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MORPHOLOGICAL AND STRUCTURAL ANALYSIS OF THE CENTRAL SECTOR OF THE TRANSMEXICAN VOLCANIC BELT

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RESUMEN

En este trabajo se analiza la evolución post-Laramídica de un sector del Cinturón Volcánico Mexicano (CVM), comprendido entre los estados de Michoacán y Guanajuato. Se reconocieron las principales unidades estructurales por medio de análisis morfológicos y datos geológicos. En particular, se establecieron cuatro tipos de unidades morfológicas:

1. Relieves pertenecientes a unidades geológicas más antiguas del CVM y afectados por las deformaciones orogénicas compresivas.
2. Superficies estructurales planas precedentes al CVM.
3. Superficies deposicionales generadas por relleno de depresiones tectónicas post-orogénicas.
4. Superficies morfológicas del CVM.

En este análisis, se reconstruyeron las etapas más importantes relacionadas con las fases tectónicas distensivas y con los eventos volcánicos principales.

Una primera etapa tectónica distensiva está asociada a la actividad volcánica de edad pre-Mioceno, en la secuencia de la Sierra Madre Occidental.

En el Mioceno tardío prevalecen las directrices rumbo NNW-SSE, relacionadas con la provincia "Basin and Range", de los Estados Unidos Americanos.

En el Plioceno, las primeras manifestaciones volcánicas pertenecientes al CVM se pueden relacionar posiblemente con fallas de dirección Californiana NW-SE. Un cambio muy importante de lineamientos estructurales se presenta a partir del Plioceno Tardío, presentando rumbo WSW-ENE. La última etapa distensiva causa la formación de grábenes orientados N-S y NNE-SSW que cruzan y fracturan las estructuras precedentes al CVM, removilizando lineamientos relacionados con la provincia "Basin and Range".

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ABSTRACT

In this paper the post-orogenic evolution of a central sector of the Mexican Volcanic Belt (MVB) in the states of Guanajuato and Michoacán is analyzed. The main structural units are recognized on the basis of a morphological analysis and geological data. Four categories of morphological units were established. These are:

1. Reliefs belonging to geological formations older than MVB and characterized by Laramide orogenic deformation.
2. Pre-MVB planar structural surfaces.
3. Depositional surfaces belonging to sedimentary or volcanoclastic infilling of post-orogenic tectonic depressions.
4. Surfaces of MVB volcanoes.

In this analysis the main morphogenetic stages were recognized; these were related to tensional tectonic phases and to the main volcanic events. An early tensional tectonic phase is associated with the volcanic activity which formed the pre-Miocene deposits of the Sierra Madre Occidental. A NNW-SSE trending system is dominant during the late Miocene and is related to the "Basin and Range" province of western U. S. A. NW-SE faulting during Pliocene along Californian trends is responsible for the initial volcanic activity of the MVB. Late Pliocene trends are WSW-ENE. The last tensional phase causes N-S and NNE-SSW grabens, as a possible reactivation of "Basin and Range" structures.

INTRODUCTION

Many papers concerning the MVB do not seem to be well supported by data with the exception of prevalently petrographic or geochemical papers that describe local sequences, e.g. Wilcox (1954); Gunn and Mooser (1970); Negendank (1972); Bloomfield (1974); Bloomfield and Valastro (1977); Luhr and Carmichael (1980); Mahood (1980); Nelson (1980); Cantagrel *et al.* (1981); Robin and Cantagrel (1982);Ferriz and Mahood (1984); Verma (1984).

Contributions concerning regional geology are rare as those of Mooser (1968); Stoiber and Carr (1973); Urrutia and Castillo (1977); Anderson and Schmidt (1983); Shurbet and Cebull (1984).

Among the few concerned with regional geological structures are those of Negendank (1972); Erffa von *et al.* (1977); and Demant (1978, 1979).

This paper hopes to add new data on the relationships between volcanism, morphology and regional structures of the central area of MVB, comprised by parts of the states of Michoacán and Guanajuato. Regional geological work was initiated by the first author (G.P.) in 1978 and completed with the others in 1984. This work is mainly based on the reconstruction of post-orogenic features of the area illustrated by Fig. 1.

Fig. 1. Regional Morphology

Depositional Surfaces

Recent Depositional Surfaces
3 - Surface D
2 - Surface E
1 - Surface F

Eroded Depositional Paleosurfaces
6 - Surface A
5 - Surface B
4 - Surface C

Erosional Surfaces

11 - Dissected erosional slopes of orogenic structures apparently affected by important tensional tectonics.
10 - Dissected erosional slopes of orogenic structures variously affected by tensional tectonics
9 - Dissected erosional slopes of volcanic structures
8 - Structural surfaces
7 - Slightly dissected slopes of volcanic centres

METHODOLOGY

The reconstruction of morpho-structural features was preceded by recognition of the principal sedimentary, volcanic and volcanoclastic units belonging to this portion of the MVB. Chemical and petrological analyses of over 200 rock samples and radiometric (K/Ar) dating of 20 rock samples whose final results are yet to be published have also been carried out.

Morpho-structural units were established on the basis of morphological features and the relationships among them. Morphometric interpretation of 1:50 000 DETENAL topographic maps, 1:1 000 000 LANDSAT images, and in key areas 1:50 000 and 1:25 000 aereal photographs were used for the recognition of morpho-structural features. The units were grouped into four main categories:

- Reliefs belonging to the geological units older than MVB and characterized by compressive orogenic deformation;
- Pre-MVB planar structural surfaces;
- Depositional surfaces belonging to sedimentary or volcano-sedimentary infilling of post-orogenic depressions;
- Surfaces of MVB volcanoes.

Each category was further divided on the basis of its morphogenetical evolution so that the main stages could be recognized, and then related to tensional tectonic phases and to the main volcanic events.

REGIONAL GEOLOGICAL FRAMEWORK

The area considered in this paper and illustrated by Figure 1 is located in the central portion of the MVB, where it overlaps the two main orogenic belts of Mexico: the Sierra Madre Occidental (SMO) and the Sierra Madre Oriental (SMOr). In the northern part, the Mexican Central Plateau extensively covers the boundary between the two belts. Southeast of the area the boundary is characterized by the overthrust of the Teloloapan unit, pertaining to the SMO up to the Guerrero-Morelos platform (Campa *et al.*, 1976; Campa and Coney, 1983).

The Tzitzio-Huétamo Mesozoic folded sequence, the El-Oro-Zitácuaro metamorphic ridge and the Sierra de León - Guanajuato plutono-metamorphic sequence belong to the orogenic complexes of Sierra Madre Occidental. Folded Mesozoic carbonatic sediments make up the SMOr. The Laramide orogeny responsible for the main deformation of the Cordilleran System and of the SMOr was followed in Oligocene and Miocene times by the calcalkaline cycle forming the volcanic plateau which covers the SMO. In the studied area, the Oligocene and Miocene volcanism shows a uniform areal distribution later fractured by polyphasic tensional tectonics. The activity of the MVB is related to these tensional tectonic phases and has been taking place since Pliocene. The early activity is represented by acidic domes yet to be precisely dated. In this area a second cycle of dacitic domes and andesitic cones and flows was recognized. It was followed by a third volcano-sedimentary episode that persisted until Pleistocene characterized by ash-flow tuff, basalt and lacustrine sediment, and by a fourth cycle consisting essentially of dacite and rhyolite domes and of andesite cones and flows.

REGIONAL MORPHOLOGICAL ANALYSIS

The current morphological configuration of the area considered in this paper is the result of a lengthy morphogenetic process acting on SMO and SMOr during post-Laramide tectonic evolution. The latter develops an impressive and complex mosaic of faulted structures mainly covered by the volcanic products of MVB, which occupies most of the central and southern portion of the studied area.

In the northeastern sector the dominant morphology is that of reliefs coinciding with the axes of SMOr folds. Here an important and parallel drainage system running into the Gulf of Mexico develops. In the southern sector, slopes are very steep and related to active erosion controlled by a transversal drainage running into the Pacific Ocean.

Due to the altimetric gradient, this active erosion has revealed Mesozoic geological units involved in the Laramide folding of the SMO and underlying its thick Tertiary volcanic cover. Tensional structures of MVB control prevalently the large central sector, and are mainly responsible for the large lacustrine basins, fed by complex drainage systems.

The presence of several tectogenic and morphogenic phases determines the repetition of depositional and erosional cycles; the result is a complex mosaic of juxtaposed surfaces. The main surfaces that form the morphological units into which the area can be subdivided are described under the following headings.

EROSIONAL SURFACES

These surfaces are those undergoing the prevalent and persistent action of erosional agents. They appear as variously dissected slopes caused by the erosion bearing on orogenic complexes, volcanic sequences and volcanic centres.

Dissected erosional slopes of orogenic structures apparently unaffected by important tensional tectonics. (number 11, Fig. 1)

In this category erosional surfaces pertaining to the SMOr appeared where the Mesozoic folded sequences of this belt are exposed beneath the Tertiary volcanic cover belonging to SMO.

Dissected erosional slopes of orogenic structures variously affected by tensional tectonics. (number 10, Fig. 1)

Mainly developed in the southern part of the area, they are represented by the Laramide structures of SMO extensively collapsed into the Sierra Madre del Sur structural province. Due to the great altitude gradient of this sector, the slopes developed are controlled by a very dense dendritic drainage.

Erosional surfaces belonging to the orogenic structures of the SMO isolated by tensional post-orogenic lineaments are found in this category. The surfaces develop prevalently in relation to two very prominent and high reliefs, these are the Sierra de León - Guanajuato complex and the El Oro - Zitácuaro ridge. The former presents an asymmetrical profile caused by the contiguity of the recent Irapuato - Querétaro depression towards which steep slopes with an average height difference of 500 m develop. The slopes of the opposite side have a more limited erosion regime due to the contiguity of structural and altimetrically high surfaces which form the top of tilted Tertiary volcanic plateaus. Also the El Oro - Zitácuaro ridge has an asymmetrical development of its steep slopes cut by a dense dendritic drainage pattern. The western flank develops with a height difference of 1 500 m caused by the contiguity of the huge Río Balsas basin, and the huge Los Azufres - Túxpan tensional structure active during Tertiary.

Dissected erosional slopes of volcanic structures (number 9, Fig. 1)

These erosional surfaces are dissected by approximately radial drainage patterns covering subcircular areas. They appear to emerge from the Tertiary volcanic plateaus of SMO, and probably represent their emission centres. Their concentration along NNW-SSE bands could indicate that this is an area of Tertiary magmatic activity controlled by important dislocation following the same trend.

Dissected structural surfaces. (number 8, Fig. 1)

These are wide structural surfaces representing the top of Tertiary SMO volcanic sequences dismembered by erosion. They reveal the wide tabular setting of the volcanic products that actually make up the sequences. Fluvial erosion dissects these surfaces with fairly straight steep-sided rivers to form a parallel or trellis drainage pattern. These surfaces often represent the top of wide tilted blocks. The presence of tectonic depressions and their related depositional basins contiguous to those blocks determines their isolation as round-edged fragments, separated specially in the minor order streams, by a dendritic drainage pattern.

Slightly dissected slopes of volcanic centres. (number 7, Fig. 1)

Surfaces of volcanic centres of MVB are grouped into this category and maintain much of their original morphology, that of lava cones and flows, domes and pyroclastic cones. Their slopes are only slightly dissected by radial drainage patterns. The best examples are those of the numerous aligned volcanic centres within the Central depression and those of the numerous Quaternary centres that cover the Tarascan plateau. This category however also comprises the surfaces of volcanic centres NW of Querétaro, which are more deeply dissected and can probably be considered as an early activity of MVB.

DEPOSITIONAL SURFACES

These units are mainly conditioned by depositional factors, even though erosive regimes may have followed. In these units hierarchy was established according to altimetric and erosion-deposition relationship. This allowed for the subdivision of depositional units into two larger categories having a chronological relation: eroded depositional paleosurfaces and recent depositional surfaces unaffected by generalized or localized erosive action.

Eroded depositional paleosurfaces

- Surface A. (number 6, Fig. 1)

Surfaces of this unit are those of depressions with an average height of 2 050 m and 2 100 m a.s.l. situated between tabular SMO Tertiary volcanic reliefs. Infilling of the depression is prevalently that of coalescent alluvial fans. However, these are not active and are unconformously dissected by shallow longitudinal streams.

- Surface B. (number 5, Fig. 1)

These are old depositional surfaces that cover the top of tabular SMO volcanic sequences. They are suspended terraces 100 to 150 m higher than the tributary valleys of the Central depression. These valleys generally form a parallel drainage pattern with low order NNW-SSE streams. These surfaces are extensively planar but are interrupted by sharp and narrow valleys that break their uniformity. Moreover there is a gradual transition to eroded structural surfaces of the top of Tertiary volcanic sequences. Therefore they seem to be related to alluvial infilling of large NNW-SSE grabens, displaced within SMO volcanic plateaus.

- Surface C. (number 4, Fig. 1)

These depositional paleosurfaces are genetically similar to surfaces B, but remain isolated as a consequence of the tectono-sedimentary cycle that generated the Central and Laguna de Cuitzeo depressions according to WSW-ENE trends. The average height of these surfaces is between 1 800 and 2 000 m a.s.l. except the area surrounding Laguna de Pátzcuaro whose height is 2 100 m a.s.l. as a consequence of the detritic infilling caused by the formation of a volcanic belt surrounding the lake. The morphology of these surfaces is planar, particularly where they correspond to lacustrine deposits. These surfaces present a disorganized drainage pattern with low order shallow streams.

Recent depositional surfaces

- Surface D. (number 3, Fig. 1)

The Laguna de Cuitzeo basin, the Zacapu and the Acámbaro lacustrine plains support surfaces of this type; their average height is 1 850 m a.s.l. These surfaces correspond with the top of recent to contemporary undisturbed lacustrine sediments deposited within depressions controlled by WSW-ENE tensional tectonics. The northern border of these depressions is characterized by the alignment of Quaternary andesite volcanoes along this tensional direction.

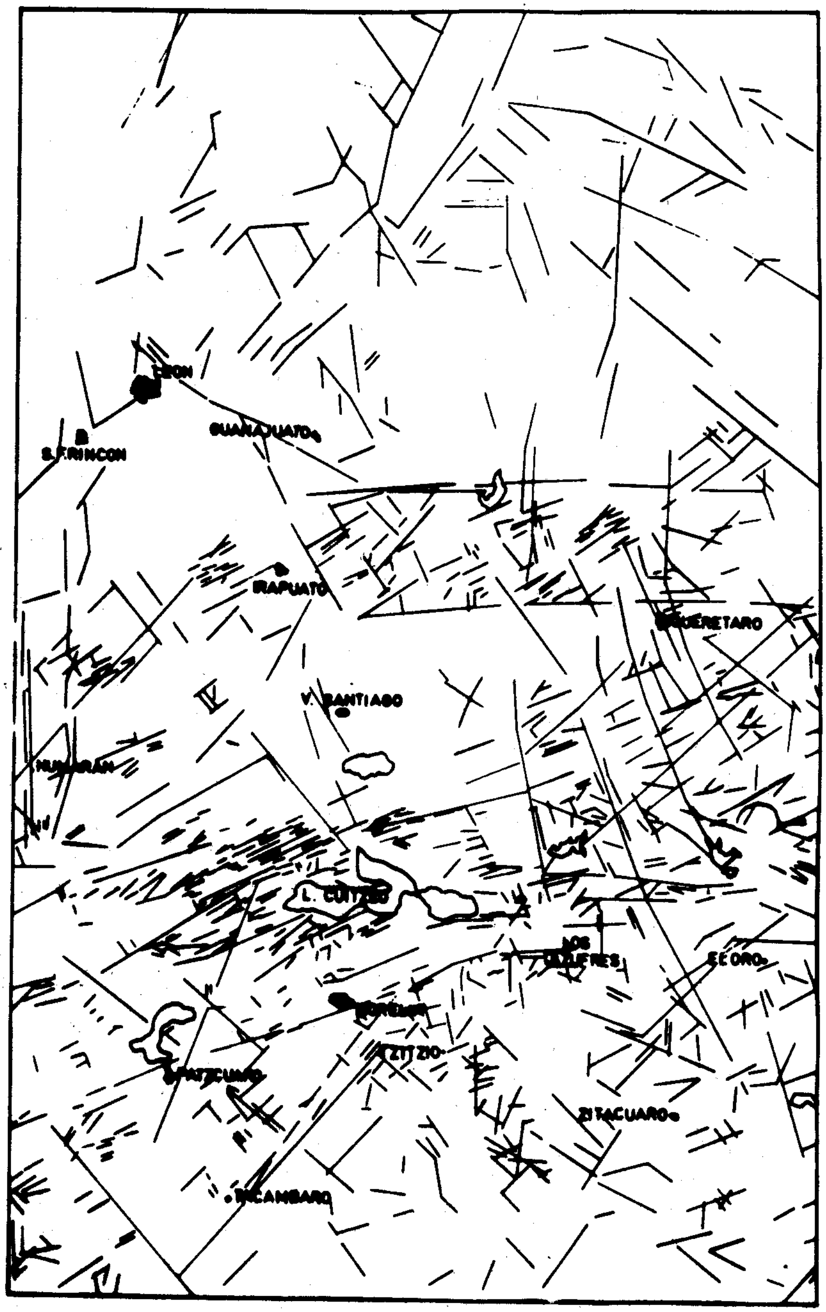

Fig. 2. Distribution of Tensional Fractures

- Surface E. (number 2, Fig. 1)

This surface is that of the top of the wide and flat Central depression developed Irapuato and Querétaro at a level height of 1 730 m a.s.l. Tectonic WSW-ENE control of the depression is the same as that of surface D, with which this surface is probably coeval. These surfaces represent the top of a recent lacustrine basin that occupied most of the Central depression; they tend to drown the bordering surfaces especially the ones related to split or tilted blocks of Tertiary volcanic plateaus. In some cases, and especially bordering the León-Guanajuato ridge, huge fan deltas link old erosional surfaces to the depression.

- Surface F. (number 1, Fig. 1)

This surface is that of the bottom of the San Luis Potosí - San Felipe graben. This depression is controlled by marked NNE-SSW tensional trends its height being 1 950 and 2 000 m a.s.l. The surface is concave towards the centre of the depression as a consequence of the presence of large transversal alluvial fans at its sides, enclosing a limited central braidplain. The drainage pattern of this unit does not interfere with those of other units, as this system runs into the Gulf of Mexico.

STRUCTURAL ANALYSIS

Regional morphological lineaments described under the previous headings are the result of the impact of complex tensional structures on Laramide orogenic structures. Laramide structures of the SMO develop with compressive NNW-SSE directions in the southern sector of the area considered, the main representatives being the Tzitzio anticline and El Oro - Zitácuaro ridge.

Compressive NW-SE structures belonging to the SMOr occupy the northeastern sector of the studied area and are extensively covered by Tertiary volcanic plateaus pertaining to the SMO. Large intermontane basins only just beyond the area considered by this paper develop parallel to these compressive trends, and testify the presence of an early tensional phase.

Post-Laramide tensional structural lineaments are the main factor responsible for the present structure of the area, and the one chiefly controlling its morphological configuration: NW-SE and NNW-SSE lineaments, related with erosional morphological units. WSW-ENE lineaments are related with partly erosive and partly depositional morphological units. Further lineaments with various directions are related with very recent depositional morphological units. (Figs. 3 and 4) Lineaments of the first category are spaced and cross the whole area diagonally, forming a framework of tilted and folded SMO Tertiary volcanic blocks. These structures represent a very early phase in the tensional tectonic evolution and are probably associated to the early volcanic activities of SMO. The second trend large differences in thickness within the Tertiary volcanic sequence of SMO are related. Bore holes of the Los Azufres geothermal area illustrate this situation, as they cross a 3 600 m thick andesite and basalt sequence without encountering metamorphic basement rocks, which however outcrop in the adjacent El Oro - Zitácuaro ridge, 2 500 m a.s.l. Radiometric ages of these lavas indicate Late Miocene (C.F.E. unpublished data). The ages of these sequences appear equivalent to those of the andesitic products of the Pachuca area studied by Cantagrel and Robin (1979) as pertaining to MVB activity. The same sequence seems to be related to a late phase of SMO volcanism overlying the folded SMOr sequence.

Adjacent to the Los Azufres area, the Tzitzio anticline is formed by a folded Mesozoic and Paleogene sequence with volcanic horizons toward the top, covered in

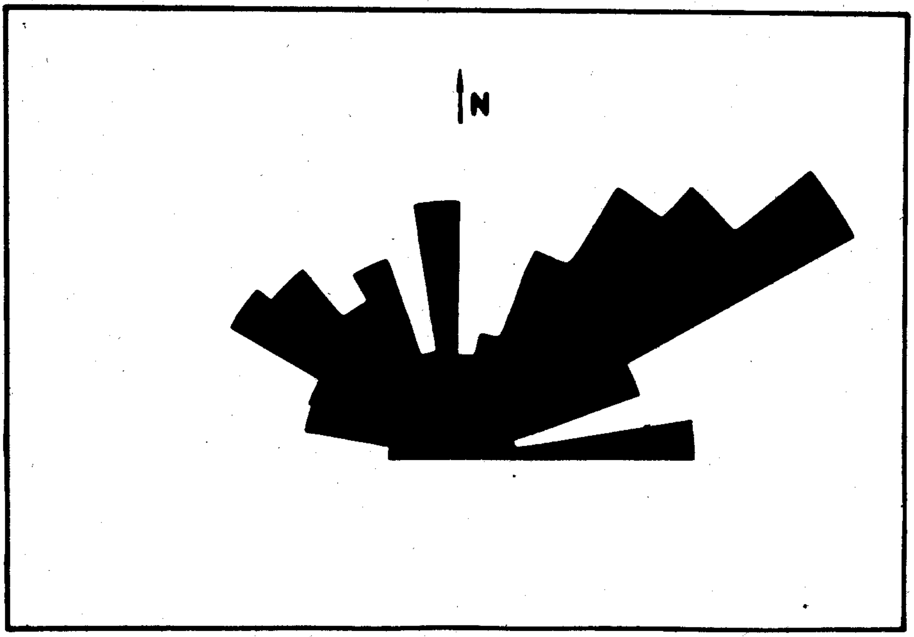

Fig. 3. Cumulative Distribution of Tensional Fractures

unconformity by a 1 000 m sequence of andesite and ignimbrite Radiometric dating of lava horizons gives Middle Miocene age (Pasquaré, unpublished data). Tensional WSW-ENE lineaments control the lacustrine depression chiefly developed in the central portion of the area considered. The Central Depression occupies most of this system and is flanked to the South by the higher Cuitzeo depression and then by tilted blocks of the Morelia area. These lineaments, especially in the Querétaro area interfere with the NNW-SSE ones breaking them into a complex mosaic of isolated blocks.

Volcanic centres of the MVB are aligned on the numerous WSW-ENE faults that limit the structural features of the preceding system and form a series of steps on both sides of the Central Depression. Numerous Plio-Quaternary volcanic centres are found at the intersection of this system with the NNW one. The Tarascan Plateau is an elevated feature belonging to this WSW-ENE system, mostly covered by Quaternary volcanic centres. The Tarascan Plateau despite its height is an area of prevalently depositional surfaces to which volcanic depositional landforms add themselves. Structural trends feeding the volcanic activity of the Tarascan Plateau are faults of the WSW-ENE system and of the NW-SE system presenting an important distribution in the whole area as illustrated by figure 3, and by the diagram of figure 4. On the Tarascan Plateau the faults of this system appear associated with NW-SE ones, as illustrated by figure 4; they constitute the main element of the huge sector collapsed south of the MVB and belonging to the Sierra Madre del Sur Province.

Recent tensional lineaments have a limited areal extension, and are associated with the S. Luis Potosí - S. Felipe, S. Francisco del Rincón - Numaran and Querétaro grabens. Their trends vary from NE to NW, but they all show very similar morphostructural features. They are formed by not very wide but long straight grabens with walls formed by recent faults; the floor is flat with immature drainage patterns not in equilibrium with the adjacent ones.

Relation between the tensional structures of SMO and of MVB suggest the following structural evolution of the studied area since Oligocene to Recent Time (Fig. 5).

Phase 1

Tensional tectonics commences after the Laramide orogenic deformation of the SMO in an undetermined moment of Paleogene. The fracture trends of this phase are feeders of the lava-pyroclastic plateaus that cover most of the orogenic structures.

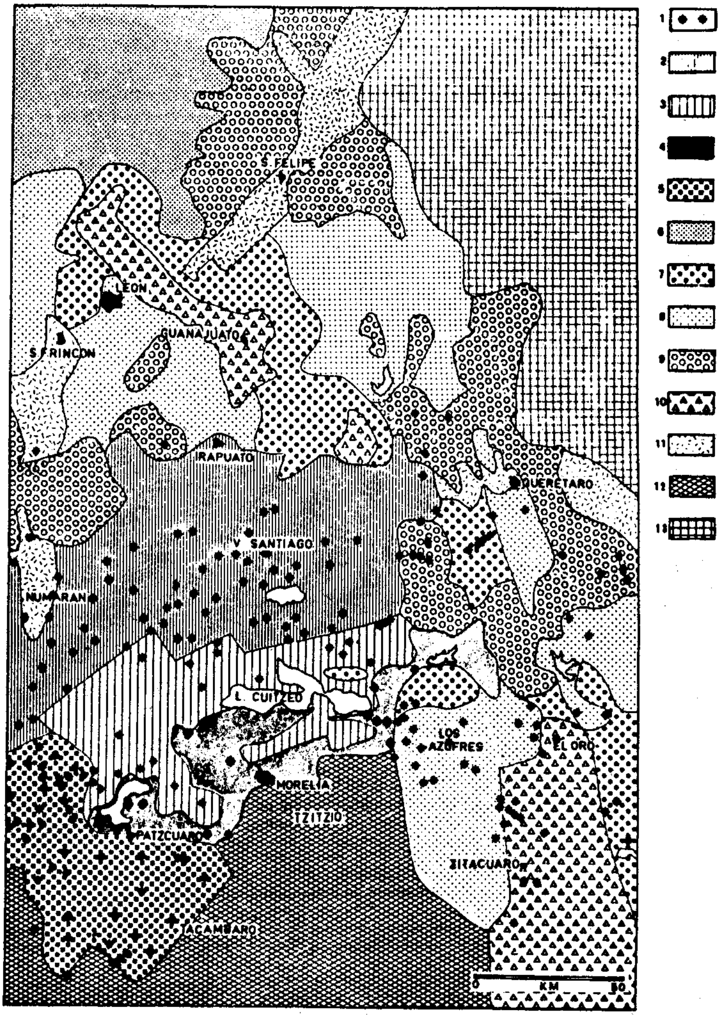

Fig. 4. Structural Map

Mexican Volcanic Belt Province
1 - Volcanic centres of Mexican Volcanic Belt
2 - Central depression
3 - Laguna de Cuitzeo depression
4 - Tilted blocks of Morelia area
5 - Tarascan plateau

Basin and Range Province
6 - Mexican central plateau
7 - Main horst
8 - Main grabens
9 - Intermediate plateau
10 - León-Guanajuato and El Oro-Zitácuaro ridges
11 - San Luis Potosí-San Felipe, Querétaro, San Francisco del Rincón, Numerous grabens (Basin and Range tectonic trends reactivated during Quaternary times).

Sierra Madre del Sur Province
12 - Southern collapsed plateau

Sierra Madre Oriental Province
13 - Mesozoic folded sediments partly covered by Tertiary volcanic plateaus.

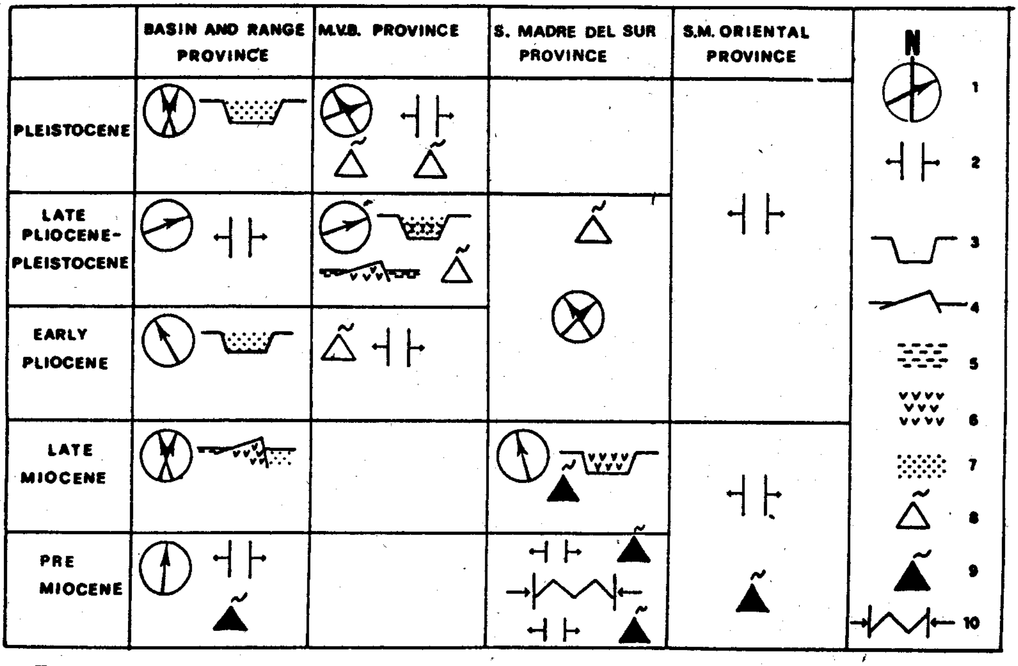

Fig. 5. Correlation between morphology, tectonics and volcanism from Oligocene to Recent.

1 - Main tectonic trends
2 - Tensional events unrelated to specific structures
3 - Grabens
4 - Faulted and tilted blocks
5 - Lacustrine infilling of tensional tectonic depression 3 and 4
6 - Volcanic and volcanoclastic infilling of depression 3 and 4
7 - Alluvial infilling of depression 3 and 4
8 - Mexican Volcanic Belt activity
10 - Compressive events

Phase 2

This important tensional phase takes place during Late Miocene and is responsible for the formation of depressions within the Tertiary lava-pyroclastic plateau of the SMO. The depressions become the seat of new volcanic activity and andesite and basalt products tend to fill them and eventually invert the relief.

The NNW-SSE trends of this phase are strongly iso-oriented conferring a faulted-block-like structure that can be considered as the southern extension of the "Basin and Range Province" of the U.S.A. (Pasquaré *et al.* 1987, this issue).

Phase 3

During this phase NW-SE trends are active; these are uniformly distributed over most of the area. The importance of this phase in relation to the birth and early development of volcanism in this area has yet to be understood, though it must have certainly been active in some early alignments transversal to the MVB, particularly on the Tarascan plateau (Pasquaré and Zanchi; in press). These trends developed since Pliocene together with the opening of the Gulf of California and with the early volcanic activity of MVB.

Phase 4

This phase is the one responsible for the complex system of blocks lowered stepwise toward the Central depression following WSW-ENE trends. The same trends control the development of lacustrine basins and paleobasins and the alignments of volcanic centres which are major expressions of the MVB activity of the area. Radiometric dating of rocks of several of these volcanic centres show Late Pliocene and Early Pleistocene ages (Pasquaré; unpublished data).

Phase 5

During this phase, grabens with trends varying from NE to NW develop, most of which are reactivation of those of phase 2. Volcanic activity related to these shows Late Pleistocene ages, as the lineaments of phreatic craters of Valle de Santiago.

CONCLUSIONS

The main morphological and structural lineaments of Central Mexico and especially those associated with the development of the MVB are present in the area considered in this paper.

Four of the five structural provinces described by Pasquaré *et al.* (this issue) that compose the MVB and its adjacent areas, were recognized. The most widespread lineaments are the mosaic of faulted blocks with NNW-SSE trends interpreted as a southern extension of the "Basin and Range Province", and the system of tilted and stepped lacustrine depressions that form the central province of the MVB.

The southern portion of the area is affected by huge regional collapses along prevalently NW and NE trends, that involve most of the folded structures of the SMO and its overlying volcanic plateau south of the MVB, which forms a collapsed sector of Sierra Madre del Sur. The NW faults are also distributed within other structural provinces and ought to be equivalent to those that define the Californian Province of the model described by Pasquaré *et al.* (this volume). The SMOr province dominates in the north-eastern sector with its folded structures only marginally affected by late tensional lineaments.

The relationship between the various morphological and structural lineaments allow the reconstruction of the main phases of tensional tectonics in the central area of the MVB. Five tensional phases were recognized in the interval between Oligocene and Late Pleistocene, to the first two between Oligocene and Late Miocene are related to the volcanic activity of the SMO, whereas the phase between Early Pliocene and Late Pleistocene is related to the volcanic activity of MVB.

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