Applications of Spectral Stratigraphy to Upper Cretaceous and Tertiary Rocks in Southern Mexico: Tertiary Graben Control on Volcanism

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Abstract

We used spectral stratigraphic techniques to interpret Landsat TM data covering northern Guerrero state in southern Mexico in order to map Upper Cretaceous and Tertiary rocks and to assess the interplay between volcanism and tectonism; results were confirmed in the field. Seven spectral stratigraphic units, each of which corresponds to a distinct lithostratigraphic unit, were delineated. Five consist of terrestrial Upper Cretaceous and Tertiary siliciclastic, volcanic, and volcaniclastic rocks; one contains Mesozoic marine rocks; and one corresponds to Quaternary alluvium. A previously undocumented NNW-trending Tertiary graben was identified in which 2,000 m of lower Tertiary volcanic rocks accumulated, suggesting volcanism coeval with graben subsidence during WSW-ENE regional extension in the early Tertiary. Overlap of the western-graben bounding fault by slightly younger lower Tertiary rocks suggests subsidence ended by the close of the early Tertiary. Continued volcanism within the graben during the late Tertiary indicates a long-lived volcanic source region within the subsurface of the NNW-trending structure and localization of younger magmatic activity within a pre-existing zone of crustal weakness.

Introduction

Spectral stratigraphic techniques (Lang *et al.*, 1987; Paylor *et al.*, 1989; Lang and Paylor, 1994) were applied to Landsat Thematic Mapper (TM) data covering a portion of northern Guerrero state in southern Mexico (Figure 1) in order to characterize remotely the distribution, areal extent, thickness, structural style, and contact relationships of Upper Cretaceous and Tertiary rocks and to assess the interplay between volcanism and tectonism. Our results include the delineation of five Upper Cretaceous to Tertiary lithostratigraphic units and the discovery of a previously undocumented NNW-trending graben, which controls the distribution and thickness of Tertiary volcanic and volcaniclastic rocks in northern Guerrero.

Most of southern Mexico is ideally suited for spectral stratigraphic analysis. Much of the stratigraphic and structural information required for regional tectonostratigraphic syntheses is lacking. Published geologic maps of central and southern Mexico are at scales of 1:250,000 or smaller and are not of sufficient detail to constrain most geologic problems. In addition, maps by different authors do not agree (SPP, 1985; de Cserna, 1981) and are, in some instances, inaccurate based on our mapping results and as discussed by Barros *et al.* (1989) and Cabral-Cano *et al.* (1993). Furthermore, Tertiary continental and volcanic strata are largely undifferentiated over much of southern Mexico.

The Pacific Coast of central and southern Mexico has been the locus of volcanism in response to subduction since late Mesozoic time (Engebretson *et al.*, 1985; Sedlock *et al.*, 1993). The relationship between volcanism and tectonism in the evolution of the continental borderland is poorly constrained, partly because southern and central Mexico lie near the juncture of five lithospheric plates: the Rivera, Pacific, and Cocos plates to the west; the North American plate to the north; and the Caribbean to the east (Figure 1). Plate interactions since the Mesozoic Era have led to complex displacements of rocks in southern Mexico. One example is the Chortis block of Honduras and Nicaragua for which an origin adjacent to southern Mexico and a subsequent history of both dextral and sinistral translation along the Mexican margin have been proposed (Sedlock *et al.*, 1993). Inherited zones of crustal weakness, therefore, may influence the formation of younger features. Indeed, the dominant physiographic province of the region, the Late Cenozoic Mexican Volcanic Belt (MVB), does not parallel the Middle America Trench, to which it is assumed to be "genetically related" according to Mooser (1972), Nixon (1982), and Verma (1985). Explanations favor the influence of upper Mesozoic and lower Tertiary structures on the orientation of the MVB (Urrutia-Fucugauchi, 1984; Urrutia-Fucugauchi and Bohnel, 1987; Johnson and Harrison, 1989).

Physiographic and Geologic Setting

The study site encompasses approximately 1,400 km^2 of the arid Tierra Caliente physiographic province between Mexico City and Acapulco (Figure 1). The terrain is rugged, and road access is limited. The towns of Nuevo Copaltepec and Ciudad Altamirano are in the extreme southeastern and southwestern corners of the area, respectively. The town of Arcelia is south of the southeastern corner of the study site (Figure 1). The southern edge of the MVB is approximately 50 km to the north. Strata in the study area are composed primarily of Upper Cretaceous and Tertiary siliciclastic and volcaniclastic, pyroclastic, and volcanic rocks equivalent to the informally named Balsas Group (Johnson, 1990; Jansma *et al.*, 1991). Strata are unconformable on older Mesozoic sedimentary rocks of the Morelos and Mal Paso formations exposed along the western boundary and are unconformable on, and faulted against, Mesozoic metamorphic rocks ex-

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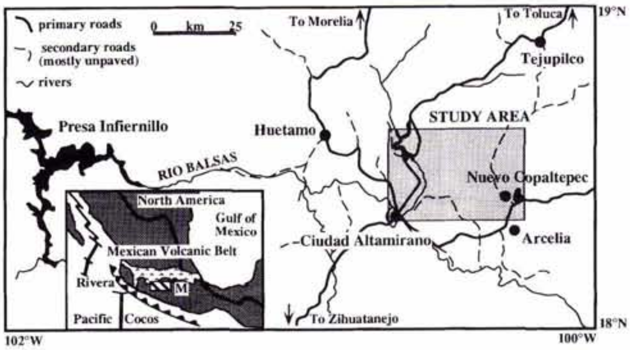

Figure 1. Map showing location of the study area. Area of the large map is shown as the diagonal hachured box in the inset map of Mexico. Within the inset map of Mexico, the Rivera, Pacific, Cocos and North American plates are identified. The Caribbean plate is off the map to the southeast. The approximate eastern limit of Laramide thrusting is shown by the heavy black line.

humed in the eastern part of the study area (Johnson, 1990; Johnson *et al.*, 1991a; Cabral-Cano *et al.*, 1993).

Northern Guerrero experienced a prolonged period of marine sedimentation in the mid Cretaceous, during which time the shallow-water carbonates of the Morelos (Albian-Cenomanian) and siliciclastics of the Mal Paso and Mexcala (Turonian-Coniacian) and equivalent formations accumulated (de Cserna *et al.*, 1978; Moran-Zenteno, 1984; Barros *et al.*, 1989; Johnson *et al.*, 1991; Sedlock *et al.*, 1993). An ENE-WSW-directed compressional event during the Late Cretaceous and early Tertiary, which is kinematically similar to the Laramide orogeny of western North America, is recognized in southern Mexico based on structural evidence (Carfantan, 1983; Ferrusquía-Villafranca, 1990; Johnson, 1990; Johnson *et al.*, 1991a; Johnson *et al.*, 1991b; Jansma *et al.*, 1991). The orogeny resulted in an abrupt end to marine conditions and produced a period of erosion prior to Tertiary volcanism and continental deposition recorded by the Balsas Group and younger volcanic units. A regionally extensive unconformity separates the metamorphic and marine sedimentary rocks from Tertiary continental and volcanic strata and may signify the end of Laramide folding and thrusting. Volcanism continued throughout Tertiary and Quaternary time and is active today in the MVB (Nelson and Livieres, 1986; Ferrari *et al.*, 1991; Pasquaré *et al.*, 1991).

The Tertiary strata of northern Guerrero were mapped previously as the Balsas Group, an informal stratigraphic unit composed of volcanic and sedimentary rocks of continental origin. The Balsas Group was originally named by Fries (1957) for a series of continental sedimentary rocks, in the states of Morelos and Guerrero, that are discordant on Upper Cretaceous marine strata and, in turn, are unconformably overlain by mid-Tertiary and younger volcanic rocks. Despite its widespread usage, the Balsas Group has not been defined formally (North American Commission on Stratigraphic Nomenclature, 1983). No type section for the Balsas exists. All red beds and volcaniclastic sequences in southern and central Mexico were assigned by early workers to the undifferentiated Balsas Group. Published thickness estimates for the Group vary from 1,000 m to 2,500 m (Edwards, 1955; Fries, 1960; Jansma *et al.*, 1991a). Common lithotypes are limestone conglomerate, volcaniclastic conglomerate, volcanic breccia, rhyolite, andesite, basalt, tuff, lacustrine limestone, gypsum, and organic-rich mudstone. Recent work shows that the Balsas Group is composed of three distinct sequences separated by two major unconformities (Jansma *et al.*, 1991; Johnson *et al.*, 1991). The oldest sequence contains tightly folded red siliciclastics as much as 2 km thick, termed the Galeana Member by Johnson (1990). The middle sequence consists of openly folded volcaniclastic sandstone and pyroclastic rocks. The youngest sequence is dominated by volcaniclastic sediments and welded tuff.

The age of the Balsas is generally assumed to be Late Cretaceous to Late Eocene (Fries, 1960; de Cserna and Fries, 1981; Sedlock *et al.*, 1993). Balsas equivalent rocks, however, are not dated in the study area. A K-Ar age of 42 ± 1 Ma is reported for basalt of the Balsas Group from an unknown locality (de Cserna and Fries, 1981). Additional K-Ar ages, ranging from 36 ± 2 Ma to 18 ± 1 Ma, are reported for volcanics near Morelia and Taxco (Pasquaré *et al.*, 1991), but the stratigraphic affinity of the rocks is not known. The abrupt change from marine to continental conditions at the end of the Cretaceous throughout Mexico, however, suggests that red beds mapped as Balsas are most likely latest Cretaceous to early Tertiary.

The upper Oligocene Tilzapotla Rhyolite, composed primarily of ignimbrite and breccia, unconformably overlies the Balsas Group and commences a sequence of upper Oligocene and Miocene volcanic rock. The Miocene volcanic sequence is composed of siliceous pyroclastic rock and andesitic to rhyodacitic lava. The upper Tertiary and Quaternary record of southern Mexico is dominated by calc-alkaline volcanics which erupted in the MVB (Pasquaré *et al.*, 1991).

Methods

Digital TM data were acquired on 25 January 1986 and were processed at the Jet Propulsion Laboratory and the University of Puerto Rico, Mayagüez, using standard interactive software packages. Procedures for processing TM data are described in Abrams *et al.* (1985), Conel *et al.* (1985), Lang *et al.* (1987), and Mazer *et al.* (1988). The techniques of spectral stratigraphy (Lang and Paylor, 1994) were applied to the Landsat TM data.

The image used in this study was a color composite which portrays TM bands 7 (2.08µm to 2.35µm), 3 (0.63µm to 0.69µm), and 4 (0.76µm to 0.90µm) as blue, green, and red, respectively (Plate 1). In this image, red beds are yellow and vegetation is red. The image scale of 1:50,000 was chosen to conform to the scale of topographic maps issued by the Instituto Nacional de Estadistica Geografia y Informatica of Mexico. The four topographic maps which cover the area are the Ciudad Altamirano, Arcelia, Palmar Chico, and Amatepec quadrangles.

Rocks in the area were divided into seven units based on spectral and morphological criteria. Layers within units were identified by image color. The minimum stratigraphic thickness, that could be resolved on the 1:50,000-scale image, was approximately 10 m in areas of shallowly dipping beds on shallow slopes that yield wide outcrop widths Three-point solutions were determined with the aid of the topographic maps in order to derive strikes and dips. Because the choice of points is critical and dips frequently are overestimated from those measured in the field (Lang *et al.*, 1987), the minimum dip configuration was used. Stratigraphic columns and cross sections were constructed from the geologic interpretation of the image to allow correlation, to estimate unit thicknesses, and to constrain structural styles. Depths to unit contacts in the subsurface were based on maximum unit thicknesses and the identification of marker horizons at the surface. Constant unit thickness was assumed in the creation of cross-sections, the estimation of displacements across faults, and the continuation of folds in the subsurface. This assumption may not be valid in areas

Plate 1. Landsat Thematic Mapper (TM) color composite image (Bands 7, 3, and 4 as blue, green, and red, respectively) of northern Guerrero between Ciudad Altamirano and Nuevo Copaltepec taken on 25 January 1986. The image is the same scale as the geologic map in Figure 2. The body of water in the lower right is the Presa Vicente Guerrero reservoir.

dominated by volcanic and volcaniclastic rocks, which typically exhibit rapid facies and thickness variations along strike. The assumption, however, allowed construction of cross-sections which were geologically reasonable.

Spectral stratigraphic units were initially classified purely by color, morphology, and texture. No age or lithologic information was included. Because direct determination of lithology is not possible from TM and topographic data alone, lithologic inferences about the units were based initially on correlation with previously interpreted spectral stratigraphic units to the south in the Mesa Los Caballos region where units were field-checked (see Jansma *et al.*, 1991). After delineation of the spectral stratigraphic units, interpretation of the geologic map, and construction of cross sections, relative age assignments were made. Nine days were spent in the field checking the image interpretation. All of this information provided data for our tectonostratigraphic interpretation.

Spectral Stratigraphic Units

We subdivided rocks in the area between Ciudad Altamirano and Nuevo Copaltepec in the state of Guerrero, Mexico into seven units based on spectral and morphological criteria (Plate 1 and Figure 2). These units were numbered in ascending stratigraphic order, and each is described, with the exception of Quaternary alluvium (Unit VII), as it appears on the TM image of Plate 1.

Unit I

Unit I is exposed in two locations in the study area, one near the western margin and another, more extensive region in the east. In the west, Unit I is restricted to a topographically high escarpment along the west central edge of the image (Plate 1 and Figure 2). There, it is characterized by alternating bands of gray and red, each of which may represent a separate lithostratigraphic unit. The overall texture is rounded. The southern terminus of a NNW-SSE-trending anticlinorium, which folds strata of Unit I, extends into the study area from the northwest where the structure was mapped by Johnson *et al.* (1991).

This same mapping unit occupies the rolling and dissected terrain of moderate relief in the eastern portion of the image. Rocks are characterized by a rough, mottled texture and blue, red, white, and green image colors. Faint, discontinuous banding can be resolved locally. Red (indicating substantial vegetation cover) dominates the topographic highs, whereas blue and green colors prevail at the lower (less vegetated) elevations.

Unit II

Unit II is exposed in a belt of NNW-trending, well-stratified outcrops in the western third of the image and in an arcuate band of outcrops in the southeastern corner (Plate 1 and Figure 2). The unit generally occupies regions of low topographic relief, which made calculation of strikes and dips difficult. Strata are characterized by smooth topography and light- to medium-green image color. Layers within the unit vary from white to light blue to brown to yellow. Individual strata can be traced for several hundred metres. A prominent west-dipping dissected hogback exists along the eastern edge of the area mapped as Unit II. Evidence for tight-folding in-

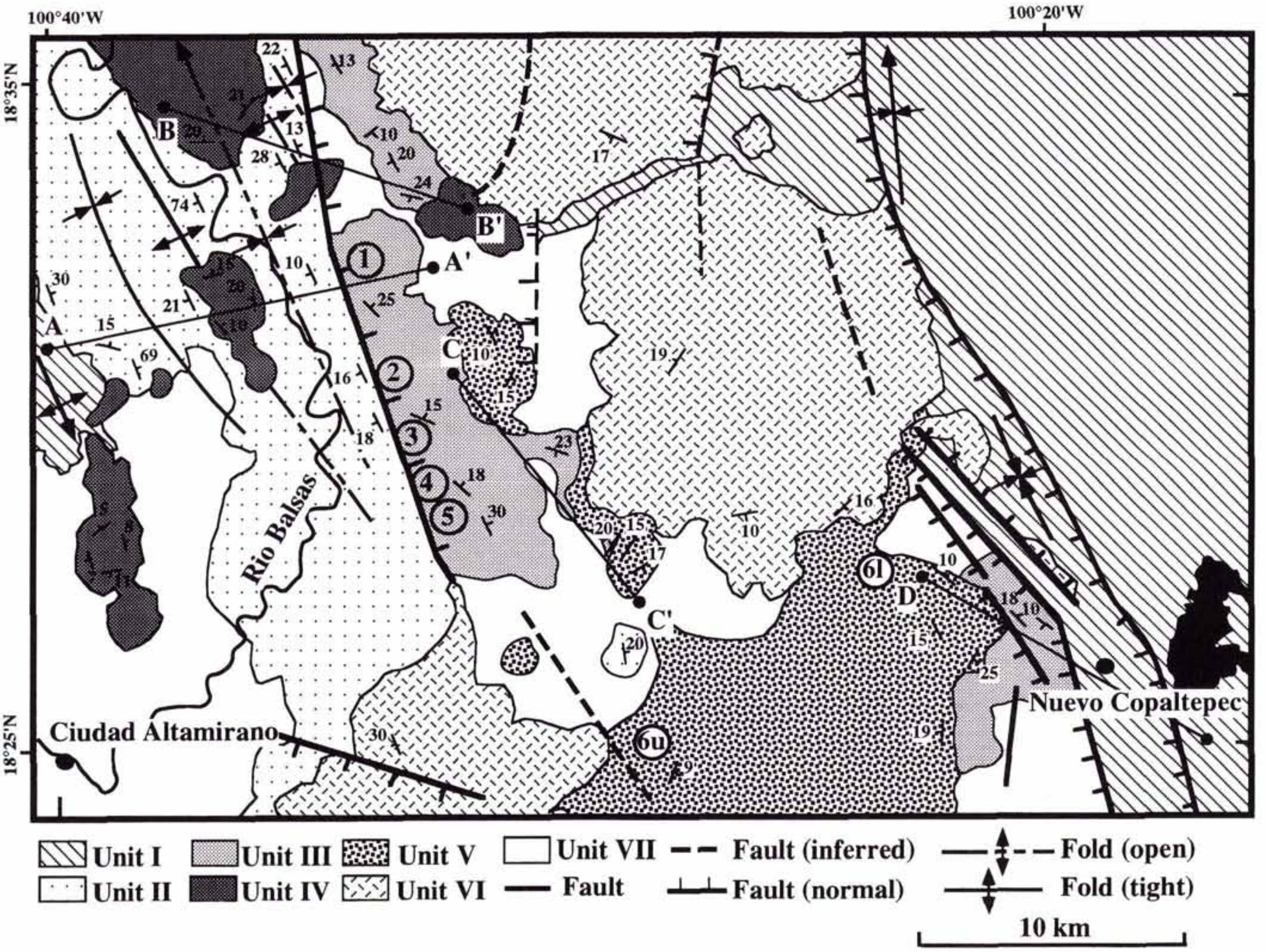

Figure 2. Geologic map interpreted from the Landsat Thematic Mapper image of Plate 1. Locations of the stratigraphic columns in Figures 3 and 4 are depicted by numbers. 6l and 6u correspond to the lower part and the upper part of column 6, respectively. Locations of cross-sections in Figure 5 are shown by heavy dark lines whose endpoints are dots.

cludes hinges of macroscopic isoclinal folds in the northwestern corner of the image and rapid changes in dip over short distances perpendicular to strike. Folds trend NNW and verge ENE.

Unit III

Unit III crops out extensively in a broad NNW-trending zone in the center of the image (Plate 1 and Figure 2). It is characterized by rough terrain, which commonly is deeply dissected, and a dark green to blue-green image color. Blue, white, red, green, brown, and yellow banding within the unit is relatively continuous over map distances of a kilometre or less, suggesting that lateral changes in facies and thickness are not substantial over short distances. More than 25 separate layers were identified (Figure 3). Two were used as marker horizons for correlation (Figure 3). The fact that these layers locally bifurcate or merge along strike suggests that minor unconformities exist in the unit. These unconformities also may produce the observed changes in both the strike and dip of layers on the order of 10 to 30 degrees. Unit thickness is approximately 2,000 m. The base of the unit is not exposed.

Unit IV

Unit IV forms a series of resistant outcrops with moderate topographic relief in the western northwestern part of the study area. It is characterized by gently dipping to horizontal red, white, brown, yellow, and black bands on the image (Plate 1 and Figure 2). Thickness is estimated to be 350 m. In the western portion of the image, these gently dipping layers are unconformable on the tightly folded strata of Unit II. Outcrops of Unit IV also occur above Unit III along the northern edge of the study area. The southern end of a NNW-trending synclinorium, which includes folds in Unit IV, is visible in the northwestern corner of the image (Plate 1 and Figure 2).

Unit V

Unit V occupies the southeastern portion of the study area (Plate 1 and Figure 2). Outcrops also occur in the center of the image. It is composed of smooth, well-stratified, low-lying hills and cliffs. Banding is primarily red, blue, brown, white, and yellow. Thicknesses of individual horizons generally decrease upsection from approximately 80 to 100 m at the base to 10 to 30 m near the top (Figure 4). The total unit

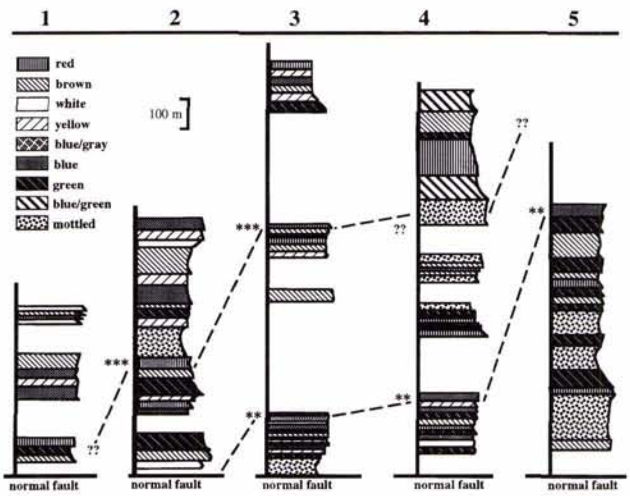

Figure 3. Stratigraphic columns for Unit III (see Figure 2 for locations). Layers with asterisks correspond to two marker horizons. Note the decreasing distance between the horizon denoted by two asterisks and the bottom of the unit as defined by the normal fault from south to north.

thickness is approximately 1,200 m. Horizons commonly bifurcate or merge along strike. The number of horizons between two layers, correlated at two different locations, therefore, can differ substantially. It is unknown if these changes along strike record faults at low angles to bedding; facies that pinch out; minor unconformities within the section; or variations in the detectability of horizons along strike caused by variations of illumination aspect or some other factor. Color and thickness changes upsection are gradual.

Unit VI

Unit VI dominates the topographically highest region in the center of the image (Plate 1 and Figure 2). Several circular to elliptical outcrops also occur in the southeastern quadrant of the study area. The unit is rough and has a mottled image texture. Few individual horizons were recognized; those that were detected were discontinuous along strike. The image color is primarily yellow and red, indicating the unit is vegetated. Some black-and-white banding can be resolved locally within the unit.

Discussion

Ages and Lithologies of Spectral Stratigraphic Units

Cross-sections derived from the interpreted geologic map and correlations of units with known lithostratigraphic units to the south (Jansma *et al.*, 1991), west (Johnson *et al.*, 1991a; Johnson *et al.*, 1991b), and east (Cabral-Cano *et al.*, 1993) establish the relative ages of the six spectral stratigraphic units (Unit VII, alluvium, was excluded from this analysis) (Figure 5). Relations among spectral stratigraphic units, which were well constrained by the multispectral data and confirmed in the field, include (1) superposition of Unit II above Unit I in the western portion of the image (Figure 5a); (2) juxtaposition of Unit IV above Unit II and above Unit III in the northwestern quadrant of the image (Figures 5a and 5b); (3) emplacement of Unit V above Unit III in the center of the image (Figure 5c); and (4) overlap of Units III and V by unit VI in the center of the image (Figure 2). The following age relations, therefore, must be true. Unit II is younger than Unit I and is older than Unit IV. Units IV and V are younger than Unit III. Unit VI is younger than Units III and V. The age of Unit I is ambiguous. The western boundary of Unit I in the eastern portion of the image is a NNW-trending normal fault, which extends through most of the eastern part of the image. The relative ages of Units II and III and Units IV and V also are not clear. Units IV and V are nowhere in contact. Units II and III are juxtaposed along a major normal fault. Similarity in structural styles of Units III and IV, in which broad folds are common, however, dictates that Unit III is younger than Unit II, in which tight folds are typical.

Evidence for the normal fault between Units II and III comes from an east-west cross-section through the center of

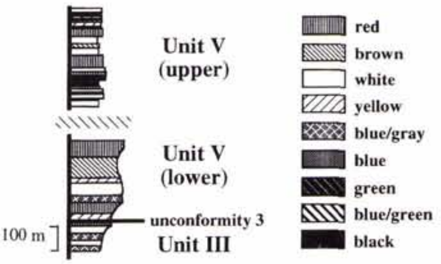

Figure 4. Composite stratigraphic column for Unit V from the lower center (Unit V-upper part) and lower right (Unit V-lower part) of Figure 2. The basal layer of the upper part is above the highest layer of the lower part, but the separation between them is unknown.

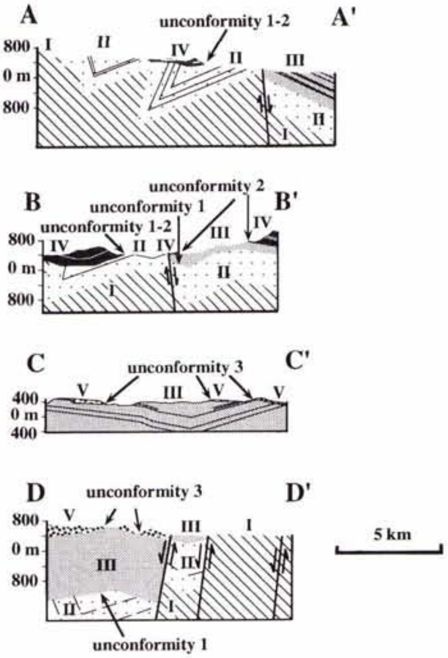

Figure 5. Cross-sections constructed from Figure 2. Constant unit thickness was assumed.

the image (Figure 5a). Basal strata of Unit II, exposed along its western outcrop margin, are exposed also near the contact between Unit II and Unit III. Lack of tight folding in Unit III, however, makes it improbable that it was subjected to the same deformational episode that affected Unit II and, more likely, Unit III had not yet accumulated. The simplest interpretation is that Unit III is younger than Unit II and the contact, which is extremely linear and continuous, is a steep, east-dipping normal fault. Field examination confirmed the existence of this fault, and revealed that the prominent hogback in Unit II, west of the fault, corresponds to a limestone conglomerate marker bed in the Balsas identified by Johnson *et al.* (1991a).

The geologic ages of the mapped units can be extrapolated from their stratigraphic positions relative to Unit I. Field-checking along the western perimeter of the study area revealed that Unit I corresponds to outcrops of the Upper Cretaceous Morelos and Mal Paso Formations (Johnson *et al.*, 1991a; Johnson *et al.*, 1991b). In the eastern study area Unit I corresponds to Cretaceous and older greenschist and low grade metasedimentary and metavolcanic rocks assigned to the Roca Verde Taxco Viejo, the Pochote beds, and a phyllite unit by Cabral-Cano *et al.* (1993). Units II through VI, therefore, can be constrained as Late Cretaceous or younger. Additional support for the Late Cretaceous to Tertiary age assignment of Units II through VI comes from southward continuation of Unit V into the Mesa Los Caballos region. There, two rhyolite horizons in Unit V were tentatively correlated with the Oligocene Tilzapotla Rhyolite near Taxco (Jansma *et al.*, 1991).

Because Unit II is at the base of the sequence that unconformably overlies the Cretaceous Mal Paso Formation, it must be late Cretaceous or younger. A late Cretaceous to early Tertiary age is most consistent with the tight ENE-verging macroscopic folding characteristic of the unit. The style and kinematics of the folding are similar to those of late Cretaceous to early Tertiary structures affecting mid Cretaceous marine strata approximately 50 km east (Barros *et al.*, 1989; Cabral-Cano *et al.*, 1993), presumed to have formed in response to ENE-WSW shortening during the Laramide Orogeny. Strata of Unit II, therefore, must be older than, or coeval with, the regional Laramide deformational event. Unconformable contact of this unit with the late Cretaceous Mal Paso Formation, however, precludes an age assignment that is older than late Cretaceous.

The absence of tight folds in Unit III suggests it accumulated after the late Cretaceous to early Tertiary deformational event. The minimum age of Unit III is constrained by deposition of Unit V, which is Oligocene. A lower Tertiary age, therefore, is assigned to Unit III.

Four unconformities are apparent in the upper Cretaceous and Tertiary section of northern Guerrero. The stratigraphically lowest unconformity is between Units II and III (unconformity 1 in Figure 5) and is not exposed in the study area. This unconformity may be partly equivalent to the major unconformity of early Tertiary age (unconformity 2 in Figure 5) recognized below Unit IV in the western half of the study area where it overlies both Units II and III. Angular discordance across the unconformities varies from less than 5° to nearly 90° because of folding in Unit II (Figures 5a and 5b). The age of the unconformity is derived from superposition of Unit IV above lower Tertiary rocks of Unit III. Rocks of Unit IV, therefore, must be latest early Tertiary or younger. The stratigraphic position of Unit IV below Unit V, however, constrains the age as latest early Tertiary. Unconformities also occur below Units V and VI (unconformities 3 and 4, respectively, in Figure 5). The angular discordance across this boundary is generally less than 30° (Figures 5 a-c).

The lithologies of Units II and V were constrained by previously reported field checking (Johnson, 1990; Johnson *et al.*, 1991a; Jansma *et al.*, 1991) and our own field observations. Unit II is composed primarily of coarse-grained siliciclastic strata, whereas Unit V is dominated by silicic volcanic and fine-grained volcaniclastic rock. The lithologies of the remaining three Upper Cretaceous and Tertiary units were inferred from their spectral and morphological characteristics and from correlation with units to the south that were described by Jansma *et al.* (1991), as well as from field examination.

Unit III contains at least 25 distinct and continuous horizons in its western exposures, which are distinguished based on image color (Figure 3). The mixture of colors and uniformity of layer thicknesses suggest that the unit is composed of a variety of lithotypes, which do not change rapidly along strike. The occurrence of yellow bands dictates the presence of red beds. Lithotypes include terrigenous sedimentary, volcaniclastic, and volcanic rocks. Correlation with strata to the south confirms this interpretation (Jansma *et al.*, 1991). Rocks of Unit III are primarily rhyolitic ignimbrites, tuffs, and andesitic breccias. Volcaniclastic sandstone, mudstone, and conglomeratic red beds form a minor part of the section.

Outcrop patterns of Unit IV suggest that it is composed of volcanic and volcaniclastic rocks, which locally are associated with plugs in the shallow subsurface. As discussed for Unit III, yellow banding indicates that these volcanic rocks also accumulated subaerially. In the northern portion of the study area, circular to elliptical exposures occur in which layers dip radially away from a central topographic high (Plate 1 and Figure 2), consistent with the interpretation that a buried intrusion lies close to the surface. Additional evidence to support a volcanic origin are resistant black bands within the unit. The black layers most likely are mafic volcanic rocks. Organic-rich mudstone or lacustrine sedimentary strata also may appear black on a TM color infrared image, but these rocks generally do not form resistant outcrops because they erode easily.

Unit VI consists of shallow intrusions and associated volcanic and volcaniclastic rocks, which accumulated subaerially as indicated by the overall yellow image color. The volcanics may have originated from the intrusions and subsequently flowed along their margins. Evidence for forceful intrusion includes the abundant circular and elliptical outcrops and the domes cored by Unit VI exposures, and the radial patterns of dips in strata surrounding Unit VI outcrops in the southern part of the study area. Black banding also occurs locally, lending further credence to a volcanic origin for the unit. The extensive outcrop, dominating the center of the image, consists of a massive pile, approximately 3,000 m thick, of pyroclastic material which blankets and obscures any parental intrusion. Correlation with units to the south and field examination confirm the inferences made from the TM data. Rocks are primarily rhyolitic plugs, tuffs, and ignimbrites.

Correlation of Spectral Stratigraphic Units with Lithostratigraphic Units

Compositional and age information allows the identification of five Upper Cretaceous and Tertiary lithostratigraphic units from the seven spectral stratigraphic units that we identified in northern Guerrero. These are (1) Unit II: Upper Cretaceous to lower Tertiary siliciclastic strata (uK?lT_1); (2) Unit III: lower Tertiary volcanic rocks (lT_1); (3) Unit IV: lower Tertiary plugs and related pyroclastic rocks and flows (lT_2); (4) Unit V: upper Tertiary distal pyroclastic rocks and flows (uT_1); and (5) Unit VI: upper Tertiary plugs and related rocks (uT_2).

The strata of uK?lT_1 include the Galeana Member of the basal Balsas Formation. The Galeana Member is composed of tightly folded siliciclastic strata and red beds. Thickness estimates for the Galeana Member in the San Lucas region, adjacent to the western edge of the study area, were on the order of 2,000 m (Johnson, 1990; Johnson *et al.*, 1991a). The total thickness of these beds in the study area is approximately 1,200 m. The unconformity above uK?lT_1 most likely correlates with the older of the two major discordances previously recognized in the Balsas Formation (Johnson *et al.*, 1991). The volcanic rocks and minor red beds of lT_1 and lT_2, therefore, constitute the bulk of the Balsas Formation in the area between Arcelia and Ciudad Altamirano. The combined thickness of the two units, according to our results, is 2,400 m, which is compatible with values of 1,000 to 2,500 m determined by earlier workers (Edwards, 1955; Fries, 1960; Jansma *et al.*, 1991). Results confirm a stratigraphic position for uT_1 above probable Balsas equivalent rocks (uK?lT_1, lT_1, and lT_2). The base of uT_1, most likely corresponds to the Oligocene Tilzapotla Rhyolite.

Tertiary Graben Control on the Distribution of Spectral Stratigraphic Units

Cross-sections based on the TM interpretation reveal a previously unidentified, NNW-trending Tertiary graben (Figure 5), here named the Arcelia graben. Truncating tight folds of uK?lT_1 (Unit II) is a steep, east-dipping normal fault which defines the western limit of the graben. Throw on this normal fault is estimated at 3,500 m based on the juxtaposition of the basal beds of uK?lT_1 (Unit II) against the upper part of lT_1 (Unit III) (Figure 5a). In contrast to the western edge, which is controlled by a single fault, the eastern graben boundary is delimited by a complex zone of steep, west-dipping faults (Plate 1 and Figures 2 and 5d). The collective displacement across the zone is on the order of 5,000 m. This value, however, is not well constrained because of difficulties in estimating the stratigraphic position of Mesozoic metamorphic rocks east of the fault zone and in uncertainties in the geologic interpretation of the TM data in the southeastern quadrant of the image. We have not ruled out the possibility of a strike-slip component on faults bounding the Arcelia graben, but we have no data to estimate such displacements. The width of the graben is approximately 20 km. The length is a minimum of 45 km; the graben extends beyond the boundaries of the study area. The western-bounding fault of the graben cuts ENE-verging uK?lT_1 (Unit II) folds and is, in turn, overlapped by lT_2 (Unit III) strata (Figure 5). Subsidence of the structure, therefore, is constrained as early Tertiary.

The distribution and thickness of Tertiary spectral stratigraphic units is controlled by the graben. Outcrops of lT_1 (Unit III), uT_1 (Unit V), and uT_2 (Unit VI) are restricted to the NNW-trending structure (Figure 5). (We assume that uK?lT_1 occurs below lT_1.) West of the graben, lT_1 (Unit III), uT_1 (Unit V), and uT_2 (Unit VI) are absent and lT_2 (Unit IV) directly overlies uK?lT_1 (Unit II) (Figure 5). Approximately 2,000 m of the lower Tertiary section (lT_1) and 4,000 m of the upper Tertiary section (uT_1 and uT_2), therefore, are missing in the western portion of the study area.

The question arises whether or not accumulation of the 2,000 m of lT_1 was restricted to the graben. Alternatively, lT_1 may have covered the region prior to graben formation and subsequently been selectively removed from topographically elevated areas after graben subsidence. The latter explanation, however, implies accumulation and later erosion of more than 2,000 m of lT_1 within the short time span between Paleogene deformation of uK?lT_1 and early Tertiary volcanism recorded by lT_2. Furthermore, the base of lT_1 maintains the same elevation across the western-bounding fault of the graben, requiring graben subsidence to be completed prior to accumulation of lT_2. We therefore favor restriction of lT_1 to the graben, which suggests that graben subsidence and lT_1 accumulation occurred during early Tertiary time. Localization of late Tertiary volcanism within the graben suggests a relatively long-lived volcanic source region within the subsurface of the NNW-trending graben. Thus, late Tertiary volcanism in northern Guerrero may have been controlled by an inherited zone of crustal weakness, similar to the Mexican Volcanic Belt (MVB) to the north (Urrutia-Fucugauchi, 1984; Urrutia-Fucugauchi and Bohnel, 1987; Johnson and Harrison, 1989) and the Colima graben to the west (Luhr *et al.*, 1985; Bandy *et al.*, 1993). Unlike the MVB, the pre-existing structure is early Tertiary and not Mesozoic in age. We cannot, however, exclude the possibility that formation of the Tertiary graben was controlled by a Mesozoic structure.

The distribution of spectral stratigraphic units and the formation of the graben suggest the following sequence of events. Siliciclastic strata of uK?lT_1, deposited on the western continental margin of Mexico, were deformed in the late early Tertiary in response to WSW-ENE shortening during the locally waning phases of the Laramide (or a temporally and kinematically equivalent) orogeny. In early late Tertiary time, WSW-ENE regional extension led to the formation of the NNW-trending Arcelia graben. This requires a change in the overall stress regime of 90° during the early Tertiary. Volcanism within the graben, presumably coeval with subsidence, produced the 2,000 m thick lT_1 flows. Plugs and related rocks of lT_2 intruded and overlapped uK?lT_1 after graben subsidence waned in the early Tertiary. Continuing volcanism within the Arcelia graben during latest Tertiary time resulted in accumulation of approximately 4,000 m of uT_1 and uT_2, which accounts for its presently high topographic expression.

Conclusions

Spectral stratigraphic techniques using TM and topographic data were applied to geologic mapping in northern Guerrero state, southern Mexico. Five Upper Cretaceous and Tertiary spectral stratigraphic units, each corresponding to a distinct lithostratigraphic unit, were delineated, allowing the distribution, areal extent, thickness, contact relationships, and structure of Upper Cretaceous and Tertiary volcanic and volcaniclastic rocks to be characterized remotely. Results were checked and refined in the field using standard geological mapping methods.

We found that volcanism during the Tertiary was largely controlled by extensional tectonism within the previously undocumented NNW-trending Tertiary Arcelia graben, whose dimensions are approximately 20 km by 45 km. A 2,000-m thick sequence of lower Tertiary volcanic rocks is restricted to the graben, suggesting volcanism coeval with graben subsidence during early Tertiary WSW-ENE extension. Overlap of graben bounding faults by lower Tertiary rocks constrains subsidence to the early Tertiary. Localization of late Tertiary volcanism within the graben indicates a long-lived volcanic source region within the subsurface of the NNW-trending structure. Thus, late Tertiary volcanism in northern Guerrero may be controlled by an inherited zone of crustal weakness, similar to that postulated for the Quaternary Mexican Volcanic Belt to the north and the Colima graben to the west.

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