Crustal structure of the Arteaga Complex, Michoacán, southern Mexico, from gravity and magnetics

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RESUMEN

La región de Arteaga, Michoacán, sur de México, es una de las pocas áreas con afloramientos del basamento en el terreno Guerrero. El subterreno Zihuatanejo está caracterizado por secuencias volcanosedimentarias de arco de islas de edad Jurásico Tardío-Cretácico Temprano que yacen discordantemente sobre las rocas metamorfizadas del Complejo Arteaga de posible edad Triásico-Jurásico. Las mediciones de gravedad de Bouguer y campo total magnético fueron realizadas a lo largo de dos perfiles SW-NE cruzando los complejos ígneo y metamórfico. El análisis espectral es usado para estimar las profundidades de Moho y de las principales interfaces corticales. El espesor de la corteza se incrementa hacia el N y NE a medida que nos alejamos del margen continental, siendo del orden de 28-32 km. El complejo metamórfico tiene un espesor promedio de 15 km. En el sector norte cerca de Tumbiscatio de Ruiz, las unidades metamórficas más superficiales presentan un contraste bajo de densidad posiblemente debido a una alteración regional. El batolito granítico y granodiorítico tiene un espesor superior a los 8 km en el sector SE. Los modelos gravimétricos son consistentes con un basamento del subterreno Zihuatanejo, constituido por el Complejo Arteaga.

Palabras Clave: Gravedad, estructura cortical, terreno Guerrero, occidente de México, Complejo Arteaga.

ABSTRACT

The Arteaga region, Michoac‡n, southern Mexico is one of the few areas with basement outcrops in the Guerrero terrane. The Zihuatanejo subterrane is characterized by Late Jurassic-Early Cretaceous island-arc volcanosedimentary sequences that rest unconformably on metamorphosed rocks of the Arteaga Complex, of possible Triassic-Jurassic age. Gravity and total field magnetic measurements were taken along two SW-NE profiles across the metamorphic and igneous complex. Spectral analysis is used to estimate depths to the Moho and major crustal interfaces. The crustal thickness increases to the N and NE away from the margin and is in the order of 28-32 km. The metamorphic complex has an average thickness of 15 km. In the southern sector near Arteaga, the uppermost metamorphic units present a lower density contrast possibly due to regional alteration. The granitic and granodioritic batholith has a thickness of up to 8 km in the SE sector. The gravity and magnetic models are consistent with proposals that the Arteaga Complex constitutes the basement of the Zihuatanejo subterrane.

Key words: Gravity, crustal structure, Guerrero terrane, western Mexico, Arteaga Complex.

INTRODUCTION

Information on the structure and characteristics of the crust beneath central and southern Mexico is needed to constrain models of pre-drift Gulf of Mexico-Caribbean continental assembly, extent and distribution of Precambrian and Paleozoic units, major lithospheric and crustal discontinuities, terrane boundaries, regional uplift, margin truncation, and structural control for arc magmatism. Because of the rarity of outcrops of the crystalline basement, earlier studies have concentrated on metamorphic terranes, isolated outcrops and xenolith-bearing localities. Regional geophysical data and oil exploration wells constitute another source of information. Proterozoic or lower Paleozoic basement has not been documented in western and central Mexico or in Baja California **(Sedlock et al., 1993)**. Most of western Mexico has been interpreted as a collage of island arcs built on oceanic lithosphere (Campa and Coney, 1983; Centeno-Garc'a et al., 1993), accreted during the Laramide orogeny (Campa and Coney, 1983). Isolated outcrops of metamorphic units **(e.g., de Cserna, 1982; Campa and Coney, 1983; Barba-López et al., 1988; Elias-Herrera and Sánchez-Zavala, 1992)**, granulitic xenoliths with Precambrian Nd model ages **(e.g., Uribe-Cifuentes and Urrutia-Fucugauchi, 1995)** and thick crust **(Molina-Garza and Urrutia-Fucugauchi, 1993)** all suggest that a lower crust of continental affinity underlies parts of western and central Mexico **(Barba-López et al., 1988; Elias-Herrera and Sánchez-Zavala, 1992; Urrutia-Fucugauchi and Molina-Garza, 1992; Monod et al., 1994; García-Pérez, 1995)**.

In this paper we report results of a gravity and magnetic study of the Arteaga Complex (Figure 1). The study was designed to investigate the crustal structure and possible major discontinuities associated with subterrane boundaries. The Arteaga Complex has been considered as an outcrop of the basement beneath a large area of western Mexico **(e.g., Barba-López et al., 1988; Centeno-García et al., 1993)**. Thus, we propose to study the depth, geometry and extension of the Arteaga Complex.

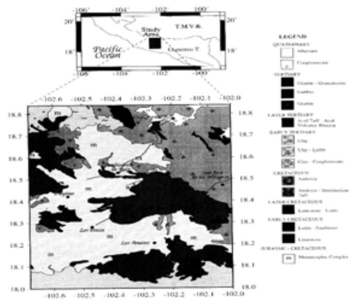

Fig. 1. (a) Simplified geologic map with the location of the study area within the Guerrero terrane. Gravity and magnetic measurements were made along two SW-NE transects along (1) Playitas-Cupuan del Río and (2) Los Pozos-San José de los Milagros.

GEOLOGIC SETTING

Campa and Coney (1983) describe most of western Mexico as part of a single large terrane, called the Guerrero terrane (Figure 1). They proposed that most of the terrane is characterized by island arc assemblages built over an oceanic basement and accreted to the North American plate during the Laramide orogeny. They also recognized its composite nature and described three subterranes south of the Trans-Mexican Volcanic Belt (TMVB) containing the following Upper Jurassic (?) to Middle Cretaceous metasedimentary and meta-volcanic magmatic arc sequences: Teloloapan-Ixtapan, Zihuatanejo, and Huetamo. Basement outcrops are relatively scarce. Large parts of the terrane are covered by Cenozoic volcanic rocks of the Sierra Madre Occidental (SMOc) and the TMVB. The more important basement outcrops are in the Tierra Caliente Complex south of Tejupilco, and between Teloloapan and Arcelia. Major metamorphic units include the Taxco schist, the Ayatusco, Ixcuinatoyac and Chapolapa Formations, the Taxco Viejo greenstone, the Arteaga Complex, the core of the Tzitzio anticline, and metamorphic rocks in southwestern Guerrero state **(de Cserna, 1982; Sedlock et al., 1993)**. Basement units may contain Early Paleozoic (?) or Early Mesozoic (?) protoliths, and the metamorphic ages range from middle Paleozoic to Jurassic, although older radiometric dates have also been reported (Sedlock et al., 1993). The Tierra Caliente Complex consists of a metamorphosed volcano-sedimentary sequence in the prehnite-pumpellyite-greenschist and lower amphibolite facies.

In the Arteaga region one of the most complete stratigraphic columns of the Guerrero terrane is exposed, including the proposed island arc sequence, the batholiths and the metamorphic basement. The Arteaga Complex, of possible Triassic-Jurassic age, is an assemblage of black shales, quartzitic sandstones and black cherts **(Centeno-García, 1994)**. Blocks of basaltic pillow lavas, light green cherts, limestones, tuffaceous sandstones and foliated diorites are found within the metamorphics. The Varales Formation is the most extensively exposed unit of the Arteaga Complex: it is composed mainly by terrigenous sedimentary rocks. The other lithological units of the Complex are: the Charapo Formation, composed of basaltic pillow lavas, massive basalts and diabases; the Jaltomate Formation with metamorphosed thin-bedded green graywackes and thin carbonate layers; and the Las Juntas metadiorite **(Centeno-García, 1994)**. According to Centeno-García (1994), the Cretaceous island arc assemblage rests in angular unconformity over the metamorphics of the Arteaga Complex. This assemblage is formed by the Agua de los Indios, Barranca, Resumidero, and Playitas Formations **(Centeno-García, 1994)**. The basal unit is a conglomerate containing fragments from the Varales Formation. The Agua de los Indios Formation is formed by interbedded shales, thin-bedded calcareous shales, volcanic and arkosic sandstones, tuffs with limestone nodules and thick beds of sandstones and tuffs. Andesitic lavas, tuffs and volcanoclastics form the Barranca Formation. The Resumidero Formation is formed by a variable thickness carbonate sequence of Albian-Cenomanian age. Conglomerates, sandstones, shales and limestones form the Playitas Formation **(Centeno-García, 1994)**.

GRAVITY AND MAGNETIC DATA

Gravity and magnetic observations were made along two SW-NE profiles across the Arteaga Complex (Figure 1). We used a LaCoste and Romberg G-247 gravimeter and a Scintrex 826 proton magnetometer (Figure 2c). Bouguer gravity was calculated using the international gravity formula and a density of 2.67 g/cm3 (Figure 2b). Profile 1 in the north is about 65 km long, between the villages of Playitas and Cupuan del R'o, through Tumbiscatio de Ruiz. Profile 2 in the south is about 95 km long, between Los Pozos and San José de los Milagros, through Arteaga. The topography is relatively steep, especially for the northern profile (Figure 2a). The elevation changes from 490 m asl in the south up to 1510 m asl in the northern sector. Both profiles cross exposures of the Arteaga Complex. The southern profile (2) runs across granitic-granodioritic outcrops of a large batholith and a Cretaceous andesitic sequence affected by low grade metamorphism. Exposures of Tertiary gabbros occur in the Las Cruces area.

The regional pattern of Bouguer gravity anomalies is roughly parallel to the coastline, suggesting a thickening crust inland **(Molina-Garza and Urrutia-Fucugauchi, 1993; De la Fuente et al., 1995; Urrutia-Fucugauchi and Flores-Ruiz, 1996)**. The available gravity maps lack sufficient resolution to map the Moho topography across and along the continental margin. To the west of the Arteaga region the aeromagnetic anomaly pattern shows regional changes that delineate the Jalisco block, which is characterized by numerous intrusive bodies of batholithic dimensions **(Rosas-Elguera et al., 1996)**. The eastern boundary of the Jalisco block is the Colima graben, which has been interpreted as an active rift **(Luhr et al., 1985)**, related to subduction of the Rivera-Cocos plate boundary **(Bandy et al., 1995)**. The gravity anomalies along an E-W transect just north of the Colima volcanic complex feature a broad anomaly which is wider than the Colima graben. The regional gravity field in the Arteaga region is attributed mainly to crustal thickness increase to the N and NE away from the margin, in the order of 28-32 km. It may also be due to variations of depth to the interface lower crust Arteaga Complex (Figures 5 and 7).

SPECTRAL ANALYSIS

We have used spectral analysis to investigate the frequency content of the gravity and magnetic anomalies and to estimate statistical depths to the top of the bodies. This method was first used in aeromagnetics **(Spector and Grant, 1970)** and was later extended to gravity **(e.g., Regan and Hinze, 1976; Pal et al., 1979)**. This method requires no a priori assumptions about the geometry and density contrasts of the bodies. A method developed by Bhattacharyya and Leu (1975, 1977) was used. The depth to the top of an ensemble of source bodies is related to the logarithmic slope of the spectrum. Plots of the smoothed amplitude spectrum as a function of the logarithm of the wave number are used to determine the depths. Uncertainties in depth estimates may arise from aliasing errors due to digitization and truncation, data spacing and window size, errors in the least-squares fit to the logarithm of spectrum, and choice of wavebands used for the linear fits **(e.g., Bath, 1974; Regan and Hinze, 1976)**.

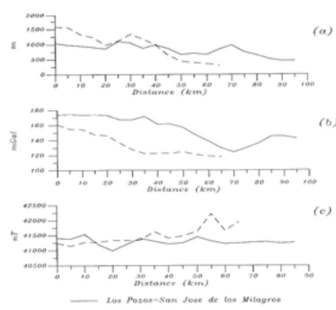

Fig. 2. (a) Topography, (b) Bouguer anomalies, and (c) Total field magnetic anomalies for the two profiles.

The spectral results of the gravity and magnetic data for the northern profile are summarized in Figure 3a,b, and in Figure 4a,b for the southern profile. In the northern profile the spectral depths are 4.7 and 1.2 km from the gravity data and 5.4 and 0.9 km from the magnetic data. In the southern profile the gravity and magnetic spectral depths are 8.0, 1.7 km and 8.4 and 2.1 km, respectively. For the low frequency segments the gravity data yields estimates of 29.1 km and 28.2 km for the southern and northern profiles, respectively. These values exceed the recommended maximum depths for the length of the profiles (Cianciara and Marcak, 1976; Urrutia-Fucugauchi and Flores-Ruiz, 1996). However, our results agree with earlier estimates of the Moho (27-30 km) derived from seismic and regional gravity studies (Urrutia-Fucugauchi and Molina-Garza, 1992; Bandy et al., 1993, 1995; Urrutia-Fucugauchi and Flores-Ruiz, 1996). There is a rough agreement between the depth estimates from the gravity and magnetic data, for depths of around 5 and 1 km in the northern profile and around 8 and 2 km in the southern profile.

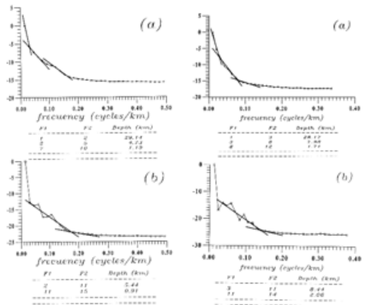

Fig. 3. Logarithmic plots of power spectra as a function of frequency for the northern transect (Playitas-Cupuan del R'o). The statistical depth estimates for the interfaces are summarized in the tables below the diagrams. F1 and F2, initial and end data points for the depth estimates. (a) Gravity data. (b) Magnetic data.

CRUSTAL MODELS AND INTERPRETATION

The depth estimates from spectral analyses and from seismic studies were used to construct crustal models for the two profiles, using the Talwani algorithms for gravity and magnetic data (Talwani et al., 1959; Talwani and Heirtzler, 1964; Talwani, 1965). Initial estimates of density contrasts were derived from gravity studies in the Colima graben west of Arteaga (Bandy et al., 1993, 1995). Further information on density contrasts was obtained from crustal models of the Tierra Caliente Complex in the region between Altamirano and Iguala (GarcÍa-PÉrez, 1995). Seismic wave velocities were converted into densities according to Grant and West (1965). The density contrast between the lower crust and the upper mantle is assumed to be 0.4 g/cc. The regional magnetic anomalies are assumed to be mainly due to induced components. The magnetic susceptibility contrasts were adopted from the work of Alva-Valdivia et al. (1991) for the Jalisco-Michoacán continental margin. These initial estimates of density and susceptibility contrasts were subsequently modified to construct gravity and magnetic crustal models with a consistent geometry. The geometry of the shallow bodies at the surface were constrained from the geologic maps of INEGI (1985) and Centeno-García et al. (1993) (Figure 1).

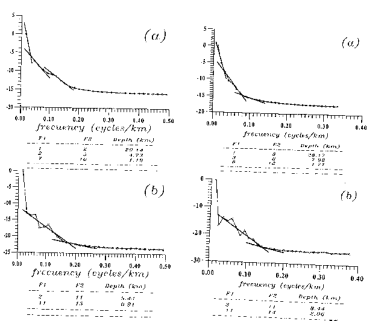

Fig. 4. Logarithmic plots of power spectra as a function of frequency for the southern transect (Los

Pozos-San José de los Milagros). The depth estimates are summarized in the tables. (a) Gravity data. (b) Magnetic data.

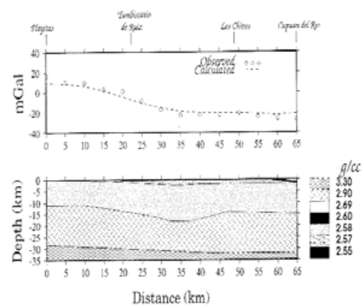

Fig. 5. Bouguer anomaly and model of the northern transect (Playitas-Cupuan del Río). Densities are given in g/cc.

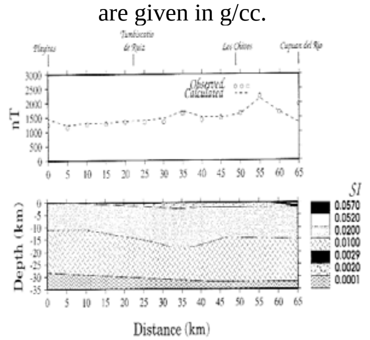

Fig. 6. Magnetic data and model for the northern transect (Playitas-Cupuan del Río). Magnetic susceptibilities are given in SI units.

The results for the northern profile (1) are summarized in Figures 5 and 6. The gravity and magnetic models include seven bodies. The density varies from 3.30 g/cc in the upper mantle to 2.55 g/cc at the surface. The magnetic susceptibility ranges from 10-4 SI to 5.7 x 10-2 SI. The crustal thickness increases towards the NE from around 28 km beneath Playitas to around 32 km beneath Cupuan del Río (Figures 5b and 6b). The average Moho depth is about 30 km, which agrees with the spectral estimate of 29.1 km. The bulk of the crust is modelled as two units with densities of 2.90 and 2.58 g/cc. The Arteaga metamorphic complex is representative of the upper crust and reaches an average thickness of 14 km. This unit may correspond to layer II in the seismic model of Valdés-Gonzalez and Meyer (1996), with p-wave velocities of 5.8-5.95 km/s. It is found at about 11 km depth beneath Las Playitas and about 14 km under Cupuan del Río; the thickness increases to 17 km between Tumbiscatio and Los Chivos in the central sector of the profile. The shallow units show slightly lower density and susceptibility, with contrasts of 0.01 g/cc and 0.1 SI. The shallow unit is up to 3 km thick and may represent an altered part of the metamorphic complex. This thickness is less than the values of 4.7 km and 5.4 km estimated from the spectral analysis of the gravity and magnetic data. Three bodies of 1 km thickness may correspond to the outcrops of granite and granodiorite (2.55 g/cc and 29 x 10-4 SI) and gabbro (2.69

g/cc and 52 x 10-3 SI) in the areas around Tumbiscatio de Ruiz and Cupuan del Río. The andesitic sequence in Cupuan del Río is modelled with a density of 2.60 g/cc and a susceptibility of 57 x 10-3 SI. Thickness of these units agrees with the spectral depth estimates of 1.2 km and 0.9 km from the gravity and magnetic data. The intrusive bodies and the volcanic sequence correspond to units with higher magnetic contrasts and cause the magnetic highs observed in the profile around km 55 between Los Chivos and Cupuan del Río (Figure 6).

Results of the gravity and magnetic models for the southern profile (2) are summarized in Figures 7 and 8. The gravity model includes five units and the magnetic model includes six units. The density varies from 3.30 g/cc in the upper mantle to 2.5 g/cc at the surface. The magnetic susceptibility ranges from 10-4 SI to 23 x 10-3 SI. The crustal thickness increases towards the NE from around 27 km beneath Los Pozos to around 30 km beneath San José de los Milagros (Figures 7b and 8b). The Arteaga metamorphic complex, which is exposed in the first 14 km of the profile between Los Pozos and Arteaga, is assumed to represent the bulk of the upper crust, with a thickness of around 13 km to 17 km. The density and susceptibility are 2.58 g/cc and 2 x 10-2 SI. The granites and granodiorites, which are extensively exposed along the profile, are modelled with a density of 2.50 g/cc and a susceptibility of 15 x 10-3 SI. The batholith gets thicker at about 65-75 km along the profile, up to 8 km. This value agrees with the spectral estimates of 8 km and 8.4 km (Figure 4). In the magnetic model (Figure 8) the upper part of the batholith, wich features large granitic boulders at the surface, shows a susceptibility contrast. Around San José de los Milagros area the Cretaceous andesitic sequence reaches a thickness of about 2 km. The sequence is modelled with a density of 2.60 g/cc and a susceptibility of 23 x 10-3 SI.

DISCUSSION

The limited number of basement outcrops in the Guerrero terrane of western and southern Mexico is a major limitation for determining the composition and age of the crust and the tectonic relationships (de Cserna, 1982; Campa and Coney, 1983; Urrutia-Fucugauchi, 1986; Sedlock et al., 1993). Available information comes from petrologic and geochemical studies of basement outcrops (e.g., Elias-Herrera and Sánchez-Zavala, 1992; Tolson, 1992; Centeno-García et al., 1993), from studies of lower crust and upper mantle xenoliths (e.g., Roberts and Ruiz, 1989; Uribe-Cifuentes and Urrutia-Fucugauchi, 1995), from regional geophysical studies and from a few oil exploration wells. The southern Mexico terrane boundaries and characteristics have been critically re-examined in recent studies (e.g., Johnson et al., 1991; Herrmann et al., 1994). Lang et al. (1996) have questioned the boundaries between several proposed terranes in northwestern Guerrero State.

The Zihuatanejo subterrane is characterized by volcano-sedimentary sequences of island arc association and numerous large intrusive bodies of batholithic dimensions. Wells drilled by Petroleos Mexicanos in the vicinity of Colima City (west of the study area) document a thick sequence of volcanic and carbonate rocks to depths of 3.5 km (Grajales-Nishimura and López-Infanzon, 1983). Gravity models for a profile north of Colima City along the Colima graben support the presence of continental crust (Urrutia-Fucugau-chi and Molina-Garza, 1992), previously interpreted as a zoned granulitic lower crust composed of crystallized basaltic cumulates and/or residues from removal of a partial melt and garnet-rich metasediments (Roberts and Ruiz, 1989). But there is no evidence for granulites or amphibolites in the Zihuatanejo subterrane. Granulitic xenoliths with Precambrian Nd model ages have been reported for the Valle de Santiago maar field to the northeast of the Arteaga region (Uribe-Cifuentes and Urrutia-Fucugauchi, 1995). Gabbroic xenoliths occur northwest of Guadalajara at the Sanganguey volcano within the Tepic-Zacoalco graben (e.g., Giossa and Nelson, 1985). The largest basement outcrop in the area is the Arteaga Complex.

CONCLUSIONS

Bouguer gravity and total field magnetic anomalies measured along two SW-NE profiles across the Arteaga region are used to model the crustal structure. The crustal thickness is around 30 km and increases towards the NE and N. The metamorphic rocks of the Arteaga complex form the largest basement outcrop in the area. They may be representative of the upper crust, with a thickness of about 14 km and up to 17 km. These results are consistent with the suggestion that these metamorphic rocks may form the bulk of the crust in the proposed Zihuatanejo subterrane (Centeno-Garc'a et al., 1993). Granitic and granodioritic intrusives represent a considerable part of the shallow rocks, particularly in the southern profile near Arteaga. The metamorphics in the Arteaga Complex, and the overlying Cretaceous strata, have been deformed and intruded. Lateral and vertical variation in lithology and mineralogy, physical property contrasts and inhomogeneities are likely to affect the crust (Smithson and Brown, 1977; Smithson, 1978). Fig. 7. Bouguer anomaly and model for the southern transect (Los Pozos-San José de los Milagros). Densities are given in g/cc. Sedlock et al. (1993) have illustrated the complexity of the region, from the Jalisco block across the Colima graben into the Zihuatanejo subterrane with a tectonically deformed metamorphic basement, an arc assemblage and numerous large igneous intrusions. The gravity and magnetic models help constrain the crustal thickness and no major vertical crustal discontinuities are found.

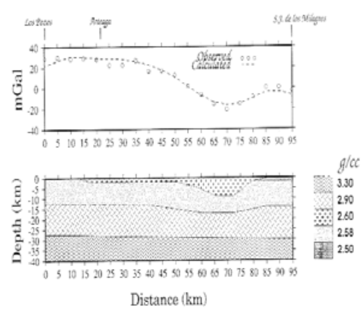

Fig. 8. Magnetic data and model for the southern transect (Los Pozos-San José de los Milagros). Magnetic susceptibilities in SI units.

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BIBLIOGRAPHY

ALVA-VALDIVIA, L., J. URRUTIA-FUCUGAUCHI, H. B...HNEL and D.J. MORAN-ZENTENO, 1991. Aeromagnetic anomalies and paleomagnetism in Jalisco and Michoacán, southern Mexico continental margin. Tectonophysics, 192, 169-190.

BANDY, W., C. MORTERA-GUTIERREZ and J. URRUTIA-FUCUGAUCHI, 1993. Gravity field of the southern Colima graben, Mexico. Geofís. Int., 32, 561-567.

BANDY, W., C. MORTERA-GUTIERREZ, J. URRUTIA-FUCUGAUCHI and T. HILDE, 1995. The subducted Rivera-Cocos plate boundary: Where is it, what is it, and what is its relationship to the Colima rift? Geophys. Res. Lett., 22, 3075-3078.

BARBA-LOPEZ, M., I. GALLO-PADILLA and M. LOPEZ-INFANZON, 1988. Complejo metam-rfico en el macizo de Arteaga, Mich., correlacionable con Xola-pa. IX Conv. Nac. Soc. Geol. Mex., p. 28-29 (abstr.).

BATH, M., 1974. Spectral Analysis in Geophysics. Elsevier Sci. Publ., Amsterdam, 563 pp.

BHATTACHARYYA, B.K. and L.K. LEU, 1975. Spectral analysis of gravity and magnetic anomalies of two-dimensional structures. Geophysics, 40, 993-1013.

BHATTACHARYYA, B.K. and L.K. LEU, 1977. Spectral analysis of gravity and magnetic anomalies due to rectangular prismatic bodies. Geophysics, 42, 41-50.

CAMPA, M.F. and P. CONEY, 1983. Tectonostratigraphic terranes and mineral resources distribution in Mexico. Can. J. Earth Sci., 20, 1040-1051.

CENTENO-GARCIA, E., 1994. Tectonic evolution of the Guerrero terrane, western Mexico. Ph.D. Thesis, Univ. Arizona, Tucson, USA. **CENTENO-GARCIA, E., J. RUIZ, P. CONEY, P. J. PATCHETT and F. ORTEGA-GUTIERREZ, 1993.** Guerrero terrane of Mexico: its role in the southern Cordillera from new geochemical data. Geology, 21, 419-422.

CIANCIARA, B. and H. MARCAK, 1976. Interpretation of gravity anomalies by means of local power spectra. Geophys. Prospect., 24, 273-286.

DE CSERNA, Z, 1982. Hoja Tejupilco, Carta Geol. Mex., Inst. Geol., UNAM Ser. 1:100,000 (Map and Text), 14Q-g(9), 28 pp.

DE LA FUENTE, M., C. AITKEN and M. MENA, 1995. Cartas Gravimétricas de la República Mexicana, I. Carta de Anomalía de Bouguer, Publ. UNAM, Mexico City.

ELIAS-HERRERA, M. and J. SANCHEZ-ZAVALA, 1992. Tectonic implications of mylonitic granite in the lower structural levels of the Tierra Caliente Complex (Guerrero State, southern Mexico). Rev. Inst. Geol., UNAM, 9, 113-125.

GARCIA-PEREZ, F., 1995. Caracterizaci-n geof'sica de la regi-n Tierra Caliente y áreas colindantes, Estados de Guerrero, México y Morelos. MSc. Thesis, National Univ. México, Mexico City, 55 pp.

GIOSSA, T.A. and S.A. NELSON, 1985. Gabbroic xenoliths in alkaline lavas in the region of Sanganguey volcano, Nayarit, Mexico. Geol. Soc. Am. Abstr. Progr., 17, 593 (abstr).

GRAJALES-NISHIMURA, M. and M. LOPEZ-INFANZON, 1983. Estudio petrogenŽtico de las rocas ígneas y metamórficas del Prospecto Tomatlán-Guerrero-Jalisco. Inst. Mex. Petrol. (IMP) Open-File Rep. C-1160.
GRANT, F. and G. F. WEST, 1965. Interpretation Theory in Applied Geophysics. McGraw-Hill Co., 584 pp.
HERRMANN, U. R., B. K. NELSON and L. RATSCHBACHER, 1994. The origin of a terrane: U/Pb zircon geochronology and tectonic evolution of the Xolapa complex (southern Mexico). Tectonics, 13, 455-474.
INEGI, 1985. Carta Geológica Hoja Lázaro Cárdenas, Instituto Nacional de Geografía y Estadística (INEGI), México, Ser. 1:250,000. **JOHNSON, C.A., H.R. LANG, E. CABRAL-CANO, C. G.A. HARRISON and J.A. BARROS, 1991.** Preliminary assessment of stratigraphy and structure, San Lucas region, Michoacán and Guerrero states, southwest Mexico. The Mountain Geologist, 28, 121-136.
LANG, H. R., J. A. BARROS, E. CABRAL-CANO, G. DRAPER, C. G. A. HARRISON, P. E. JANSMA and C. A. JOHNSON, 1996. Terrane deletion in northern Guerrero state. Geofís. Int., 35, 349-359.
LUHR, J., S. A. NELSON, J. ALLAN and I. S. E. CARMICHAEL, 1985. Active rifting in southwestern Mexico: Manifestations of an incipient eastward spreading ridge jump. Geology, 13, 54-57.
MOLINA-GARZA, R. and J. URRUTIA-FUCUGAUCHI, 1993. Deep crustal structure of central Mexico derived from interpretation of Bouguer gravity anomaly data. J. Geodyn., 17, 181-201.
MONOD, O., M. FAURE and D. THIEBLEMONT, 1994. Guerrero terrane of Mexico: its role in the southern Cordillera from new geochemical data-Comment. Geology, 22, 477.
PAL, P. C., K. K. KHURUNA and P. UNNIKRISHNAN, 1979. Two examples of a spectral approach to source depth estimation in gravity and magnetics. Pure Appl. Geophys., 117, 772-783..
REGAN, R.D. and W.J. HINZE, 1976. The effect of finite data length in the spectral analysis of ideal gravity anomalies. Geophys., 41, 44-55. **ROBERTS, S. and J. RUIZ, 1989.** Geochemistry of exposed granulite facies terrains and lower crustal xenoliths in Mexico. J. Geophys. Res., 94, 7961-7974.
ROSAS-ELGUERA, J., L. FERRARI, V.H. GARDUNO-MONROY and J. URRUTIA-FUCUGAUCHI, 1996. Continental boundaries of the Jalisco block and their influence in the Pliocene-Quaternary kinematics of western Mexico. Geology, 24, 921-924.
SEDLOCK, R. L., F. ORTEGA-GUTIERREZ and R. C. SPEED, 1993. Tectonostratigraphic terranes and tectonic evolution of Mexico. Geol. Soc. Am. Special Pap., 278, 153 pp.
SMITHSON, S. B., 1978. Modeling continental crust: structural and chemical constraints. Geophys. Res. Lett., 5, 749-752.
SMITHSON, S. B. and S. K. BROWN, 1977. A model for lower continental crust. Earth Planet. Sci. Lett., 35, 134-144.
SPECTOR, A. and F.S. GRANT, 1970. Statistical models for interpreting aeromagnetic data. Geophysics, 35, 293-302.
TALWANI, M., 1965. Computation with the help of a digital computer of magnetic anomalies caused by bodies of arbitrary shape. Geophysics, 30, 797-817.
TALWANI, M. and J.R. HEIRTZLER, 1964. Computation of magnetic anomalies caused by two-dimensional structures of arbitrary shape. In: Computers in the Mineral Industries, Stanford Univ. Publ. Geol. Sci., 464-480.
TALWANI, M., J. L. WORZEL and M. LANDISMAN, 1959. Rapid gravity computations for two-dimensional bodies with application to the Mendocino submarine fracture zone. J. Geophys. Res., 64, 49-59.
TOLSON, G., 1992. Structural geology and tectonic evolution of the Santa Rosa area, SW State of Mexico, Mexico. Geofís. Int., 32, 397-413. **URIBE-CIFUENTES, R. M. and J. URRUTIA-FUCUGAUCHI, 1995**. Lower crustal xenoliths from the Valle de

Santiago maar field: Crustal structure and tectonic implications. Geol. Soc. Am. Abs. Progr., A-392 (abstr.)
URRUTIA-FUCUGAUCHI, J., 1986. Crustal thickness, heat flow, arc magmatism and tectonics of Mexico -preliminary report. Geofís. Int., 25, 559-573.
URRUTIA-FUCUGAUCHI, J. and R. MOLINA-GARZA, 1992. Gravity modelling of regional crustal and upper mantle structure of the Guerrero terrane - I. Colima graben and southern Sierra Madre Occidental, western Mexico. Geofís. Int., 31, 493-507.
URRUTIA-FUCUGAUCHI, J. and J. H. FLORES-RUIZ, 1996. Bouguer gravity anomalies and regional crustal structure in central Mexico. Int. Geol. Rev., 38, 176-194.
VALDES-GONZALEZ, C. and R. P. MEYER, 1996. Seismic structure between the Pacific coast and Mexico City from the Petatlán earthquake (Ms=7.6) aftershocks. Geofís. Int., 35, 377-402.

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