Available online at www.sciencedirect.com
ScienceDirect
Journal of Volcanology and Geothermal Research 158 (2006) 1–5
Journal of volcanology and geothermal research
www.elsevier.com/locate/jvolgeores

Interaction between volcanoes and their basement

A. Tibaldi [a,*], A.M.F Lagmay [b]

[a] Dipartimento di Scienze Geologiche e Geotecnologie, Università di Milano-Bicocca, Milano, Italy
[b] National Institute of Geological Sciences, University of the Philippines, Diliman, Quezon City, Philippines

Received 10 April 2006; accepted 10 April 2006
Available online 14 June 2006

Keywords: basement; tectonics; volcanoes; volcano collapse; faults; magma paths

The reciprocal influence of volcanoes on their substrate and vice versa in different geodynamic settings is relatively poorly understood. Over the past few decades, there has been a growing realization of the importance of the interaction between volcanoes and their basement in reconstructing the evolution of volcanoes and the understanding of eruptive behaviour.

Research on the global data set of volcanoes has shown that edifice failure, dike orientations and the distribution of flank vents are related to the regional stress field (Nakamura and Uyeda, 1980; Moriya, 1980; Siebert, 1984). More recently, it has been recognized that the orientation and kinematics of faults in the substrate are related to the direction of volcano collapses (Tibaldi, 1995; van Wyk de Vries and Merle, 1996; Vidal and Merle, 2000; Lagmay et al., 2000). The growth of the volcanic edifice has also been considered to induce changes in its substrate, such as the spreading of weak basement or localized rifting (Walker, 1992; Borgia, 1994). This results in the volcano substrate having distinctive structural and geological characteristics. Furthermore, large volcanic masses may create perturbation of the regional tectonic stress field and induce variations in the geometry and kinematics of coeval faulting in the basement (e.g., Tibaldi and Ferrari, 1992; van Wyk de Vries and Merle, 1996; Kozhurin et al., 2006).

Under the aegis of the United Nations Education and Scientific Organization–International Union of Geological Sciences–International Geoscience Programme (UNESCO–IUGG–IGCP), a concerted global and multidisciplinary initiative was carried out to advance the understanding of the interplay between volcanoes and their underlying basement. This was implemented through the IGCP Project 455 entitled “The Effects of Basement Structural and Stratigraphic Heritages on Volcano Behaviour and implications for human activities”. Results of the researches conducted in different geodynamic settings (Fig. 1), were compiled, correlated and evaluated (Tibaldi et al., 2005).

Among the salient findings resulting from the collaborative work is the recognition of common features in volcanoes affected by their basement (Tibaldi et al., 2005). These are the following: (1) faults propagate from the substrate through small and large volcanoes alike, with fault geometry and kinematics assuming more complex patterns within the cone; (2) there is a strong link between the location of craters and fissure eruptions and basement tectonic features, both as inherited discontinuities as well as in response to active tectonic forces propagating from the basement far-field stress; (3) the influence of basement faults on the geometry of flank

* Corresponding author.
E-mail address: alessandro.tibaldi@unimib.it (A. Tibaldi).

doi:10.1016/j.jvolgeores.2006.04.011

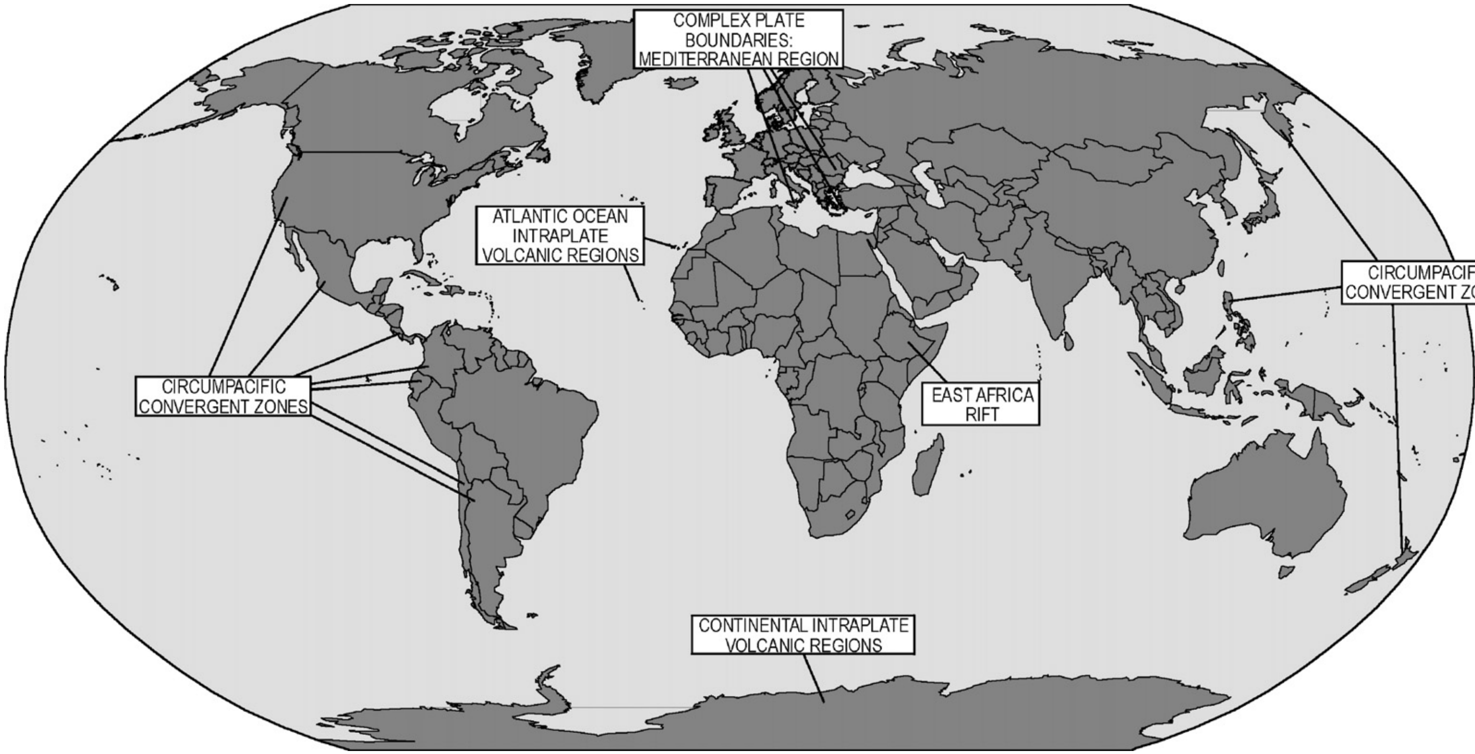

Fig. 1. Location of studied areas within the UNESCO–IUGS–IGCP Project 455 (boxes). The articles contained in this special issue are examples of these works.

failures in volcanoes varies as a function of fault orientation and kinematics; (4) in zones of high magma production rate, recurrence intervals of sector collapses in a volcanic group can be in the order of 30 years to a few hundred years; (5) on single large volcanoes, multiple sector collapses appear to be a common feature with cases ranging from 2 to 14 main events during their lifetime; (6) once flank failure has occurred, the collapse morphology strongly influences the location and configuration of new craters and dykes; and (7) occurrence of collapses strongly influences the morphology of the regions surrounding the volcano, which is expressed as river damming, formation of lakes, and high-sediment transport downstream of the volcanic edifice.

On the other hand, features peculiar to specific geologic–tectonic environments are the following (Tibaldi et al., 2005): (1) in regions with normal and transtensional faulting, sector collapses are more diffuse compared with transpressional and reverse tectonic regions. Gravitational instability appears to be related to tilting and topographic offsets within the basement; (2) reverse, transpressional and transcurrent tectonics are present in areas with coeval volcanism to a larger extent than previously thought; (3) crater opening direction occurs generally at an acute angle relative to an underlying transcurrent fault in convergent margins and perpendicular to basal normal fault in divergent zones; and (4) the presence of certain lithotypes in the substrate of the volcano, such as clay, gypsum and highly altered rocks, can generate rheological conditions that favour volcano instability.

Manuscripts in this special issue contain the results of researches dealing with the aforementioned issues. These results were presented in the session on “Volcano tectonics” at the 32nd International Geological Congress (IGC) in Florence, Italy (August 2004), which served as the venue for the 4th annual meeting of the UNESCO–IUGS–IGCP project 455 participants. The contents of this volume are a contribution to the body of knowledge on volcano tectonics (Gudmundsson et al., 2005, and references therein), with the aim of developing a more holistic view of the evolution and behaviour of volcanoes and the substrate on which they are created.

The paper by Szakács and Krézsek (2006-this volume), illustrates a new interpretation of the structures affecting the Eastern Carpathians thrust-and-fold belt and the Transylvanian Basin. This new view, based on geological and geophysical data, takes into account the effects of volcano loading as well as of salt-diapirism and regional tectonics. The authors suggest that the salt-related tectonics has been enhanced by volcano-induced compressive forces. Moreover, the post-salt succession, including volcanic deposits, has been tilted due to salt withdrawal processes and rotation along a main salt-layer acting as a detachment surface. In turn, the peripheral deformation of the pre-volcanic shallow sedimentary basement induced sagging and spreading of the nearby large volcanic edifices. This process combined with the effect of increased heat-flux may have strongly enhanced salt-diapirism as well.

Bellotti et al. (2006-this volume) present an approach integrating morphostructural and stratigraphic data of a volcano to understand the tectonic history of a region. The authors applied this method to the Nevado de Toluca volcano, Mexico, and adjacent volcanic fields to better assess the complex structural evolution of the eastern-central sector of the Trans Mexican Volcanic Belt. This reconstruction was in turn used to understand the influence of changes in the tectonic setting on the complex growth and evolution of the Nevado de Toluca volcanic edifice.

The paper by Petrinovic and Colombo Piñol (2006-this volume) demonstrates that two main Pleistocene eruptions in Argentina took place during an increment in the tectonic activity of the Calama–Olacapato–El Toro Fault. Both eruptions produced explosive deposits emitted from vents located along normal en-echelon faults related to strike-slip faults. In particular, pyroclastic surge deposits linked to the second episode offer evidence of syndepositional faulting with listric growth faults.

The paper by Guzmán et al. (2006-this volume) investigates the tectonic settings of the Los Gemelos and El Saladillo monogenetic, basaltic–shoshonitic volcanoes that constitute the easternmost recognized examples of mafic Plio-Quaternary volcanism in the southern Central Andes. These authors demonstrate that the emplacement of these volcanoes should be related with a transpression zone. The magmas were derived from a small degree of partial melting of an enriched, garnet-bearing mantle source. The analysed rocks have a primitive signature and evidence of crustal contamination with felsic rocks. Geochemical and tectonic data suggest that rapid magma ascent across 60 km of continental crust was guided by magmatic overpressure favoured by tectonic stresses. A process of assimilation during turbulent ascent (ATA) to explain the contamination at crustal levels is also proposed.

The paper by Lara et al. (2006-this volume) focuses on the nature of the relationships between volcanism and tectonics in the Southern Andes (Chile), where different kinematics in two orthogonal active fissure systems show apparently incompatible arrays of volcanic chains. Whereas NE-trending monogenetic cone alignments can be interpreted as regional tension cracks in a Quaternary dextral transpressional domain, a NWtrending volcanic fissure system can result from extensional fault reactivation. These different kinematic environments cause contrasting magma evolution and eruptive styles. Moreover, a local Quaternary compressive regime is inferred from basement faults. A two-way coupling mechanism is suggested to explain the departure of the local stress field from the regional stress field, the geometric array of extensional features, and the final magmatic evolution.

According to the study of Mattioli et al. (2006-this volume) in the Altiplano–Puna Volcanic Complex (APVC) of the Andean Central Volcanic Zone, Chile, it is possible for some mantle-derived magma to rise with negligible fractional crystallization. These magmas are, however, modified by crustal contamination "en route" to the surface. Their data suggest that a tectonic phase of Quaternary crustal relaxation in the APVC favoured the ascent of small batches of magma, through a "flank by-pass" mechanism, passing newly established conduits not belonging to the main plumbing system of the Ollagüe volcano and its related convecting magma chamber. They have also suggested that the La Porunita scoria cone basaltic andesite could be the result of a flank by-pass as well, although their porphyritic nature implies a crustal residence in shallow (or deeper) reservoirs.

Cimarelli and de Rita, (2006-this volume) present a strain analysis on the Latian dome complexes (Cimini, Tolfa and Ceite-Manziate) in Central Italy, concluding that regional tectonics did not control their emplacement. Higher magmatic strain rates compared to the tectonics strain rates are reflected in roof lifting of the sedimentary carapace where the domes intruded. Their calculations further suggest that these subvolcanic bodies experienced a very rapid evolution indicating negligible interruption in the volcanic activity with insignificant compositional changes in the volcanic products related to the extrusion of the domes.

Ponomareva et al. (2006-this volume) describe detailed geologic and geomorphologic data of major volcanoes in Kamchatka (Russia) and surrounding basement tectonics, where 18 out of 30 active volcanoes experienced sector collapses. The largest sector collapse here identified has a volume of 20–30 km^3 of resulting debris-avalanche deposits, and took place at Shiveluch–Avachinsky volcanoes in the Late Pleistocene. During the last 10 ky, the most voluminous sector collapses have occurred on extinct Kamen' (4–6 km^3) and active Kambalny (5–10 km^3) volcanoes. The largest number of repetitive debris avalanches (>10 during just the Holocene) has occurred at Shiveluch volcano. Large failures have occurred on both mafic and silicic volcanoes, most related to volcanic activity. Orientation of collapse craters is controlled by local tectonic stress fields rather than regional fault systems.

Lagmay and Valdivia (2006-this volume) analyse the relationships between regional stress state and the directions of crater breaching and collapse in Philippine and Indonesian volcanoes. Several volcanoes in different regions have been described by means of morphological and structural features, in order to highlight the direction of Holocene sector or flank collapses. These data were then related to regional tectonics and in particular with the modern stress state obtained by the data of the world stress map. The results corroborate findings in similar research on Japanese and Indonesian volcanoes, indicating that the opening of craters occurs at an acute angle relative to the horizontal maximum stress direction. The studied volcanoes in the Philippines appear to have amphitheatre craters opening in the direction related to the fault underlying the volcano. These observations are consistent with those derived from analogue models of volcanic cones deformed by basal strike-slip faulting.

The paper by Carrasco-Núñez et al. (2006-this volume) analyses the relations between main volcano collapses in Mexico, basement geometry/geomorphology, the possible triggering mechanisms of failure, and the factors controlling collapse directions. No direct evidence was found for magmatic activity associated with the initiation of catastrophic flank collapses of several volcanoes located west of the Gulf of Mexico depression. Instability of the volcanic edifices was influenced by intense hydrothermal alteration, abrupt topographic change, and fracturing. In addition to the eastward slope of the substrate, the reactivation of pre-volcanic basement structures during the Late Tertiary, and the regional stress regimes may have played an important role in the preferential movement direction of the debris avalanches.

The paper by Corazzato and Tibaldi (2006-this volume) uses a coupled morphometric and stratigraphic analysis of parasitic cones of the SE flank of Mount Etna, Italy, to explain a poorly understood actively deforming zone of the volcano. They also present a general classification of pyroclastic cones based on the parameterization of coeval eruption points along the same magma-feeding fracture. Their study suggests a transitional weakness zone between the N–S Rift and the releasing system represented by the Trecastagni and Mascalucia Faults. This is suggested as an E-W-oriented local component of extension that is possibly related to the interplay between the gravitational spreading of the volcano and the regional Timpe Fault system.

The last paper of the volume (Neri and Acocella (2006-this volume)) describes the structural aspects of the 2004–

2005 eruption of Mount Etna, Italy, using field observations. These observations were then compared with analogue models that were conducted earlier by the authors. They suggest that the 2004–2005 eruption of Mount Etna resulted from the propagation of a dike into the intersection of an incipient fracture system with the SE Crater. According to the authors, significant acceleration of this flank deformation may have been induced by magmatic movement.

References

Bellotti, Capra, L., Groppelli, G., Nocini, G., 2006. Tectonic evolution of the central-eastern sector of Trans Mexican volcanic belt and its influence on the eruptive history of the Nevado de Toluca Volcano (Mexico). J. Volcanol. Geotherm. Res. 158, 21–36. doi:10.1016/j.jvolgeores.2006.04.023.

Borgia, A., 1994. The dynamic basis of volcanic spreading. J. Geophys. Res., 99, 17,791-17,804.

Carrasco-Núñez, G., Díaz-Castellón, R., Lee, S., Bernard, H., Michael, S.F., Raúl, R.S., 2006. Multiple edifice-collapse events in the Eastern Mexican Volcanic Belt: the role of sloping substrate and implications for hazard assessment. J. Volcanol. Geotherm. Res. 158, 151–176. doi:10.1016/j.jvolgeores.2006.04.025.

Cimarelli, de Rita, 2006. Relatively rapid emplacement of dome-forming magma inferred from strain analyses: the case of the acid Latian dome complexes (Central Italy). J. Volcanol. Geotherm. Res. 158, 106–116. doi:10.1016/j.jvolgeores.2006.04.015.

Corazzato, C., Tibaldi, A., 2006. Fracture control on type, morphology and distribution of parasitic volcanic cones: an example from Mt. Etna, Italy. J. Volcanol. Geotherm. Res. 158, 177–194. doi:10.1016/j.jvolgeores.2006.04.018.

Gudmundsson, A., Acocella, V., De Natale, G. (Eds.), 2005. The tectonics and physics of volcanoes. J. Volcanol. Geotherm. Res. 144, 1–4.

Guzmán, S.R., Petrinovic, I.A., Brod, J.A., 2006. Pleistocene mafic volcanoes in the Puna-Cordillera Oriental boundary, NW-Argentina. J. Volcanol. Geotherm. Res. 158, 51–69. doi:10.1016/j.jvolgeores.2006.04.014.

Kozhurin, A., Acocella, V., Tibaldi, A., Kyle, P.R., Lagmay, F.M.A, Melekestsev, I.V., Rust, D., Tunesi, A., Corazzato, C., Rovida, A., Tengonciang, A., Uy, H., 2006. Trenching active faults in Kamchatka, Russia: paleoseismological and tectonic implications. Tectonophysics 417 (3–4), 285–304.

Lagmay, A.M.F., Valdivia, W., 2006. Regional stress influence on the opening direction of crater amphitheaters in Southeast Asian volcanoes. J. Volcanol. Geotherm. Res. 158, 139–150. doi:10.1016/j.jvolgeores.2006.04.020.

Lagmay, A.M.F., van Wyk de Vries, B., Kerle, N., Pyle, D.M., 2000. Volcano instability induced by strike-slip faulting. Bull. Volcanol. 62, 331–346.

Lara, L.E., Lavenu, A., Cembrano, J., Rodríguez, C., 2006. Structural controls of volcanism in transversal chains: resheared faults and neotectonics in the Cordón Caulle-Puyehue area (40.5°S), Southern Andes. J. Volcanol. Geotherm. Res. 158, 70–86. doi:10.1016/j.jvolgeores.2006.04.017.

Mattioli, M., Renzulli, A., Menna, M., Holm, P.M., 2006. Rapid ascent and contamination of magmas through the thick crust of the CVZ (Andes, Ollague region): evidence from a nearly aphyric high-K andesite with skeletal olivines. J. Volcanol. Geotherm. Res. 158, 87–105. doi:10.1016/j.jvolgeores.2006.04.019.

Moriya, 1980. "Bandaian eruption" and landform associated with it. Collection of articles in memory of retirement of Prof. Nishimura from Tohoku Univ., pp. 214–219.

Nakamura, K., Uyeda, S., 1980. Stress gradient in arc-back arc regions and plate subduction. J. Geophys. Res. 85, 6419–6428.

Petrinovic, I.A., Colombo Piñol, F., 2006. Phreatomagmatic and phreatic eruptions in locally extensive environments of Southern Central Andes: Tocomar Volcanic Centre (24°10′S–66°34′W), Argentina. J. Volcanol. Geotherm. Res. 158, 37–50. doi:10.1016/j.jvolgeores.2006.04.013.

Ponomareva, V.V., Melekestsev, I.V., Dirksen, O.V., 2006. Sector collapses and large landslides on late Pleistocene–Holocene volcanoes in Kamchatka, Russia. J. Volcanol. Geotherm. Res. 158, 117–138. doi:10.1016/j.jvolgeores.2006.04.016.

Szakács, A., Krézsek, C., 2006. Volcano-basement interaction in the Eastern Carpathians: Explaining unusual tectonic features in the Eastern Transylvanian Basin, Romania. J. Volcanol. Geotherm. Res. 158, 6–20. doi:10.1016/j.jvolgeores.2006.04.012.

Siebert, L., 1984. Large volcanic debris avalanches: characteristics of source areas, deposits, and associated eruptions. J. Volcanol. Geotherm. Res. 22, 163–197.

Tibaldi, A., 1995. Morphology of pyroclastic cones and tectonics. J. Geophys. Res., 100, B12, 24,521–24,535.

Tibaldi, A., Ferrari, L., 1992. Latest Pleistocene–Holocene tectonics of the Ecuadorian Andes. Tectonophysics 205, 109–125.

Tibaldi, A., Lagmay, A.M.F., Ponomareva, V., 2005. Effects of basement structural and stratigraphic heritages on volcano behaviour and implications for human activities. Episodes 28 (3), 158–170.

van Wyk de Vries, B., Merle, O., 1996. The effect of volcanic constructs on rift fault patterns. Geology 24, 643–646.

Vidal, N., Merle, O., 2000. Reactivation of basement faults beneath volcanoes: a new model of flank collapse. J. Volcanol. Geotherm. Res. 99, 9–26.

Walker, G.P.L., 1992. 'Coherent intrusion complexes' in large basaltic volcanoes — a new structural model. J. Volcanol. Geotherm. Res. 50, 41–54.