Effect of strain rate in the distribution of monogenetic and polygenetic volcanism in the Transmexican volcanic belt

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ABSTRACT

In the Transmexican volcanic belt, polygenetic and monogenetic volcanism has taken place concurrently with extensional deformation since the late Miocene. At a regional scale, the deformation is manifested by two groups of faults. The dominant group consists of normal faults nearly parallel to the arc, as the other group are north-northeast-trending normal faults that cross the arc and, in places, form the boundaries of crustal blocks. The larger strain-accumulates of the Transmexican volcanic belt are aligned in north-south volcanic chains along some of these faults, whereas monogenetic volcanoes are usually located along arc-parallel normal fault systems. Because the arc-parallel faults are 15° oblique to the subduction plate boundary, and mantling stretching perpendicular to the trench, the extensional deformation field facilitates activation of both arc-parallel and arc-transverse structures, the former having a higher displacement rate than the latter. We observe that in the Transmexican volcanic belt polygenetic volcanoes develop along faults having small strain rate and monogenetic volcanoes are emplaced along faults having higher strain rate. The agreement with the theoretical model in which monogenetic or polygenetic volcanism depends on the magmatic input rate and the regional stress is true only assuming a linear relation between regional differential stress and local strain rate, as in a continuous and homogeneous medium. We propose that the local strain rate rather than the regional stress field controls the coexistence of both types of volcanism in the Transmexican volcanic belt.

INTRODUCTION

The Transmexican volcanic belt is a 1000-km-long continental volcanic arc related to the subduction of the Rivera and Cocos plates under the North America plate (Pardo and Suárez, 1993). The largest part of the Transmexican volcanic belt trends east-west and forms an angle of 15° with respect to the Acapulco-Mexican-American trench. Since the first descriptions of the Transmexican volcanic belt (e.g., Demant, 1976), it was observed that the main stratovolcanoes are aligned in north-south-trending chains nearly orthogonal to the volcanic belt (Fig. 1). The main examples are the chains limited by the Cerro de Porete and Pico de Orizaba. Iztaezcuuhtli and Popocatépetl-Pico Huete and Nevado de Toluca-Cuautitlán and Volcán de Colima, and Iztaccíhuatl and Cerro Grande (Fig. 1). However, monogenetic volcanoes, including cinder cones, lava cones, domes, and lava flows erupted from fissures, are usually aligned parallel to the main normal fault system mapped along the arc. The alignments of monogenetic volcanoes shown in Figure 1 are mainly cinder cones.

Extensional tectonics commonly accompanies the volcanism in modern volcanic arcs (Hamilton, 1995), and monogenetic and polygenetic volcanoes coexist in the arc. The occurrence of one or the other type of volcanism has been related to the magma supply rate (Fedkin, 1985) or both magma supply and regional differential stress (Takahara, 1989, 1994). The coexistence of monogenetic and polygenetic volcanoes is thus explained by variations in the magma supply rate or in the differential stress.

In this paper we show that in the Transmexican volcanic belt the local strain rate is the dominant factor controlling the type of volcanism. Monogenetic and polygenetic volcanoes may coexist under a single regional stress field and the same magma input rate, provided at least two fault systems with different strain rates are active at the same time.

STRESS FIELD AND TYPES OF VOLCANISM

Relationships between magmatic activity and the stress field have been widely documented. It is currently accepted that the dikes are emplaced due to magma-fracturing when the magma pressure is higher than the minimum principal compressive stress plus the strength of the rock (e.g., Nakamura, 1977). Takada (1989) proposed that the regional stress field influences the magma transport and the formation of magma reservoirs. The crack growth is governed by the magmaic excess pressure (P - P - S), defined as the difference between the magma pressure (P) and the minimum principal compressive stress (S). To maintain the crack propagation upward, the vertical stress gradient (dP/dz) must be greater than the magma pressure vertical gradient (dPm/dz). The crack propagates toward the direction of maximum magmaic excess pressure and can be trapped at some level in the crust permitting the coexistence of magma-filled cracks.

To test his hypothesis, Takada (1994) made an output-stress diagram using worldwide examples of volcanic regions, where the ordinate is the output rate normalized to periods of 10^6 yr. over an area of 10^6 km^2, and the abscissa is the differential stress, which he deduced from strain rates assuming a linear relation between them. The main conclusions of Takada’s (1994) model are (1) at high magma input rates, both polygenetic and monogenetic volcanoes can occur, but the former are favored where there are small stress differences; and (2) at low magma input rate, monogenetic volcanism occurs when the differential stress is small.

VOLCANIC STYLE AND STRAIN RATE IN THE TRANSMEXICAN VOLCANIC BELT

In this work, we consider the local strain as the strain accommodated by slip on a fault or fault system, and the equivalent strain at depth accommodated by other strain mechanisms, including magmatic strain.

Volcanoes in the Transmexican volcanic belt span from about 15 Ma to the present (Ferrar et al., 1992). In the western and eastern parts, the volcanism is principally represented by andesitic and dacitic stratovolcanoes, whereas in the central part, basaltic cinder and lava cones are dominant. Faults in the Transmexican volcanic belt can be grouped in two main sets.

Figure 1. Comparison between late Miocene to Quaternary fault systems of Transmexican volcanic belt (TMVB) and distribution of polygenetic and monogenetic volcanoes (based mainly on Ferrari et al., 1994, 1997; Suter, 1991). TZRF = Tepic-Zacoalco rift; CR = Colima rift; ChR = Chapala rift; MF = Morelia fault zone; PF = La Pera fault zone; OF = Oaxaca fault; CP = Cocos plate; JB = Jalisco block; TMVB = Transmexican volcanic belt. Main alignment of polygenetic volcanoes: (1) Las Navajas and Cerro Grande; (2) Cántaro and Volcán de Colima; (3) Pico Huér- fano and Nevado de Toluca; (4) Iztaczęuhtl and Popocatépetl; (5) Cofre de Perote and Pico de Orizaba. Other minor polygenetic volcanoes not aligned along north-south structures not shown.

(Fig. 1). The dominant set contains fault zones that trend almost parallel to the arc axis; they trend west-northwest in the western Transmexican volcanic belt and approximately east-west in the remaining part of the arc. The other group contains fewer fault systems that trend nearly perpendicular to the arc axis; the strikes of these faults range from north-south to north-northwest.

The western Transmexican volcanic belt is emplaced along the boundary between the Sierra Madre Occidental and the Jalisco block, and trends west-northwest, parallel to the Rivera trench. The deformation produced by the relative movement between these blocks has been accommodated along the Tepic-Zacoalco rift, composed of discontinuous but parallel grabens and half grabens having a general west-northwest trend (Fig. 2). The average vertical displacement rates estimated for the main fault system are ~0.45 mm/yr for the Pliocene and ~0.1 mm/yr for the Quaternary (Ferrari et al., 1997).

Monogenetic volcanism was widespread during both the Pliocene and Quaternary. By contrast, the main polygenetic volcanoes are all Quaternary (Ferrari et al., 1997). This suggests that the decrease of the strain rate allowed the formation of polygenetic volcanoes. Furthermore, during the Quaternary, the cinder cones only developed along west-northwest–trending fault zones (Fig. 2) (Ferrari et al., 1997), whereas, in the Tepic area, there is marked north-south alignment of polygenetic volcanoes (Fig. 2).

In the central Transmexican volcanic belt the east-west Morelia–Acambay fault system crosses the north-northwest–trending Tepic–San Miguel de Allende fault zone (Suter et al., 1992; Demant, 1978) (Fig. 3). Along the Tepic–San Miguel de Allende fault zone both volcanism and faulting migrated from north to south from late Miocene to the present, but the volcanism remained polygenetic (Fig. 3). The central part of the fault zone offset an 8 Ma basaltic plateau (Pasquaré et al., 1991) as much as 100 m but did not affect the 4.7 Ma Amealco ignimbrite (Aguirre-Díaz, 1996), giving a vertical displacement rate of 0.03 mm/yr for this time span. By contrast, monogenetic volcanoes follow the traces of the east-west Morelia–Acambay fault system (Suter, 1991). In the Acambay region a middle to late Quaternary slip rate of 0.04 to 0.07 mm/yr has been calculated along one of the faults (Suter et al., 1992, 1995).

In two areas east of Mexico City, north-south–trending chains of polygenetic volcanoes coexist with approximately east-west alignment of monogenetic centers (Fig. 4). In the Sierra de Chichinautzin, several east-west alignments of cinder cones follow the La Pera normal fault, a major active fault zone south of and bounding the Transmexican volcanic belt (Delgado-Granados et al., 1997). Several stratovolcanoes, including Popocatépetl and Iztaccíhuatl, are aligned north-south (Fig. 4). In the easternmost Transmexican volcanic belt, five polygenetic centers, including the Quaternary Cofre de Perote and Pico de Orizaba volcanoes (Fig. 4), are aligned north-south, on the northern prolongation of the Oaxaca fault (Nieto-Samaniego et al., 1995), a long-lived shear zone with normal fault activity in the Cenozoic (Alaniz-Alvarez et al., 1996).

The north-south to northwest faults in the Transmexican volcanic belt are parallel to older faults that are found in northern and southern Mexico.
Figure 3. Style of volcanism at the intersection between the Morelia-Acambay and the Taxco-San Miguel de Allende fault systems in the central Transmexican volcanic belt (based in part on Suter et al., 1992). Note that the arc-transverse Taxco-San Miguel de Allende fault system favored the growth of polygenetic volcanoes since late Miocene, whereas monogenetic volcanoes followed arc-parallel faults.

(Nieto-Samaniego et al., in press) and were interpreted as belonging to the Basin and Range province (Henry and Aranda-Gómez, 1992). Suter et al. (1995) and Ferrari et al. (1994) suggested that the east-west and north-south fault systems in the Transmexican volcanic belt could have had synchronous movement.

DISCUSSION

When a crustal block having preexisting planes of weakness undergoes deformation, the planes may be reactivated, new faults may form, or both phenomena may occur. It is expected that less differential stress is needed to produce slip along a preexisting plane than to form a new fault. A major fault will be a feasible reactivation plane if it has low cohesion, high permeability, and gouge with low coefficient of friction. Near the surface, a major fault can be reactivated even if it is nearly perpendicular to the minimum principal compressive stress (Alaniz-Alvarez et al., 1998). The strain field may be liberated by movement along preexisting planes but would need additional movement along other planes to be liberated completely (Fig. 5A) (Nieto-Samaniego and Alaniz-Alvarez, 1995); the displacement along each fault depends on the fault orientation.

Seismicity in volcanic arcs shows that the strain field is subhorizontal extension normal to the arc (Apperson, 1991). In the Transmexican volcanic belt, there are two nearly orthogonal groups of faults that were activated almost simultaneously with slip vectors controlled by the general strain field. There are not enough field data to determine the displacement rate of each group of faults. However, it is clear that both fault systems show mainly normal displacement.

In order to show qualitatively the relative amounts of displacements along the two groups of faults, we used the orientation of the principal stresses for the Morelia fault zone (Suter et al., 1995). We considered the mean orientation of the minimum principal compressive stresses (σ2 = 0059/04°); the maximum principal stress was vertical and the stress ratio R = (σ3 - σ1)/(σ1 - σ3) = 0.39. The stresses were plotted on the graphs of Wallace (1951) to determine the shearing stress on the planes of both groups. We determined that the shear stress on the north-south planes approaches up to one-half the shear stress on the east-west planes. Assuming the same shear modulus for both groups, it is clear that the displacement rate on the east-west faults is higher than on the north-south faults.

Another way to show differences in displacement rates is to consider the horizontal strain instead of the stress field. We can assume that the major strain occurred as extension perpendicular to the trench, i.e., N20°E. The horizontal north-south extension was principally accommodated by the approximately east-west normal faults as they approached the ideal Coulomb orientation. Therefore, the horizontal east-west extension was principally accommodated by the north-south normal faults. In the special case when both faults are pure normal slip, the horizontal strain in the east-west direction is 0.36 the horizontal strain in the north-south direction (εeast-west = tan20°εnorth-south) (Fig. 5B). Consequently, we expected that the north-south faults should have only about one-third of the horizontal displacement rate of the east-west faults. In the northwestern part of the Transmexican volcanic belt, the Rivera trench is almost parallel to the normal faults, so the strain rate in other directions is a minimum.

The distribution of monogenetic and polygenetic volcanism in the Transmexican volcanic belt supports the output-stress diagram of Takada (1994), suggesting that the magma is trapped in fault zones having a low
displacement rate. The location of the stratovolcanoes on the traces of pre-existing approximately north-south-trending faults is not in agreement with the idea that magma propagates upward filling Type I cracks, but opens the possibility that the magma transport from the magmatic chamber to the surface was along pre-existing shear structures.

Magmatic input rate can be considered uniform at the scale of analyzed examples (40 x 40 km) compared with the magnitude of the melt generation zone needed to produce the Quaternary volcanic arc (~700 x 100 km). However, we observed a clear separation between the alignment of monogenetic volcanoes along an east-west direction and polygenetic volcanoes along a north-south direction. This indicates that during its ascent through the crust the magma is channeled into zones of different strain rate that induce the formation of polygenic and monogenetic volcanoes.

CONCLUSIONS

Extensional deformation in the Transmexican volcanic belt was accommodated by two approximately orthogonal groups of faults. The extension was synchronous with the volcanism since Miocene time. The alignments of monogenetic volcanoes are preferentially oriented parallel to the high displacement rate structures, whereas stratovolcanoes are aligned along low displacement rate structures. The distribution of volcanoes in the Transmexican volcanic belt agrees with the empirical relationship between type of volcanism and strain rate found by Takada (1994), if local strain rate is considered. In the Transmexican volcanic belt, the displacement rate of each fault strongly influences the type of volcanism, and polygenetic and monogenetic volcanoes can coexist under the same regional differential stress and in zones sufficiently small to consider uniform magma input rate.

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