano in 1929. After that, only brief descriptions were given in Hantke and Parodi (1966), Pichler et al. (1976) and Hall (1977), up to geologic and petrographic data of Aguilera et al. (1988) and Barragan and Baby (1999). The previous last eruption occurred in January-April 1976 and was described in Hall (1977, 1980), followed by another eruption in November 2002-February 2003 (Toulkeridis and Aguilera, 2003; Hall et al., 2003).

El Reventador is a stratovolcano consisting of a succession of lava, pyroclastic and volcanoclastic deposits, which suffered two main lateral collapses interleaved by regrowth phases. Some lava domes are also present along the lower parts of the edifice. The lavas are basaltic andesites, andesites, rhyolites and dacites that belong to a medium-high-K calcalkaline suite. The oldest rocks crop out along the western, northern and southern part of the edifice (*Malo Synthem*, Figure 3). This unit is composed of lava flows with interbedded autoclastic breccias, epiclastic deposits and pyroclastic deposits. Along the eastern volcano flank, a debris avalanche deposit rests directly upon the *Malo Synthem* rocks. The next younger volcanic stage is expressed by a series of rocks here grouped into the *Coca Synthem* (Figure 3) made of thin flows with intercalated pyroclastic flow deposits. To the east, this succession ends with another debris avalanche deposit. In unconformity above this deposit, there are much younger volcanic pyroclastic and lava deposits erupted from the recent/active cone. Moving up the succession, there are alluvial and lacustrine deposits that crop out along the Rio Coca valley south-west of the debris deposits and that resulted from damming of the valley by the previous debris deposit. The amphitheatre of the summit part of the volcano hosts a few hundreds-meters-high cone whose pyroclastic and lava deposits rest in unconformity above the other older products (Figure 3).

These data indicate that two collapse events occurred interleaved by constructive phases. The first collapse occurred in the late Pleistocene with an in-place volume of collapsed material of 12.9 ± 1.8 km³. The edifice was rebuilt to an elevation of 3700 ± 150 m high a.s.l. when it collapsed again ~ 19 ky BP with an in-place volume of 6.7 ± 1.5 km³. Both sliding surfaces cut the main magma conduit zone and dip to the ESE.

The late Quaternary basement tectonics around the coeval El Reventador volcano are characterised by N-S-striking right-lateral reverse faults and NNE-striking right-lateral strike-slip faults. Some of these faults pass through the volcano creating differential uplift along N-S- to NNE-trending tectonic blocks. East of the volcano, N-S-trending fault-propagation folds and NE-striking strike-slip faults are present. Compressional seismic activity is still present in the

Figure 3 Geological sketch map of the El Reventador volcano and surrounding basement based on Tibaldi (2004b). Deposits of the *Malo Synthem* are affected by several N-S- to NNE-striking faults whose escarpments guided the successive emplacement of the lavas of the *Coca Synthem*. Line X-X' is section trace of Figure 4.

studied region. All these data indicate that this is one of the few documented examples of a volcano developed in a compressional tectonic environment.

Edifices for which a critical mass overloading threshold is overcome will be prone to collapse. At El Reventador this threshold was lowered as a result of successive flank failures that modified the material mechanical properties of the rocks. In order to quantify the possible influence of the topography of the substratum as a triggering mechanism of the collapse or as a possible control on the orientation of the collapse, a numerical modelling was performed by applying a finite difference code. Variation in the state of stress between the two collapses and possible deformations of the edifice due to river excavation at the volcano foothill have been computed with the FLAC 4.00 code (Fast Lagrangian Analysis of Continua, Itasca, 2000). In both sections the real physical and mechanical properties of the involved rock masses have been considered based on the field recognition of the lithotypes present in the basement of the volcano as well as in the rock successions of El Reventador. Rock mass parameters and Mohr-Coulomb fit values for each rock type have been assigned in the model, based on geomechanical surveys on El Reventador and on geotechnical tests performed on the same types of rock masses. Figure 4A thus represents the reconstruction of the edifice after the growth of the Coca Synthem and shows a state of stress where the tensors in the volcano are symmetrically distributed on both flanks with the vertical stress generally coinciding with the σ_1 . Figure 4B, which represents the volcano prior to the second sector collapse, contains an excavated Rio Coca valley with a geometry of the valley prior to the second refilling by collapse materials. Results show no variation in the state of stress occurred between the two stages of model development. In section B it is also important to stress that volcano displacement due to river excavation is extremely

low both in vertical (X) and horizontal (Y) direction, in the order of less than 1 cm, thus numerical modelling shows that river toe erosion has no effect on this volcano development.

The data collected on El Reventador and in the surrounding basement indicate that:

- 1) the value of the critical mass overloading tends to decrease in successive failures affecting the same sector of the volcano;
- 2) volcanism here developed in a compressional tectonic environment where contractional and transpressional deformations affect both the substratum and the volcano;
- 3) the presence of the Rio Coca valley and its deepening for river erosion have no influence on the state of stress and displacement field of the El Reventador volcano, and, as a consequence, cannot be claimed as triggering of the sector collapses neither as guiding their orientation;
- 4) the first collapse could have been incepted by deformation related to right-lateral reverse faulting across the cone, whereas the second collapse was likely accompanied by magma intrusion in the cone;
- 5) strong fracturing developed preferentially along the lateral ramps and bottom part of the gliding plane of the first collapse caused a marked decrease in the mechanical properties of the edifice;
- 6) both collapse surfaces developed eastwards under the dominant influence of E-vergent tectonic contractional deformation along N-S-striking structures with possible tectonic bulging due to local enhancement of deformation. This is induced by uplift along an upward-concave fault.

Northern Volcanic Group, Kamchatka (Russia)

Detailed geologic and geomorphologic mapping of young volcanic

Figure 4 Numerical modelling by a finite difference code (FLAC 4.00 code, Fast Lagrangian Analysis of Continua) in order to calculate the state of stress and strain of the El Reventador edifice between the two sector collapses and the influence of basement topography. The two sections coincide with the trace in Figure 3. In both sections the real physical and geomechanical properties of the involved rock masses have been considered. (A) represents the reconstruction of the edifice after the growth of the Coca Synthem edifice and shows a state of stress where the tensors in the volcano are symmetrically distributed on both flanks with the vertical stress generally coinciding with the greatest principal stress (σ_1). (B) represents the volcano displacement field prior to the second sector collapse induced by the excavation of the Rio Coca valley. In both cases the thin, east-dipping layer with quite poor mechanical characteristics represents the gliding plane and debris avalanche deposit of the previous sector collapse. The boxes on the right are enlargements of the state of stress around the Coca river valley and show a symmetric distribution of stresses with a very low stress increase in (B) localized only very close to the valley slopes, and thus not affecting the volcano.

terrains in Kamchatka and observations on historical eruptions revealed that volcano rockslides of various scales, from small to catastrophic (up to 20–30 km³), are widely spread. Moreover, rockslides are one of the most effective and fast acting agents of those changing morphology of volcanic edifices, from large volcanoes and calderas to small cinder cones, extrusive domes and craters. Voluminous sector collapses are most common on large dominantly pyroclastic volcanoes and on extrusive volcanoes. Large failures happened on both basaltic and silicic volcanoes; most of them were related to volcanic activity. From 30 recently active Kamchatka volcanoes at least 18 experienced flank failures, some of them repetitively.

Northern Volcanic Group of Kamchatka (Figure 1) comprises active Shiveluch, Kliuchevskoi, Bezmyanny, Ushkovsky (Plosky Dal'nii) and Plosky Tolbachik volcanoes as well as ten more large eruptive centers and numerous small vents (Figure 5). This is the most productive volcanic cluster, which accounts for more than a half of the Kamchatka's volcanic activity. This volcanic group is located in the Central Kamchatka depression, which during the Holocene has been developing as a right-lateral transtensional graben structure of crustal importance. Late Pleistocene-Holocene faults are widely spread in the region and form NNE-trending systems, the largest of which separates the Northern Volcanic Group from the uplifting Kumroch Range at the east.

Detailed geologic mapping of this area, along with tephrochronology has allowed us to document and date major Late Pleistocene-Holocene debris avalanches. Specific features

of some debris avalanche deposits are *allochtones or toreva* blocks—huge almost intact fragments of volcanic edifice involved into failure. The largest landslides and toreva were documented at active Shiveluch, Bezymianny, Ushkovsky and Plosky Tolbachik volcanoes as well as at extinct Kamen', Krestovsky and Ostryi Tolbachik volcanoes.

On Old Shiveluch, a large sector collapse occurred ~30 ka BP and formed a debris avalanche deposit with a volume of ~30 km³ (Braitseva et al., 1995). Position of the 9 km-wide collapse depression, open to the south, was controlled by a normal fault with vertical displacement of ~500 m. Fourteen debris avalanches occurred on Shiveluch during the Holocene; most of them also traveled southwards (Ponomareva et al., 1998). The most recent of avalanches immediately preceded a large plinian eruption on November 12, 1964 (Belousov, 1995). In addition, two Holocene debris avalanches associated with flank extrusive domes traveled down the western volcano slope. The maximum travel distance of an individual Holocene avalanche exceeds 20 km. Tephrochronological and radiocarbon dating of the avalanches shows that the first large Holocene avalanches were emplaced about BC 4530–4350. From ~BC 2490 at least 13 avalanches occurred after intervals of 30 to 900 years. Six large avalanches were emplaced in a short time span between AD 120 and 970 with recurrence intervals of 30 to 340 years. All the debris avalanches were followed by eruptions which produced various types of pyroclastic deposits. Most avalanche deposits are composed of fresh andesitic rocks of extrusive domes, so the avalanches might result from the high magma supply rate and the repetitive formation of the domes.

One of the largest Holocene Kamchatkan avalanche (4–6 km³) took place on extinct Kamen' volcano ~1.2 ka BP during strong

activity of the neighbouring Bezymianny (Melekestsev and Braitseva, 1984). On Ostry and Plosky Tolbachik, Krestovsky and Ushkovsky volcanoes catastrophic landslides with formation of toreva accompanied collapse of the Hawaii-type calderas. The largest of toreva, earlier mapped as a separate volcano (Sredny, now 2978 m a.s.l.), was once a summit of Krestovsky volcano (4057 m a.s.l.) and was displaced during the formation of a 4-km-wide caldera ~9 ka BP (Melekestsev, in prep.).

High frequency of collapse events in the Northern Group is associated with high volcanic productivity and seismicity. Most of the collapse depressions are oriented in accordance with the general NNE-strike of regional fault systems.

Galeras (Colombia)

The Galeras stratovolcano is located in the Colombia Andes (Figures 1 and 6). Here the Andes are composed by three NNE-trending ranges, the Western, Central, and Eastern Cordilleras, which present different geological features. The Western Cordillera is mainly composed of oceanic rocks accreted to the western margin of South America during the Mesozoic and Cenozoic (Aspden and McCourt, 1986; Paris and Romero, 1994; Kellogg and Vega, 1995). The Central and Eastern Cordilleras are composed of a Precambrian-Paleozoic metamorphic basement intruded by several Mesozoic-Cenozoic plutons. A thick sequence of Mesozoic and Cenozoic deformed sedimentary rocks covers the metamorphic basement of the Eastern Cordillera. Finally, recent volcanic activity characterises the Central Cordillera. A fault swarm known as Romeral Fault System and composed of east dipping reverse and strike-slip NE-striking faults, separates the Western from the Central and Eastern cordilleras.

Galeras lies along this fault system (Figure 6). It is made by calcalkaline lavas and pyroclastic flow and fall deposits dated 1.1 Ma-Present (Calvache et al., 1997). These deposits are ascribed to six constructive volcanic phases, named from the oldest to the youngest Cariaco, Pamba, Coba Negra, Jenoy, Urcunina and Galeras stages, interrupted by destructive ones (calderas formation and lateral collapses). Another volcanic centre is present on the southwestern slope of Galeras, the 166 ± 34 ka old Cerro La Guaca pyroclastic cone (Calvache et al., 1997).

Calvache et al. (1997) demonstrated that at ~560 ka BP a major caldera (Coba Negra caldera) formed with its center ~5 km west of the present-day active volcano top. This caldera is 5 km in diameter and elongated E-W. Another caldera 4 km in diameter formed successively during the Jenoy volcanic stage. Its center is located ~2 km SW of the present-day crater. The wall of the Jenoy caldera cuts glacial morphology indicating a post-glacial (< ca. 20 ka) age. These data suggest that the location of the eruptive main centers changed several times, moving to the east and to the NE. The E-W trend of migration of the volcanic centers is also equal to the E-W elongation of the Coba Negra caldera. Between 12.8 and 5 ka the summit portion of the cone collapsed toward WSW and formed the youngest debris avalanche deposits (Figure 6). The collapse scar is opened toward the WSW and has a horseshoe shape in plan view. The sliding surface would almost certainly have cut across the main magma conduit; thus this collapse is of the sector type. The presence of other older debris avalanche deposits suggests previous lateral collapses whose scars can be individuated on the upper southern slope of the volcano. The active cone lies in the uppermost part of the sector collapse depression.

The Cerro La Guaca cinder cone is aligned in a NE-SW direction with a fault swarm (Telpis Lake) affecting the Galeras cone, the southern scarp of the youngest Galeras sector collapse, the active main crater, and the possible extension of a main basement fault. The late Pleistocene-Holocene tectonics of the subvolcanic basement in the area are characterized by dominant right-lateral strike-slip motions along NE striking vertical to subvertical faults, with a subordinate uplift of the northwestern fault blocks (Tibaldi and Leon, 2000). These data, the focal mechanism, and the fault stress tensor suggest that the upper crust of the southern Colombian Andes is

Figure 5 Sketch map of the debris avalanche deposits at the foot of Shiveluch volcano, Kamchatka, Russia. A large Late Pleistocene depression, open to the south, formed ~40 ka BP as a result of a sector collapse: a rim of the crater is shown as a line with open teeth, deposits of the Late Pleistocene debris avalanche are shown with open debris beyond the boundaries of the Holocene avalanches. Deposits of the 14 Holocene debris avalanches are shown with various fillings. Deposits exposed only in the outcrops are shown with the circles. Suggested boundaries of the deposits of the avalanches V, VI and X are shown with dashed lines at the southern foot of the volcano. Thick dashed lines north of the 1964 crater show faults inferred from airphotos interpretation. Inset shows ages and volumes of the Holocene debris avalanches.

Figure 6 Geological map of Galeras volcano and surroundings, Colombia. This stratovolcano is located along the Romeral Fault System that consists of east dipping reverse and strike-slip NE-striking faults, separating the Western from the Central and Eastern cordilleras. Focal mechanisms and fault stress tensors suggest that the upper crust of the southern Colombian Andes is subject to a compressional state of stress characterized by a horizontal E-W-trending tectonic σ_1 and a N-S horizontal σ_3 (large black arrows). A series of clues suggest that magma feeding the Galeras Volcano and the La Guaca cinder cone uprose to the substrate-volcano interface along a NE-striking transcurrent fault: (1) the NE alignment of the two craters and of two parasitic vents, (2) the possible ideal southward prolongation of the late Pleistocene-Holocene basement fault, (3) the presence of the Cerro La Guaca-Telpis Lake fault swarm, and (4) a NE striking pre-Holocene fault SW of the La Guaca volcano.

subject to a compressional state of stress characterized by a horizontal E-W-trending tectonic σ_1 , while the tectonic σ_3 is also horizontal and trends N-S (Figure 6).

A series of clues suggest that magma feeding the Galeras Volcano and the La Guaca cinder cone uprose to the substrate-volcano interface along a NE-striking transcurrent fault. These data are (1) the NE alignment of the two craters and of two parasitic vents, (2) the possible ideal southward prolongation of the late Pleistocene-Holocene basement fault, (3) the presence of the Cerro La Guaca-Telpis Lake fault swarm, and (4) a NE striking pre-Holocene fault SW of the La Guaca volcano (Figure 6).

Mayon Volcano (Philippines)

Mayon Volcano is located on the Bicol Peninsula in the southeastern portion of Luzon Island, Philippines (Figure 1). It is an andesitic stratovolcano associated with the Bicol Volcanic Arc, which is related to subduction along the Philippine Trench (Fitch, 1972; Aurelio, 2000). Famous for its symmetrical cone and steep-sided slopes, Mayon is also the most active volcano in the Philippines, with forty-seven episodes of eruptive activity since its first recorded eruption in 1616 (Catane et al., 2003).

Along with the other volcanoes of the Bicol Volcanic Arc, Mayon is situated within the Bicol Basin (Bureau of Mines and Geosciences, 1981), a generally flat area underlain by sedimentary rocks and interbeds of volcanoclastic deposits. This basin is traversed by structures, many of which pass through or beside the edifice of the Bicol Arc volcanoes. One of these structures is the San Vicente-Linao fault system, a pair of northwest-striking faults (Bureau of

Mines and Geosciences, 1963; Travaglia and Baes, 1979; Ferrer et al., 1985; Philippine Institute of Volcanology and Seismology, 2000), the northern segment of which can be traced down to the western foot of Mayon where it disappears (Figure 7).

Analysis of the structural setting of Mayon suggests that the Bicol Peninsula is situated within a releasing bend of the Philippine Fault. Stress generated along this bend during left-lateral strike slip movement, produce transtensional northwest-striking faults. These structures cut across the western and eastern regions of the central segment of the Philippine Fault. A regional pull-apart structure is generated, forming the Bicol Basin, as well as northwest-striking transtensional structures that cut through it (Hilawan, Minas, San Vicente-Linao, San Miguel Fault Extension). The San Vicente-Linao Fault, forms a northwest-trending graben with its northern boundary trace projecting to the foot of the western portion of Mayon Volcano where it disappears. This feature, however, is not unexpected since faults are known to curve as they meet the base of volcanic cones (Lagmay et al., 2000). Seismic data suggests that the strike-slip faults in this region are active, including the San Vicente-Linao Fault. Furthermore, epicenter plots of local tectonic earthquakes in the Legaspi Bay suggests an eastern offshore continuation of the northern portion of the San Vicente-Linao Fault system.

Fieldwork conducted on Mayon Volcano reveal the presence of steeply-dipping fault structures on its east and west flanks. The identification of faults and analysis of kinematic movement along fractures found in the field are based on map view strike-slip features, which include en echelon faults, right stepping fractures, structural edges, and anastomosing structures. The structures found on the slopes of Mayon volcano indicate left-lateral sense of movement. Plots of fractures measured in the field (rose diagram plots) indicate dominant northwest and minor northeast fracture trends. These two trends form an acute angle, with the bisector oriented east-west. These deformation structures recognized on the slopes of Mayon are consistent with the regional deformation.

The identification of faults on the slopes of Mayon is the first recognition of such features on this volcano. Many articles have been written on Mayon volcano but none have focused on the identification of deformation structures traversing its edifice. Although very well studied, most of the published material are on the descriptions of its eruptions deposits, geochemistry and eruption monitoring. The lack of studies on fractures (faults and joints) on Mayon's edifice is perhaps brought about by the difficulty in identification of fracture related lineament structures in topographic maps as well as aerial and satellite imagery. The occurrence of faults and joints on maps and images are easily masked by the radial drainage, dense vegetation, persistent erosion, active deposition of pyroclasts, and levees of lava deposits. Moreover, the loose and unconsolidated character of pyroclastic deposits does not favour the preservation of brittle deformation structures. The use of SAR imagery, shaded relief imagery and slope aspect maps in the analysis of deformation in Mayon volcano, facilitate the distinction of lineament structures that are amenable for verification in the field.

Several published works have shown that faults play an important role in volcano instability (Siebert, 1984; Francis and Wells, 1988; Van Wyk de Vries and Merle, 1998; Lagmay et al., 2000; Van Wyk de Vries et al., 2001). Apart from acting as pathways for

Figure 7 Landsat satellite image of Mayon Volcano, Philippines and vicinities showing areas affected by brittle and plastic deformation. Field and remotely-sensed data indicate that the basement surrounding the Mayon volcano is affected by strike-slip and oblique normal faults, indicating a transtensional tectonic setting.

hydrothermal circulation that weaken the volcano, faults in the volcanoes interior can act as failure planes in the event of volcano edifice collapse. The presence of faults on Mayon's slopes is thus an indicator of a volcano collapse hazard. Such collapses can even be accompanied by directed blasts (Christiansen and Peterson, 1981; Mullineaux and Crandell, 1981). The proper monitoring of these faults and tectonically related surface deformation structures on Mayon's flanks should be considered seriously.

Conclusions

Under the aegis of the UNESCO-IUGS-IGCP project 455, a series of joint collaborations among researchers from various countries were conducted. Collaborations enabled the development of several field and laboratory studies conducted on a multidisciplinary basis. Joint researches were carried out by using already existing research funds and newly accepted project proposals during the period 2001-2004. Several important results on the interplay between volcanoes and their basement have already been reached with more studies underway that are likely to continue beyond the end of this 5-year project.

The comparative study of several volcanic areas in different geological and tectonic settings enabled the recognition of a series of features common to all the studied regions and attributes peculiar to certain geologic-tectonic environments.

Common features that were found are the following:

- tectonic faults can easily propagate from the substrate through small and huge volcanoes alike, but the fault geometry and kinematics assume more complex patterns in the cone body;
- location of craters and fissure eruptions is strongly linked with basement tectonic features both as inherited discontinuities as well as in response to active tectonic forces propagating from the basement far-field stress;
- in general, basement tectonics influence the geometry of flank failures in volcanoes, but the geometric relationships are a function of the type of fault kinematics;

- large flank failures, which also involve the summit of huge volcanoes (sector collapses) appear to be more common than previously thought. In zones of high magma production rate, recurrence intervals of sector collapses in a volcanic group can be in the order of 30 yrs to a few hundreds years;

- volcanic debris avalanches are definitively the largest landslide events which can occur on Earth, ranging from 1 km³ to 30 km³;

- on single large volcanoes, multiple sector collapses seem to be a common feature with cases ranging from 2 to 14 main events during their lifetime;

- once flank failure has occurred, the collapse depression and the new geometry of the volcanic edifice strongly influence the location and configuration of new craters and dykes;

- the multiple occurrences of lateral collapse also strongly influence the morphological and geological evolution of the region surrounding the volcano. This is mostly expressed by multiple damming of rivers with subsequent formation of lacustrine environments, followed by periods of high sediment transports along down valley river segments.

Among the features peculiar to certain geologic-tectonic environments are the following:

- in normal faulting and transtensional tectonic regions, volcanic activity is frequent due to stress conditions in the upper crust that favour magmatic activity;

- in normal faulting and transtensional tectonic regions, sector collapses are more diffuse compared to transpressional and reverse tectonic regions. Gravitational instability increase is related to tilting and topographic offsets within the basement;

- reverse, transpressional and transcurent tectonics are present in areas with coeval volcanism at a larger extent than previously thought;

- preferential directions of sector collapse development depend upon orientation of basement faults, their kinematics, and the basement dip and inclination;

- the presence of particular lithotypes in the substrate of the volcano, such as clay, gypsum and highly altered rocks, can create rheological conditions that favour volcano lateral instability.

These data contribute to elucidate the role of the substrate in changing the geological, structural, and volcanological framework of the volcanic edifice and vice versa. In addition to the well developed studies on geochemical, petrological, and geodynamic deep conditions of magmatic regions, one of the main global contributions of this project is the revelation and emphasis that upper crustal basement tectonics play a crucial role in influencing various aspects of the evolution of volcanoes. Tectonic events in fact, completely change the shape, structure and distribution of lithotypes in the volcanic edifice. They also change the local, and distant substrate geology and geomorphology, which coincide with major changes in magmatic characteristics. It also appears that lateral collapses strongly influenced by substrate tectonics, represent a fundamental transformation stage in the normal development of a volcano. This new perception of the crustal tectonic role in volcanic-related processes serves as a guide to researchers who aim to assess volcanic hazards. This would be in terms of the following: i) identification of the location and possibility of lateral and eccentric vent opening; ii) characterization of the geometry of intrusions within the cone; and iii) assessment of the probability of flank failure. Moreover, the studies of this project contribute to improve the data and methodologies useful for economic applications such as geothermal and mineral exploitation.

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