General Disclaimer

One or more of the Following Statements may affect this Document

- This document has been reproduced from the best copy furnished by the organizational source. It is being released in the interest of making available as much information as possible.

- This document may contain data, which exceeds the sheet parameters. It was furnished in this condition by the organizational source and is the best copy available.

- This document may contain tone-on-tone or color graphs, charts and/or pictures, which have been reproduced in black and white.

- This document is paginated as submitted by the original source.

- Portions of this document are not fully legible due to the historical nature of some of the material. However, it is the best reproduction available from the original submission.

Produced by the NASA Center for Aerospace Information (CASI)

9950 - 983

This report was prepared for the Jet Propulsion Laboratory, California Institute of Technology, sponsored by the National Aeronautics and Space Administration.

Contract N. 956432

SIR-A Imagery in Geologic Studies of the Sierra Madre Oriental, Northeastern Mexico.

Part 1 (Regional Stratigraphy):

The Use of Morphostratigraphic Units in Remote Sensing Mapping

(NASA-CR-175457) SIR-A IMAGERY IN GEOLOGIC STUDIES OF THE SIERRA MADRE ORIENTAL, NORTHEASTERN MEXICO. PART 1 (REGIONAL STRATIGRAPHY): THE USE OF MORPHOSTRATIGRAPHIC UNITS IN REMOTE SENSING G3/43 N85-19497 Unclas 14304

Jose F. Longoria and Oscar H. Jimenez
Programs in Geosciences
The University of Texas at Dallas
Box 688
Richardson, Texas 75080

RECEIVED GEOSCIENCES DEPT.

ABSTRACT

SIR-A imaging was used in geological studies of sedimentary terrains in the Sierra Madre Oriental, northeastern Mexico. Geological features such as regional strike and dip, bedding, folding and faulting were readily detected on the image. The recognition of morphostructural units in the imagery, coupled with field verification, enabled geological mapping of the region at the scale of 1:250 000. Structural profiling lead to the elaboration of a morphostructural map allowing the recognition of en echelon folds and fold trends which were used to postulate the tectonic setting of the region.

INTRODUCTION

Spaceborne radar imagery is an important remote sensing technique for regional geological studies. Recent studies using imagery from SIR-A (Elachi et al., 1982) have centered on the detection of gross geological features such as the detection between metamorphic and sedimentary terrains

(e.g. Sabins, 1983).

The objective of the present study was to test the SIR-A imagery in geologic interpretations of sedimentary terranes such as the Sierra Madre Oriental of northeastern Mexico. This area was choosen because it has: 1) strong relief contrast, 2) dense vegetation, 3) complex geologic setting, 4) lithologic homogeneity, i.e. it is formed of sedimentary rocks displaying enormous thickness, and 5) importance in understanding the geologic history of the Gulf of Mexico and Caribbean region.

Location of the Studied Area

The study area lies approximately between parallels 24 50'and 25 30', and meridians 99 30'and 101 00' covering the southeast corner of the State of Coahuila and the south-central part of the State of Nuevo Leon, in northeastern Mexico. Part of this area was covered by swath 22 of the SIR-A imagery (Figure 1). Physiographically, it is located in the Transverse Ranges of the Sierra Madre Oriental Province, and corresponds to the place where the Sierra Madre Oriental abruptly bends towards the west. It lies in the Victoria Segment of the Sierra Madre Oriental geologic province of northeastern Mexico. The paleogeographic reconstruction of northeastern Mexico has been a difficult task. Early workers (Humphrey, 1956) believed that the present day physiographic provinces correspond to paleogeographic elements. Accordingly, the Sierra Madre Oriental would be related to the Mesozoic Mexican Geosyncline, and the Coahuila Folded Belt to the Jurassic Sabinas Basin. As pointed out by Weide (1968) and Longoria (1984) the existence of those paleogeographic elements throughout the Mesozoic needs to be documented.

GEOLOGIC INTERPRETATION OF THE SIR-A IMAGES OF NE MEXICO

Geomorphologic Description of the Image

The geological interpretation of the SIR-A images from northeast Mexico was based on the visual analysis of morphological, stratigraphic, and tectonic features. Due to the particular geological setting of the region under study, mainly formed of homogenous piles of sedimentary rocks, special emphasis was given to the recognition of stratigraphic units which could be mapped at the image scale. The direct relationship betwen textural differences and topographic expression of lithologies was used as the fundamental basis for the diagnosis of morphostratigraphic units. The concept of image texture introduced by Ford (1980, 1982) is herein followed.

The region studied is characterized by elongated subparallel, narrow ridges which are separated by narrow, dip valleys in the northwest and wide, shallow valleys in the southeast. The ridges correspond to both anticlinal and synclinal structures, varying from fan-shaped to recumbent. The contrast of the image is high and mainly enhances topographic features; however, stratification and structural trends are also highlighted. The brightest points corresponding to the steep slopes of eroded asymmetric anticlines whose limbs, in the form of alligned ridges, faced the incident radar beam. The brightness observed in the southwest corner of the area is due, in part, to the scattered gypsiferous outcrops (grids H3, H4, I5) and clearly to cultural features such as towns, electric plants and high voltage cables. The dark areas on the image correspond mainly to the slopes that face away from the incident radar beam. Some of the darkest areas correspond to valleys with thick alluvial cover (grids J1,K1,L1,M1,K3,L3,M3 and M4), which probably are associated to ground water reservoirs. Where the alluvium-sediments are thin, probably few meters, it is possible to follow the bedding below it.

Most of the region under consideration is densely vegetated with the

exception of the SE part, whereby arid conditions predominte. The ridges and mountainous areas are covered by coniferous and mixed deciduous forests. The wide valleys are cultivated or otherwise densely covered with grassy vegetation. Although tonal variations such as in grids G3, G4, H3, and H4 are due to the presence of vegetation, the underlying rock terrain is still well displayed in the image.

In general the ridges have slopes varying between 25 and 40 though in some steep areas, slopes can range from 50 to 70 degrees. Slopes with more than 35 degrees are present over more than 65 percent of the area. The valleys have gently undulating floors but in several places they form deep narrow intermontane valleys. The drainage pattern is not obvious on the image. An intricate network of streams, however, can be observed on the slopes of the high ridges. Smaller streams and meandering rivers are seen in the deep valleys. All of them are tributaries to the trellis drainage system developed in a series of arcuate, roughly parallel anticlines and synclines, resulting in a characteristic denudation. Where erosion is well-advanced breached anticlines are developed.

Geologic Features Observed on the SIR-A Image

The examination of the SIR-A images was focused on the mapping of features such as: a) Bed attitude, b) Lithologic type, c) Faults, d) Folds, e) Morphostructural trends, and f) Structural profiling.

a) Bed Attitude.- Regional strike and dip of bedding planes were hard to obtain from visual examination of the image. It seems like the observation of bed attitude greatly depends upon the incidence of the beam angle at which the image was taken. Furthermore, the geologic complexity of the region under study makes it even harder to obtain regional strike and dip directions. However, morphological trends were used to infer the

regional attitude of strata. When the illumination is perpendicular to bedding trends, as in grids I2, I3 excellent attitudes were obtained. On the other hand, the lack of well-defined bedding attitudes such as in grids B4 and B5 helped to interpret structural deformations such as twisted and doubly plunging structures. These structures were later confirmed during field verification.

b) Lithologic Type.- Visual analysis of the SIR-A images permits the recognition of Morphostratigraphic Units herein defined as lithological packages which mantain their textural expresion in the images throughout the region. Their visual identification on the images is vital in that they are the remote sensing mapable units comparable with lithostratigraphic units (formations) recognized on detailed aereal photographs or detailed ground mapping. The Morphostratigraphic Units are herein regrarded as the main basis for remote sensing geology in sedimentary terranes. Their recognition in this image resulted in the elaboration of a remote sensing geologic map of the region at the scale of 1:250 000 (Figure 5). During the present study three morphostratigraphic units were mapped throughout the area (Figure 2).

c) Faults.- High angle reverse, strike-slip and thurst faults were recognized in the region (Figure 3). The geometric arrangement of the morphostratigraphic units as well as their morphostructural relationship were used to distinguish the three kind of faults on the image. Thrust faults occur in the eastern part of the image and were the more difficult to recognize. Their morphology is characterized by narrow ridges separated by close, V-shaped, deep valleys. Reverse faults are associated to strike-slip faulting and were detected on the image because of their abrupt topograhic break in relation to the surrounding ranges. The down thrown block forms

wide open valleys. Strike-slip faults are readily identified on the image by the horizontal disruption of the morphostructural ranges involved in the faulting.

b) Folds.- The majority of the ranges in the area correspond to folds giving an excellent opportunity to study folding in sedimentary terranes. These folds include wide open, symmetric, fan-shaped and recumbent types (Figure 4). Geometry of folds and fold variations, including en echelon, periclinal, plunging , and bifurcated folds were easily recognized using the geometric arrangement of the morphostratigraphic units.

e) Morphostructural trends.- As stated above, the majority of the individual ranges correspond to folds (Figures 3 and 4). The general trend of mountain ranges define morphostructural zones, i.e., areas within the region unified by the general morphologic expression of the structures. Contiguous morphostructural zones can be separated from one another by their fold trend and thier boundaries may be delineated by changes in fold trends or they may be bounded by faults. The morphostructural zones recognized in the area are shown in Figure 3.

f) Tectonic Profiling.- Scale and resolution of SIR-A imagery permit generation of direct structural profiles. In the studied region the profiling was fundamental in understanding the tectonics of northeastern Mexico. Image profiling was compared with field profiling during field verification (Figure 4).

Stratigraphy

Four morphostratigraphic units were established for the Mesozoic of the region under study (Figure 2). Their geographic distribution was traced on the image resulting in a remote sensing geologic map of the area (Figure 5). It is important to note that in some valleys the continuity of the bedding

was followed in the SIR-A image underneath thinner alluvial cover (grid D2).

Morphostratigraphic Unit 0.- The alluvium cover is widely exposed in the region and was considered as a separate mappable unit. Unit 0 consists of continental sediments derived from fluvial, lagoonal and probably playa lake sedimentation during early Quaternary and Recent time.

Morphostratigraphic Unit 1.- Morphostratigraphic Unit 1 is recognized on the image by its characteristic medium "granular" texture, high contrast and low definition. Lithologically it is predominantly evaporitic, consisting of an impure gypsum mass in the lower part and sandstone, sandy conglomerate and shale in the upper part. The lower part of the unit is characterized by an earthy appearance of whitish coloration, easily erodable. The upper part is formed of a flyschoidal interbedding of sandstone, black and varicolored shale and minor amounts of conglomeratic sandstone. Locally the sandy conglomerate is more extended (grids H3,I3 and H4) while in others places (grids A1,A2,B1,B2 and B3) the shale is the main constituent. Unit 1 is the oldest in the study area and is assigned to the Upper Jurassic , it is transitionally overlain by unit 2. Morphostratigraphic unit 1 is widely exposed in Morphostructural Zone I and is distributed in the topographic lows formed in the breached anticlines.

Morphostratigraphic Unit 2.- On the image, this unit displays: 1) high contrast, 2) fine to coarse granularity , and 3) high definition. It is formed of a homogenous pile of carbonate rocks, varying from thin to thick-bedded limestone, locally black chert nodules and layers are abundant alternating with thin-bedded dark shale. Unit 2 generally forms elongated ridges with steep slopes displaying well-developed bedding planes. Unit 2 is observed in the whole region of study. It ranges from Upper Jurassic to Upper Cretaceous and is the predominant lithology observed in

morphostructural zones III and IV, where it forms elongated, semiparallel anticlinal ridges corresponding to topographic highs. Although there is a pitching of the structures that form the ridges, producing depressions and culminations, the ridge-forming rocks in Zone IV (I1, I2, I3, H2, H3, and H4) are formed by the lower part of Unit 2. The E-W distribution of unit 2 reflects a regional tilting and bending of the ridge forming structures. Consequently, the youngest ridge-forming rocks in Zone III, and neighboring areas of Zone IV, belong to the upper part of the unit 2, exposing rocks in the western parts of Zone IV that correspond to the lower part of the same unit.

Morphostratigraphic Unit 3.- Unit 3 is formed of a rhythmic alternation of thin to medium-bedded, varicolored shale and limestone with arenaceous layers. It is a predominantly terrigenous unit easily erodable which was deformed contemporaneously with the previous units. It crops out on the flanks of the ridge-forming limestone of unit 2, and in the middle of the synclinal valleys where it has not been covered by alluvium or else by stream denudation. It was identified in zones III and IV. In general, Unit 3 displays low to medium contrast, low definition and fine granularity.

Morphostructure

Five morphostructural zones were defined on the image (Figure 3). Their characterization was based on: 1) Topographic expression of individual ranges, 2) Fold trends, 3) Fold distribution, and 3) Morphostratigraphic character of the lithologies.

Morphostructural Zone I.- This Zone is located in the southern part of the image (Figure 3). It contains poorly defined synclines and anticlines surrounded by low, wide valleys composed of evaporites. The Cerro del Potosi is the more prominent structure in this zone, with more than 1000 m

of relief (Figure 4); however, it is important to notice that on the SIR-A image this structure lacks topographic expression.

Morphostrucutral Zone II.- This Zone covers the northeastern part of the image (Figure 3). Several SSE-NNW trending reverse faults and east verging thrusts are found in this zone. (profile K-K', Figure 4). Bedding planes are well defined on the slopes of the ranges (see grids I2). The Cerro Rayon is the more prominent structure in this zone. In general structures in this zone display an imbricated arrangement.

Morphostructural Zone III.- Zone III covers the central part of the image (Figure 3). The structures in this zone have an ESE-WNW general trend. They are recumbent anticlines and synclines most of which show a characteristic twisting becoming more pronounced towards the eastern end of the structures (see profiles G-G', F-F', and E-E', Figure 4). Sierra La Marta, Sierra La Ventana and Sierra Los Pilares are typical examples of the structures from Zone III.

Morphostructural Zone IV.- This zone occupies the western half of the image. The strucutres observed have an E-W general trend, froming subparallel, en echelon patterns (profiles A-A', C-C', D-D', Figure 4). They vary from recumbent, twisted anticlies such as Sierra de Tapanguillo, Sierra El Arenal, Sierra Chapultepec, Sierra La Esmeralda, and Sierra El Pinal Alto to doubly plunging anticlines with bifutrcated ends such as Sierra San Lucas, Sierra La Nieve, Sierra La Marta, Sierra San Antonio, and Sierra Zapaliname.

Morphostructural Zone V.- This Zone is located in the southern and western portions of the image (Figure 3). Zone V includes areas with alluvium cover represented by wide, low and undulating valley floors. The darkest parts of this zone seem to correspond to places where the alluvial

cover is the thicker. The high contrast, coarse granularity, high definition and finelly mottled appearance is also persistent in the imagery response.

CONCLUSIONS

This study shows that spaceborne radar imagery can be used for geologic mapping of complex sedimentary terrains whereby abrupt topography and dense vegetation impede making direct geologic observations. As in any other remote sensing technique, visual analysis of the SIR-A imagery should be followed by field verification. Examination of the SIR-A images from the Sierra Madre Oriental lead to postulate the following: 1) the continuity of ridges can be traced under a thin alluvial cover. 2) Bedding can be detected in the slopes of the elongated ridges where the incident radar beam is close to perpendicuclar. 3) the stratification combined with the topographic expression of the flanks of the ridges and hills can be used to define morphostratigraphic units, i.e., packages of rocks that can be distinguished from other units above and below by means of their visual textural expression. The definition of these morphostratigraphic units permits geological mapping. The use of morphostratigraphic units instead of formations in remote sensing geologic mapping avoids the complexities of lithostratigraphic nomenclature which in this region has hindered the paleogeographic and tectonic interpretations. 4) Major morphological and structural elements are indentified allowing the recognition of morphostructural zones, i. e., zones within the studied area whose general morphologic expression is the result of common structural behavior. Five zone were thus defined. 5) Structural profiles can be generated from the images by interpreting the geometric arrangement of the morphostratigraphic units. Several previously unrecognized tectonic patterns in the region

including en echellon folding and strike-slip and associated reverse faults were so detected. We interpret the existence of these structures as the result of transpression associated to active sea floor spreading in the Gulf of Mexico in the late Jurassic. Consequently, transpressional tectonics is invoked to explain the observed structural arrangement in NE Mexico. Circumstantial evidence shows that the required subsurface (basement) transcurrent faults are likely to exist in the subsurface of this region. This tectonic model is discussed in a separate paper.

REFERENCES CITED

Elachi, C., Brown, W. E.; Cimino, J. B.; Dixon, T.; Evans, D. L.; Ford, J. P.; Saunders, R. S.; Breed, C.; Masursky, H.; McCauley, J. F.; Schaber, G.; Dellwing, L.; England, A.; MacDonald, H.; Martin-Kaye, P. and Sabins, F., 1982, Shuttle Imaging Radar Experiment: Science, v. 218, n. 3, p.996-1003.

Ford, J. P., 1980, Seasat orbital radar imagery for geologic mapping: Tennessee-Kentucky-Virginia: American Association of Petroleum Geologists Bulletin, v. 64, no. 12, p. 2064-2094.

Ford, J. P., 1982, Analysis of the SIR-A and SEASAT SAR images of the Kentucky-Virginia. In Cimino, J. A. and Elachi, C. D., eds., Shuttle Imaging Radar-A (SIR-A) experiment: National Aeronautics and Space Administration, Jet Propulsion Laboratory, JPL Publication 82-77, p. 4-10/4-18.

Humphrey, W. E., 1956, Tectonic framework of northeast Mexico: Gulf Coast Association of Geological Societies Transactions, v. 6, p. 25-35.

Longoria, J. F. , 1984, Stratigraphic studies in the Jurassic of northeastern Mexico: Evidence for the origin of the Sabinas Gulf. In Ventress, P. S., Bebout, D. G., Perkins, B. F. and Moore, C. H.

(eds.) The Jurassic of the Gulf Rim. Gulf Coast Section Society of Economic Paleontologists and and Mineralogists, Foundation Third annual Research Conference, march, 1984, p. 171-193.

Sabins, F. F., 1983, Geologic interpretation of the Space Shuttle Radar Images of Indonecia: American Association of Petroleum Geologists Bulletin, v. 67, n. 11, p. 2076-2099.

Weidie, A. E., 1968, The myth of the Mesozoic Mexican Geosyncline [Abs.]: Geological Society of American, Abstract with Programs, p. 314.

ACKNOWLEDGMENTS

The present investigation was carried out at the University of Texas at Dallas (U.T.D. Contribution 458). The research for this report was founded by the Jet Propulsion Laboratory (JPL Contract 956430). We express our gatitude to the Programs in Geosciences, U.T.D., for the facilities made available to us for the preparation of this research. Our appreciation is here expressed to Tim Dixon (J. P. L.) for critically reviewing the manuscript. Special thanks are due to Mr. Manuel Valenzuela (U.T.D.) for his help in drafting the figures.

FIGURE CAPTIONS

Figure 1. Index map of Mexico showing the location of the study area and the track of SIR-A swath 22 (parallel lines).

Figures 2. Diagnostic features of the morphostratigraphic units recongized.

Figure 3. Structural elements and morphostructural interpretation of the SIR-A image of the Sierra Madre Oriental, northeast Mexico.

Figure 4. Structural profiles of the Sierra Madre Oriental as interpreted from the morphostratigraphic units recognized on the image (see Figure 3 for location of profiles).

Figure 5. Remote sensing (SIR-A) geologic map of part of the Sierra Madre Oriental, northeastern Mexico.

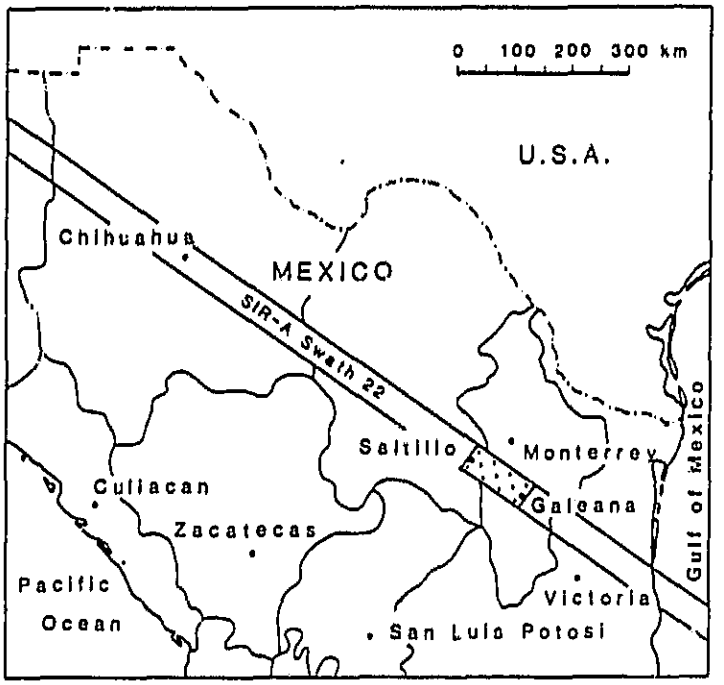

0 100 200 300 km
U.S.A.
Chihuahua
MEXICO
SIR-A Swath 22
Saltillo
Monterrey
Culiacan
Galeana
Zacatecas
Pacific
Ocean
Victoria
San Luis Potosi
Gulf of Mexico

Figure 1

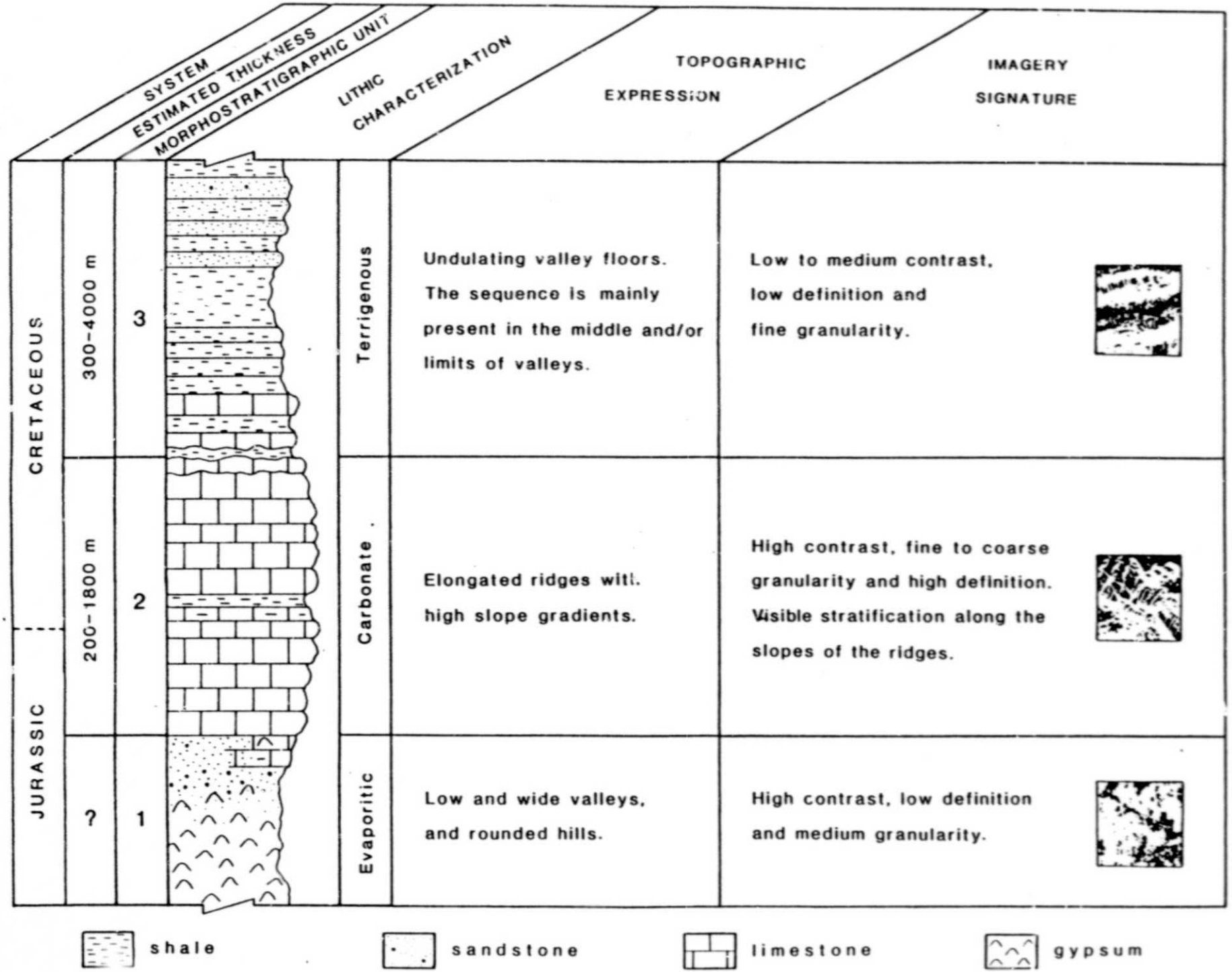
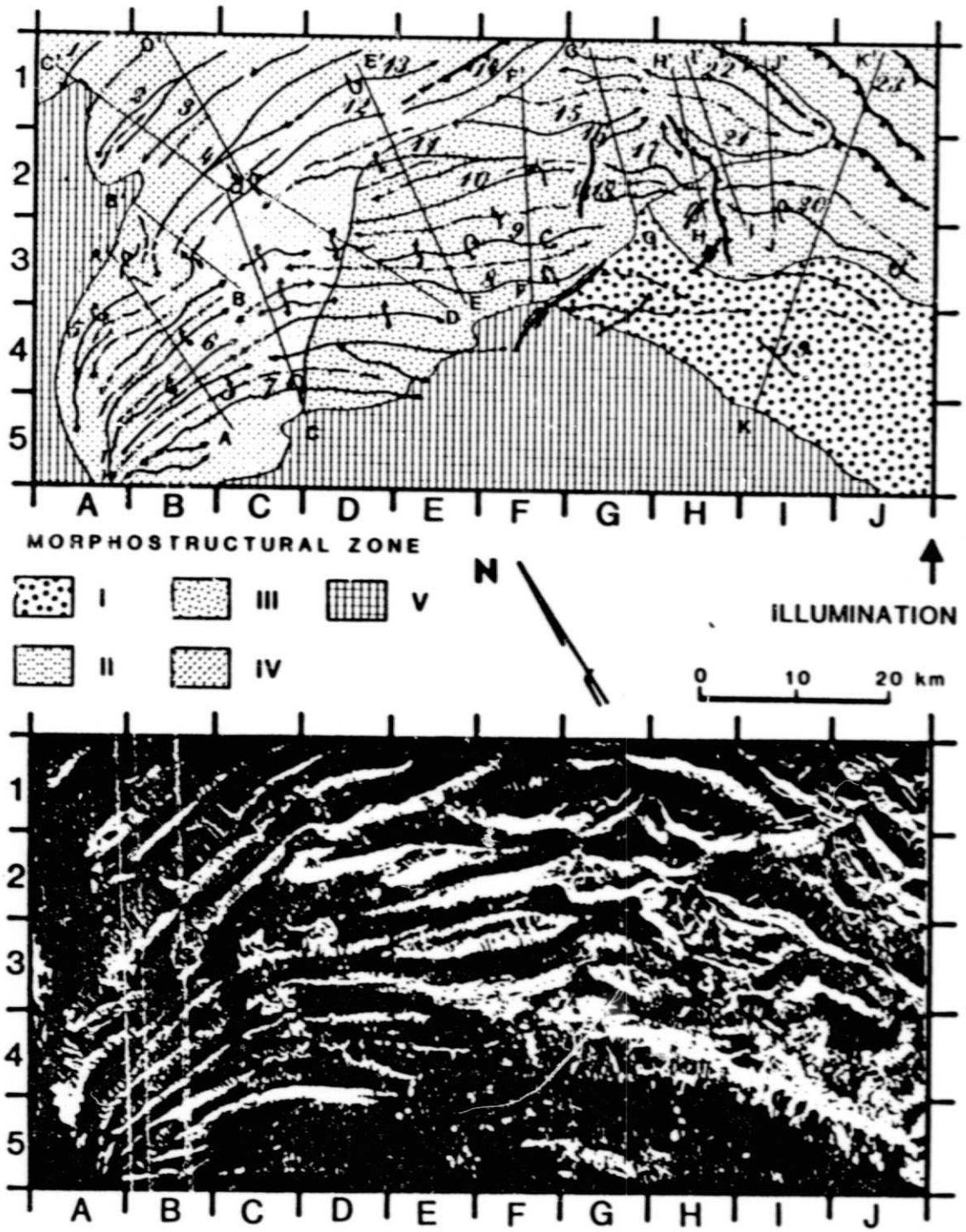

SYSTEM
ESTIMATED THICKNESS
MORPHOSTRATIGRAPHIC UNIT
LITHIC CHARACTERIZATION
TOPOGRAPHIC EXPRESSION
IMAGERY SIGNATURE
CRETACEOUS
JURASSIC
300-4000 m
200-1800 m
?
3
2
1
Terrigenous
Carbonate
Evaporitic
Undulating valley floors. The sequence is mainly present in the middle and/or limits of valleys.
Elongated ridges with high slope gradients.
Low and wide valleys, and rounded hills.
Low to medium contrast, low definition and fine granularity.
High contrast, fine to coarse granularity and high definition. Visible stratification along the slopes of the ridges.
High contrast, low definition and medium granularity.
shale
sandstone
limestone
gypsum

Figure 2

Figure 3



ANTICLINAL AXES

- Recumbent
- Periclinal
- Twisted
- Plunging
- Bifurcated
- Culminational

SYNCLINAL AXES

- Recumbent
- Periclinal
- Twisted
- Plunging
- Depressional

FAULTS

- Thrust
- Reverse
- Strike-slip

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

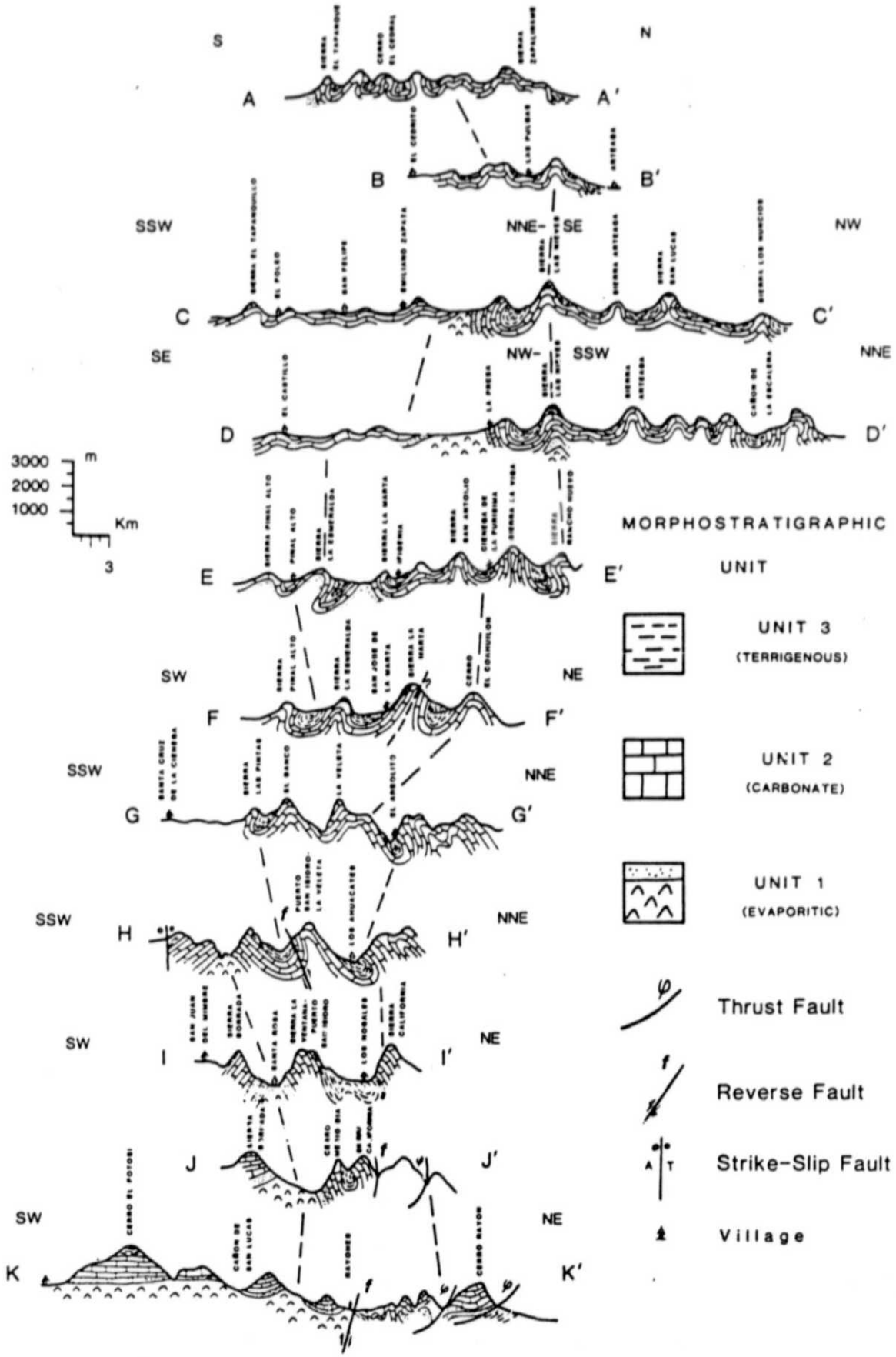

S
N
A
A'
B
B'
SSW
NNE-
SE
NW
C
C'
SE
NW-
SSW
NNE
D
D'
3000
2000
1000
m
Km
3
E
E'
SW
NE
F
F'
SSW
NNE
G
G'
SSW
NNE
H
H'
SW
NE
I
I'
J
J'
SW
NE
K
K'
MORPHOSTRATIGRAPHIC UNIT
UNIT 3
(TERRIGENOUS)
UNIT 2
(CARBONATE)
UNIT 1
(EVAPORITIC)
Thrust Fault
Reverse Fault
Strike-Slip Fault
Village

Figure 4

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

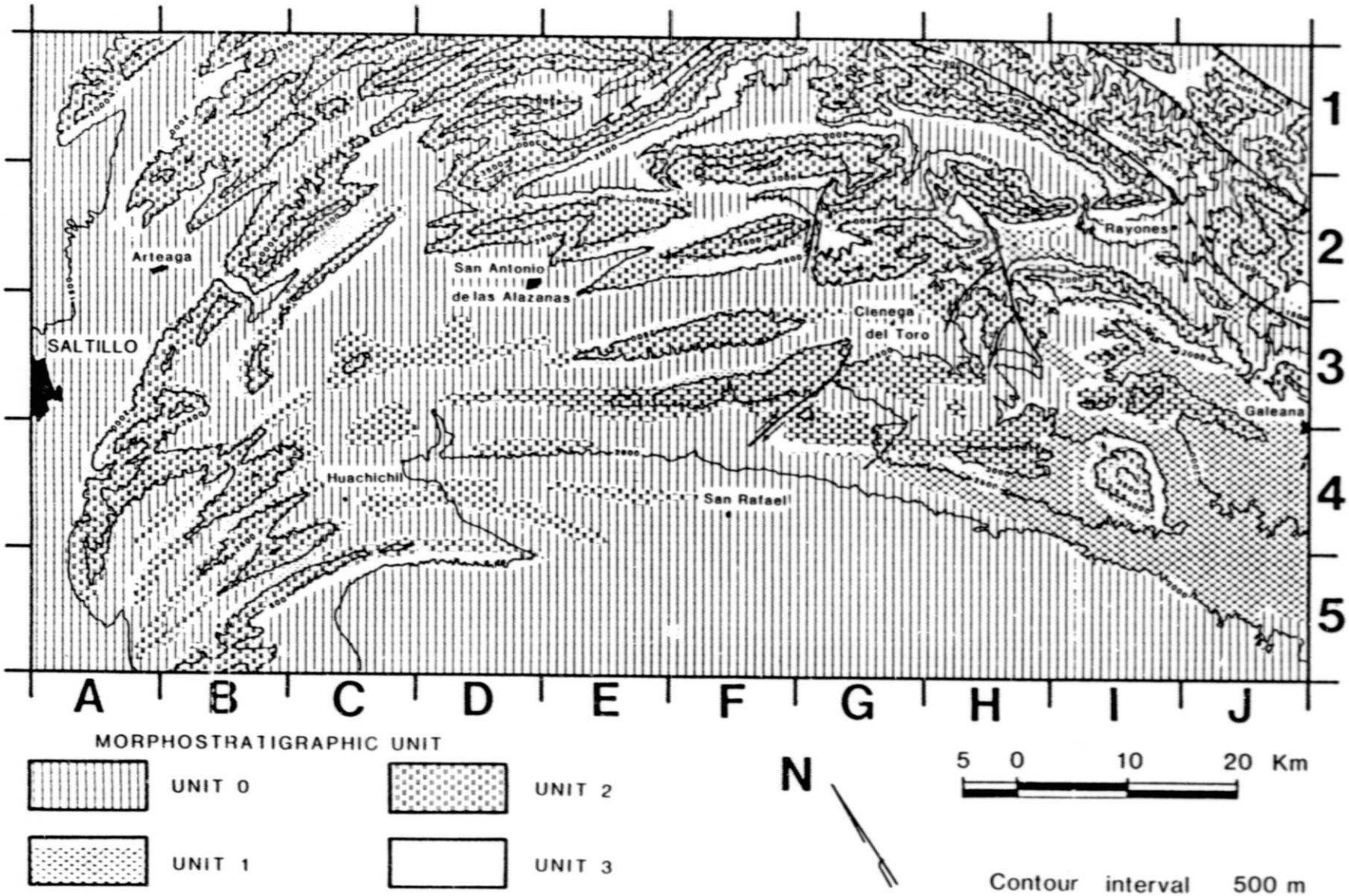


Figure 5

Contract No. 956432

SIR-A in Geologic Studies of the Sierra Madre Oriental, Northeastern Mexico. Part 2, Tectonic Transpression: An Alternative Model

Jose F. Longoria and Oscar H. Jimenez
Programs in Geosciences
Box 688
Richardson, Texas 75080

ABSTRACT

The visual analysis of the Shuttle Imaging Radar (SIR-A) of northeast Mexico revealed the existence of several geological features including: 1) a well-developed pattern of en echelon folds, 2) juxtaposition of tectonostratigraphic domains, 3) fold structures varying from fan-shaped, asymmetric to recumbent doubly plunging anticlines, 4) anticlinal-synclinal trends associated to regional plunging and tilting of the structures, and 5) strike-slip faults oblique to the fold trends. These structures are interpreted as the result of transpressional stress related to a complex, anastomosed wrench-faulting system in the basement reactivated several times since the Late Jurassic. This transpressional orogenic belt in northeastern Mexico is linked to the spreading phase in the Gulf of Mexico.

INTRODUCTION

In spite of the fact that the first tectonic interpretations of

northeast Mexico date back to the begining of this century and also that excellent field studies have been done since the thirties, no attempts have been done to conciliate the diffrence in geologic interpretations and relate the geology of this region to the dynamic processes taking place in the Gulf of Mexico during the Mesozoic.

Recent geologic studies in northeastern Mexico using Space Shuttle Columbia Imaging Radar (SIR-A Experiment) permited a re-evaluation of the tectonic significance of the structures observed in the Saltillo-Galeana Folded Belt. Visual analysis of the SIR-A images was combined with field verification. The extension of the observed geologic features outside the SIR-A image was accomplished using LANDSAT images. The SIR-A images studied were covered by Swath 22 (Figure 1). The geologic interpretation of these images is presented in a separate paper (Longoria and Jimenez, 1984). Our purpose in this paper is to present a transpressive tectonic model as a mechanism to account for the deformation observed in northeastern Mexico.

TECTONIC SETTING OF NE MEXICO

The area under study lies in the Victoria Segment of the Sierra Madre Oriental geologic province of northeastern Mexico (Figure 1). Three general tectonic styles have been postulated to explain the tectonic evolution of northeastern Mexico: 1) simple "compresional stresses" with vertical movements of the basement of unknown mechanism (Bose, 1923; Humphrey, 1956); 2) sliding of a detached cover above a decollement zone by a gravity induced mechanism (Avenius, 1982); and 3) large-scale thrusting (Tady et al., 1975) as consequence of an "alpine-type tectonics" in the region. Several combinations of the three main styles are identified: a) compressional stress and salt movement (Wall et al., 1961), b) compressional stress and decollement (Cserna,1956), c) compressional stress on a

pre-Mesozoic transformally displaced basement (Alfonso, 1976), d) thrusting and nappe-forming over transcurrent faults (Tardy, 1980), and e) decollement associated to strike- slip movement (Padilla, 1982).

BASES FOR TECTONIC TRANSPRESSION IN NE MEXICO: A DISCUSSION

The identification of a transpressive system in northeastern Mexico is linked to transcurrent faults in the basement. This tectonic model will be analyzed in light of four kinds of geological observations:

1. Theoretical Considerations.- The basis of wrench-tectonics was extensively discussed by Moody and Hill (1956), providing the theoretical grounds for understanding the deformation of a sedimentary pile above a horizontally desplaced basement. The concept of wrench tectonics has been applied in different parts of the world at both regional and continental scales (Woodckok and Robertson, 1982). Experimental models have also demonstrated the possible mechanism of the wrench faulting (Closs,1955; Wilcox et al., 1973). Recently, the concepts of tectonic transpression and oblique-slip mobile zones have been introduced by Harland (1971) and Ballance and Reading (1980), respectively. The reader is referred to those papers for details on the theoretical principles of transpressive tectonics and oblique-slip mobile zones and their realtionto wrench-tectonics.

2. The Saltillo-Galeana Folded Belt.- The Saltillo-Galeana Orogenic Belt covers a surface of about 5,000 km2. It displays considerable morphological and structural variations (Figure 2). The geology of this area was interpreted from the SIR-A image couple with field verification. The stratigraphic and structural aspects of the area were presented in a separate paper (Longoria and Jimenez, 1984). Among the significant regional structural features observed are the following (Figure 2): 1) the en echelon folding, 2) the doubly plunging folds, displaying an ellipsoidal

patern, and 3) strike-slip faults. Local structures include: 1) the rotations of the fold axes as displayed by the Sierra La Nieve, Sierra La Esmeralda and Sierra Zapaliname, 2) bending of the structures such as in Sierra El Cedral, Sierra El Pinal Alto and Sierra La Borrada, and 3) branching of the fold structures such as in Sierra La Nieve and Sierra San Antonio.

Following the observations by Campbell (1958), Tanner (1961), Wilcox et al. (1973) and Odonne and Vialon (1983), the plunge culminations and depretions, recumbent folds, and thrusting of the folds of the Saltillo-Galeana Belt are interpreted as due to an advanced stage of the development of horizontal movements in the basement. They also interpreted "en echelon folding" as the result of deformation of a stratified cover above a wrench-fault system in its basement. As noted by Odonne and Vialon (1983) the geometry and orientation of the folds depends on the magnitud of the wrenching.

Consequently, we postulate herein that the structures observed in northeastern Mexico, typified by the Saltillo-Galeana Belt (figure 2), are the result of deep, ancient transcurrent faults present in the subsurface (basement) of the region, perhaps since the late Paleozoic but reactivated during the Jurassic and Cretaceous. As discussed below our working hypothesis conciliates the difference in tectonic styles, as well as the diffences in fold vergences and stress directions much debated among previous authors (Figure 5).

3. Regional pre-late Jurassic Fault Trends.- Major pre-Late Jurassic lineaments described by several authors fron North America have been compliled in Figure 3. Most of these correspond to Paleozoic transcurrent faults. Unfortunately, very little is known on the few isolated Paleozoic

and Precambrian outcrops in northeastern Mexico, and much less is even known on the dynamics of the basement in this region. Recently, Anderson and Schmidt (1983) postulated the extension of the Mojave-Sonora Megashear (left-lateral transcurrent fault) into northeast Mexico. Although the timing of the dislocation has been controversial, it is likely that a major horizontal translation of Early Jurassic terranes in north-central Mexico took place in the Middle Jurassic (Longoria, 1984a). This mid-Jurassic transcurrence invoked by Longoria (1984a) in east-central Mexico is herein considered as the southern boundary of the transpressive system in the subsurface of northeastern Mexico. From paleomagentic studes by Gose et al. (1982), it becomes evident that large portions of northeastern Mexico (the Sierra Madre Oriental) have rotated 130 degrees in a counterclockwise direction in the early Mesozoic.

In surounding regions, major lineaments of continental extent now related to transcurrent movements have been postulated by Hills (1962), Sales (1968) and Walper (1977). Sales (1968) Texas Lineament is of funadmental siginficance in NE Mexico since this ESE-WNW trending destral fault parallels a major left lateral transcurrence in the Victoria Segment of the Sierra Madre Oriental (Figure 4). Walper (1977) indicated the likely existence of such transcurrences in northern Mexico parallel to the Wichita Lineament. King (1975) postulated several prominent Paleozoic discontinuities of undetermined character associated to transcurrent faults and rift trends in eastern United States. He related these faults to the late Proterozoic. From the examples given by Molinar and Tapponnier (1975) it is clear that transcurrent faults are associated to the effect of contiental collision since this type of faults are common features in those settings. Accordingly, transcurrent faults form after the direct

compressive stress is transmited far into the contiental masses, then becoming inactive ("latent"), until another major tectonic event takes place breaking the static equilibrium.

4. Plate Tectonic Reconstruction of Mexico and the Geologic Evolution of the Gulf of Mexico and Caribbean Region.- The geologic history of NE Mexico is directly linked to the plate tectonic history of the Gulf of Mexico-Caribbean region and undoubtedly was a part of this region since Paleozoic time. Any plate tectonic reconstruction of this region will certainly involve large scale horizontal despacements of continental blocks such as the present day basement of northeast Mexico. Attempts to unravel the plate tectonic history of the Gulf of Mexico and the Carribbean by Walper and Rowet (1982), Pindell and Dewey (1982) and Anderson and Schmidt (1983) are well-known to invoke the existence of large scale horizontal despacement, via transcurrent faults or megashears, providing circunstancial evidence to assume that the basement of northeastern Mexico is bounded by an intricate system of transcurrent faults some of which, logically, may have been active since the Precambrian.

PROPOSED TECTONIC MODEL IN NE MEXICO

It is suggested herein that the deformation of the Mesozoic sedimentary succession found in northeastern Mexico is the result of tectonic transpression active perhaps since the Late Jurassic. This transpressive regime is directly related to a wrench-faulting system in the basement. The proposed wrench-fault system in northeastern Mexico (Figure 4) is bounded on the north by the Texas Lineament, and on the south by the Walper Lineament [megashear proposed by Longoria (1984a), herein named after Jack L. Walper who first suggested the presence of this lineament]. These first order transcurrent faults trend ESE-WNW (N60W). Second order faults include the

San Marcos and La Babia faults, trending SE-NW (N40W) and intersecting the first order wrench-faults at a 20 degree angle. The Torreon-Monterrey Fractrue described by Cserna (1971) is considered as a thrid order fault, trending in an F-W (N90W) direction and intersects the San Marcos fault at a 50 degree angle. Fourth order transcurrent faults include the Galeana and Chihuahua faults (N05W9), trending almost in a N-S direction, and intersecting first order faults at a 90 degree angle. These faults have been verified in the ground at a few localities (Figure 4), their interelation is inferred from the regional (large-scale) deformational patterns they produce. Their assumed geometric arrangement is interpreted from theoretical models.

Consequently, the structural style of deformation observed in northeastern Mexico is attributed to a transpressive regime as defined by Harland (1971). The relation between the transpressive deformation and the postulated wrench fault zone is evident since the transcurrent faulting is considered as a component of transpression (Figure 4). The sinistral transpression is regarded as a local response to the sinistral transcurrence operating within the wrench fault system in NE Mexico. The Victoria Segment of the Sierra Madre Oriental displays the combined effects of an early Tertiary transpressive deformation and, in part, a wrench tectonic phase (Figure 5). This transpressive regime in NE Mexico (Figure 4) is associated to an oblique-slip mobile zone related to the Late Jurassic spreading phase in the Gulf of Mexico (Longoria, 1984a). The propsed tectonic transpression explains the diference in structural styles observed in northeastern Mexico, and accounts for the different present-day physiographic provinces of the region (Figure 5).

CONCLUSIONS

Local and regional structural elements of northeastern Mexico give evidence for a transpressional regime related to the existence of an intricated system of wrench faults. Circunstancial evidence also shows that transcurrent faults are likely to occur in the basement of the region. The origin of this wrench fault system is linked to Tectonic Event II (Shearing Phase) described by Longoria (1984a) from east-central Mexico. The transpressive tectonic model herein presented gives an adequate senario to integrate all the previously described, apparentely incompatible, deformational models for northern Mexico, and conciliates the differences in fold vergence in the region (Figure 5). Lateral movements along transcurrent faults in the basement resulted in seven tectonic elements which account for present-day geologic provinces recognized in northeastern Mexico (Figure 5): 1) The Victoria Segment of the Sierra Madre Oriental, including a) the Transverse Folded Belt, and b) the East Front, 2) The Coahuila Folded Belt, and 3) The Sierras Tamaulipecas. Transcurrent faults in NE Mexico resulted from the rejuvenation of ancient Paleozoic faults. This faults resulted from: 1) The collision of the southernmost part of the craton when Pangea was formed, 2) The break up of Pangea, and 3) The origin of the Gulf of Mexico. Active seafloor spreading in the Gulf of Mexico (Tectonic Event III described by Longoria, 1984a) is the more likely mechanism to break up the static equilibrium of ancient Paleozoic faults, via transform faulting at the spreading center, reactivating the continetal area (basement), a somewhat similar mechanism to that observed in the South Atlantic between Africa and South America as discussed by Sibuet and Mascle (1978). The La Babia and San Marcos transcurrent faults are likely to represent a Miocene reactivation of the Late Jurassic transcurrent faults described by Longoria (1984).

REFERENCE CITED

Alfonso Zwansinger, J., 1978, Geologia regional del sistema sedimentario Cupido: Boletin de la Associacion Mexicana de Geologos Petroleros, v. 30, nos. 1-2, p. 1-55.

Anderson, T. H. and Schmidt, V. A., 1983, The evolution of the Middle America and the Gulf of Mexico-Caribbean Sea Region during Mesozoic time: Geological Society of America Bulletin, v. 94, p. 941-966.

Avenius, C. G., 1982, Tectonics of the Monterrey Salient, Sierra Madre Oriental, northeast Mexico [Ms. Thesis]: New Orleans, University of New Orleans, 83 p.

Ballance, P. F., and Reading, H. G., 1980, Sedimentation in oblique-slip mobile zones: an introduction: Special Publication no. 4, International Association ofSedimentologists, v. 4, p.1-5.

Bose, E., 1923, Vestiges of an Ancient Continent in Northeast Mexico: American Journal of Science, 5th Series, v.6, p. 127-136, 196-214, 310-337.

Campbell, J. D., 1958, "En Echelon" Folding: Economic Geology, v. 53, p. 448-472.

Charleston, S., 1981, A summary of the structural geology and tectonics of the State of Coahuila, Mexico, In Katz, S. B. and Smith, C. I., eds., Lower Cretaceous stratigraphy and structure of Northern Mexico: West Texas Geological Society Fieldtrip Guidebook, Publication no. 81-74, p. 28-36.

Closs, E., 1955, Experimental analysis of fracture patterns: Geological Society of America Bulletin, v. 66, p. 241-256.

Cserna, Z. de, 1956, Tectonica de la Sierra Madre Oriental de Mexico, entre Torreon y Monterrey: Congreso Geologico Internacional, 20th Sesion,

Mexico, 87 p.

Cserna, Z. de, 1971, Tectonics of northern Mexico (Mesozoic sedimentation, magmatic activity and deformation in northern Mexico), in Seewald, K., and Sundeen, D., eds., The geologic framework of the Chihuahua tectonic belt: West Texas Geological Society Publication 71-59, p. 99-118.

Gose, W. A., Belcher, R. C., and Scott, G. R., 1982, Paleomeagnetic results from northeastern Mexico - Evicence for large Mesozoic rotations: Geology, v. 10, no. 1, p. 50-54.

Harland, W. B., 1971, Tectonic transpression in Caledonian Spitsbergen: Geological Magazine, v. 18, no. 1, p. 27-42.

Hills, J. M., 1963, Late Paleozoic tectonics and mountain ranges, western Texas to southern Colorado: American Association of Petroleum Geologists Bulletin, v. 47, no.9, p. 1709-1725.

Humphrey, W. E., 1956, Tectonic framework of northeast Mexico: Gulf Coast Association of Geological Societies Transactions, v. 6, p. 25-35.

King, P. B., 1975, Ancient southern margin of North America: Geology, December, P. 732-734.

Longoria, J. F., 1984, Stratigraphic studies in the Jurassic of northeastern Mexico: Evidence for the origin of the Sabinas Gulf: Gulf Coast Section, Society of Economic Paleontologists and Mineralogists, Annual Research Conference Proceedings, March 1984, p. 171-193.

Longoria, J. F. 1984a, Mesozoic tectonostratigraphic domains in east-central Mexico: In Westermann, G. E. G. (ed.), Jurassic-Cretaceous Biochronology and Paleogeography of North America. Geological Association of Canada, special paper 27.

Longoria, J. F. and Jimenez, O. H., 1984. SIR-A imager in regional

mapping of the Sierra Madre Oriental, northeastern Mexico: Geology (in press)

Molnar, P., and Tapponier, P., 1975, Cenozoic tectonics of Asia -Effects of a continental collision: Science, v. 189, n.o. 4201, p. 419-423.

Moody, J. D., and Hill, M. J., 1956, Wrench-fault tectonics: Geological Society of America Bulletin, v. 67, no.3, p. 1207-1246.

Murray, G. E., 1961, Geology of the Atlantic and the Gulf Coastal Province of North America: Harper & Brothers, Publishers, 629 p.

Odonne, F., and Vialon, P., 1983, Analogue models of folds above a wrench fault: Tectonophysics, v. 99, p. 31-46.

Padilla y Sanchez, R. J., 1982, Geologic evolution of the Sierra Madre Oriental between Linares, Concepcion del Oro, Saltillo and Monterrey, Mexico [Ph.D. dissert.]: Austin, University of Texas, 217 p.

Pindell, J., and Dewey, J. F., 1982, Permo-Triassic reconstruction of western / Caribbean Region: Tectonics, v. 1, no.2, p. 179-211.

Sales, J. K., 1968, Crustal mechanisms of cordilleran foreland deformation -A regional and scale-model approach: American Association of Petroleum Geologists Bulletin, v. 52, no. 10, p. 2016-2044.

Sibuet, J-C., and Mascle, J., 1978, Plate kinematic implications of Atlantic equatorial fractures zone trends: Journal of Geophysical Research, v. 83, no. B7, p. 3402-3421.

Tanner, W. F., 1961, Surface structural patterns obtained from strike-slip models: Journal of Geology, v. 70, p. 101-107.

Tardy, M., 1980, Contribution a l'etude geologique de la Sierra Madre Orientale du Mexique [These de Doctorat d'Etat]: Paris, Universite Pierre et Marie Curie, 459 p.

Tardy, M., Longoria, J. F., Martinez, J., Mitre, L. M., Patino, M.,

Padilla y Segura, J. R., and Ramirez, C., 1975, Observaciones generales sobre la estructura de la Sierra Madre Oriental: la aloctonia del conjunto Cadena Alta-Altiplano Central, entre Torreon, Coah. y San Luis Potosi, S.L.P., Mexico: Universidad Nacional Autonoma de Mexico, Revista del Instituto de Geologia, v. 75, no. 1, p. 1-11.

Wall, J. R., Murray, G. E., and Diaz, T. 1961, Geology of the Monterrey area, Nuevo Leon, Mexico: Gulf Coast Association of Geological Societies Transactions,v. 11, p. 57-71.

Walper, J. L., 1977, Paleozoic tectonics of the southern margin of North America: Gulf Coast Association of Geological Societies Transactions, v. 27, p. 230-241.

Walper, J. L., and Rowett, C. L., 1982, Plate tectonics and the origin of the Caribbean Sea and the Gulf of Mexico: Gulf Coast Association of Geological Societies Transactions, v. 22, p. 105-116.

Wilcox, R. E., Harding, T. P., and Seely, D. R., 1973, Basic Wrench Tectonics: American Association of Petroleum Geologists Bulletin, v. 57, no. 1, p. 74-96.

Woodcock, N. H., and Robertson, A. H. F., 1982, Wrench and thrust tectonics along a Mesozoic- Cenozoic continental margin - Antalya Complex, SW Turkey: Journal of the Geological Society of London, v. 139, p. 147-163.

ACKNOWLEDGMENTS

The present investigation was carried out at the University of Texas at Dallas (U.T.D. Contribution 459). Founds for the preparation of this research were obtained from the Jet Propulsion Laboratory, NASA (JPL Contract 956430).

FIGURE CAPTIONS

Figure 1. Index map of Mexico showing the location of the study area and track of SIR-A swath 22 (parallel lines).

Figure 2. Structrual elements of the Saltillo-Galeana Folded Belt (shadow area), and general trend of anticlinal folds in NE Mexico: 1) Sierra Los Nuncios, 2) Sierra San Lucas, 3) Sierra de Arteaga, 4) Sierra Las Nieves, 5) Sierra de Zapaliname, 6) Cerro El Cedral, 7) Sierra El Tapanque, 8) Sierra Pilar Alto, 9) Sierra La Esmeralda, 11) Sierra San Antonio, 12) Sierra La Viga, 13) Sierra Rancho Nuevo, 14) Sierra Potrero de Abrego, 15) Cerro el Coahuilon, 16) Sierra La VEleta, 17) Cerro El Banco, 18) Sierra Las Pintas, 19) Cerro El Potosi, 20-21) Sierra Borrada, 22) Sierra California, 23) Cerro Rayon, 24) Sierra La Ventana, 25) Cerro de la Silla, 26) Cerro Loma Larga, 27) Cerro Las Mitras, 28) Cerro Topo Chico, 29) Sierra Pichachos, 30) Sierra Potero Grande, 31) Sierra Potero Chico, 32) Sierra Las Grutas, 33) Sierra los Muertos, 34) Sierra Catana, 35) Sierra El Toro, 36) Cerro El Venado, 37) Sierra El Jabali, 38) Sierra Las Mazmorras, 39) Sierra La Tomita, 40) Sierra Las Vallas. M) Monterrey, S) Saltillo, G) Galeana.

Figure 3. Hypothetical trace of pre-Late Jurassic lineaments, megashears, and transcurrent faults according to different authors: 1) San Andreas Fault, 2) Walkerlane Fault, 3) Hurricane-Seiver Lineament, 4) Texas Lineament [Moody and Hill, 1956], 5) Park Lineament, 6) White River Lineament, 7) Uncompaghre Lineament, 8) Zuni Lineament, 9) Walker Lineament [Kelley, 1955 and Hills, 1968], 10, 11, 12, 13) Paleozoic Discontinuities [King, 1975], 14) Wichita Lineament, 15) Texas Lineament [Sales, 1968], 16) Sabinas Fault, 17) Monclova Fault, 18) Padilla Fault [Alfonso, 1976], 19) Saltillo-Monterrey Fracture Zone [Murray, 1961], 20) Zacatecas Fracture Zone, 21) Torreon-Monterrey Fracture Zone [Cserna, 1971], 22) Mojave-Sonora

Megashear [Anderson and Schmidt, 1984].

Figure 4. Proposed tectonic transpressional model, and its relation to Late Jurassic sea floor spreading in the Gulf of Mexico. Latters refer to areas whereby field data was obtained: m) Mexicali, n) Nogales, c) Caborca, h) Hermosillo, ch) Chihuahua, to) Torreon, b) Boquillas, d) Delicias, mo) Monterrey, mc) Monclova, ma) Matehuala, v) Victoria, t) Tampico, sa) San Antonio.

Figure 5. Index map of northeasten Mexico showing the location of Mesozoic sections studied, and the relation of the wrench-faults to present-day geologic provinces. Dotted lines indicate the assumed trace of postulated faults. Arrows indicate the general direction of fold vergence and local decollemant.

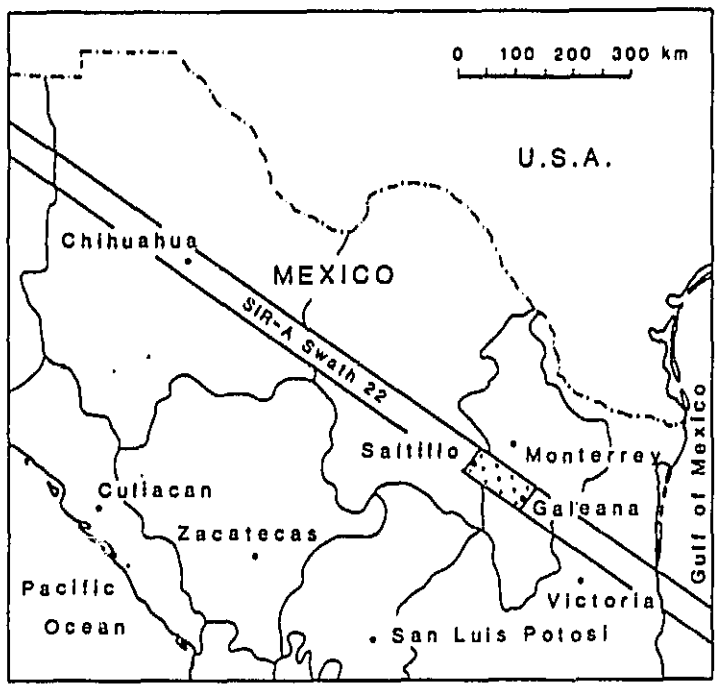

0 100 200 300 km
U.S.A.
Chihuahua
MEXICO
SIR-A Swath 22
Saltillo
Monterrey
Culiacan
Galeana
Zacatecas
Pacific
Ocean
Victoria
San Luis Potosi
Gulf of Mexico

Figure 1

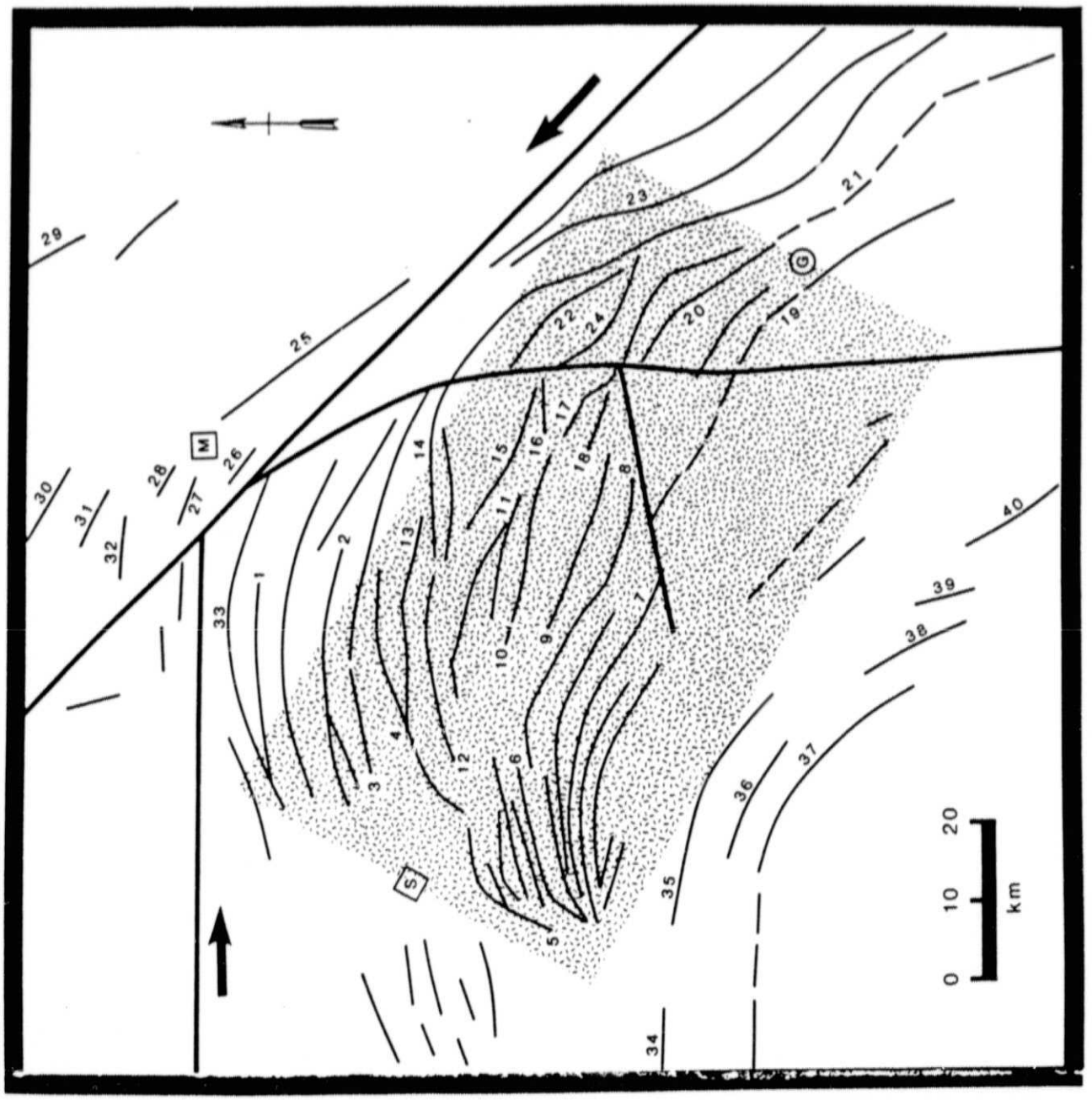


Figure 2

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

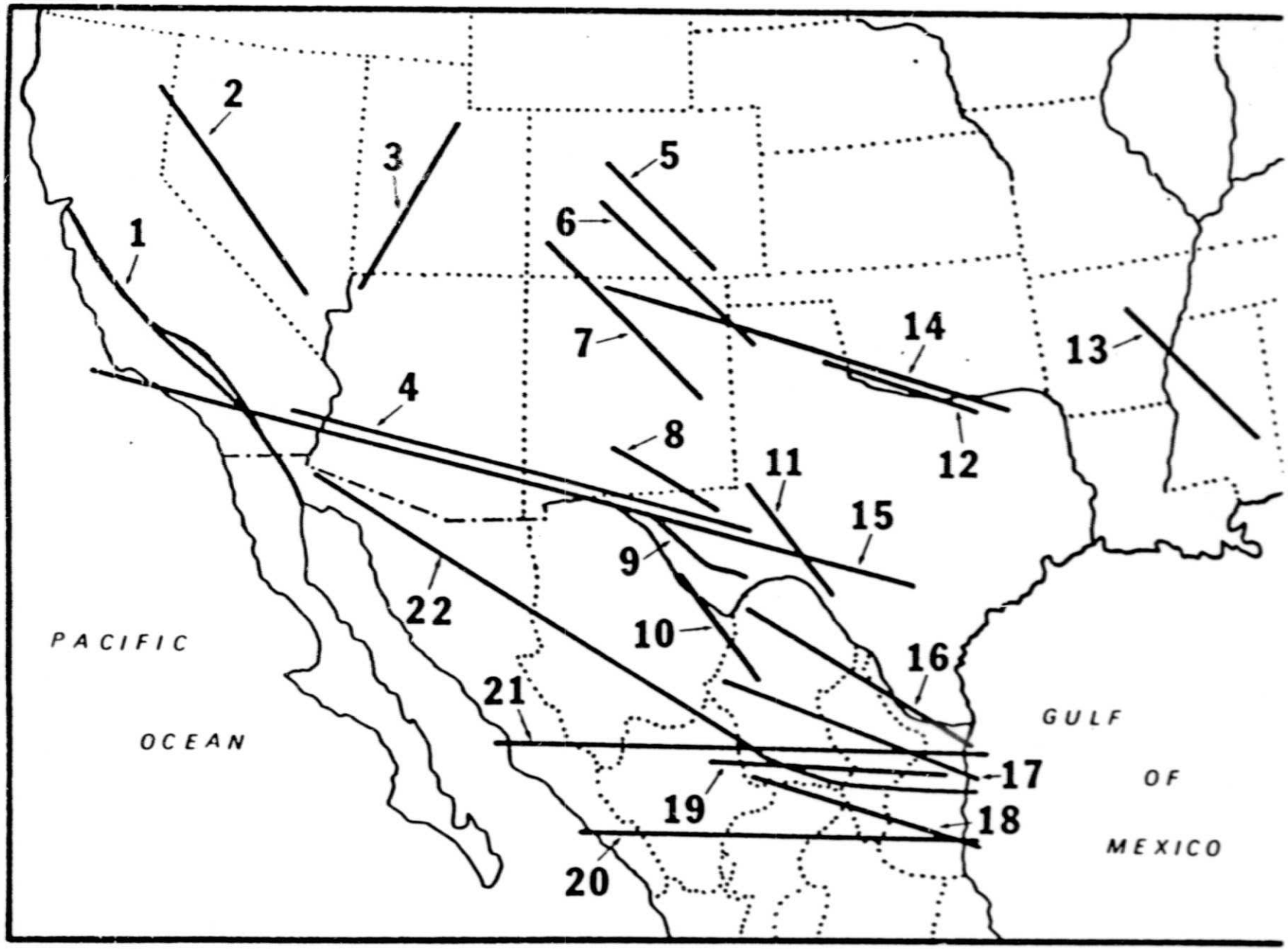

2
3
5
1
6
7
14
13
4
8
12
11
15
9
22
10
16
PACIFIC
OCEAN
21
GULF
OF
MEXICO
17
19
18
20

Figure 3

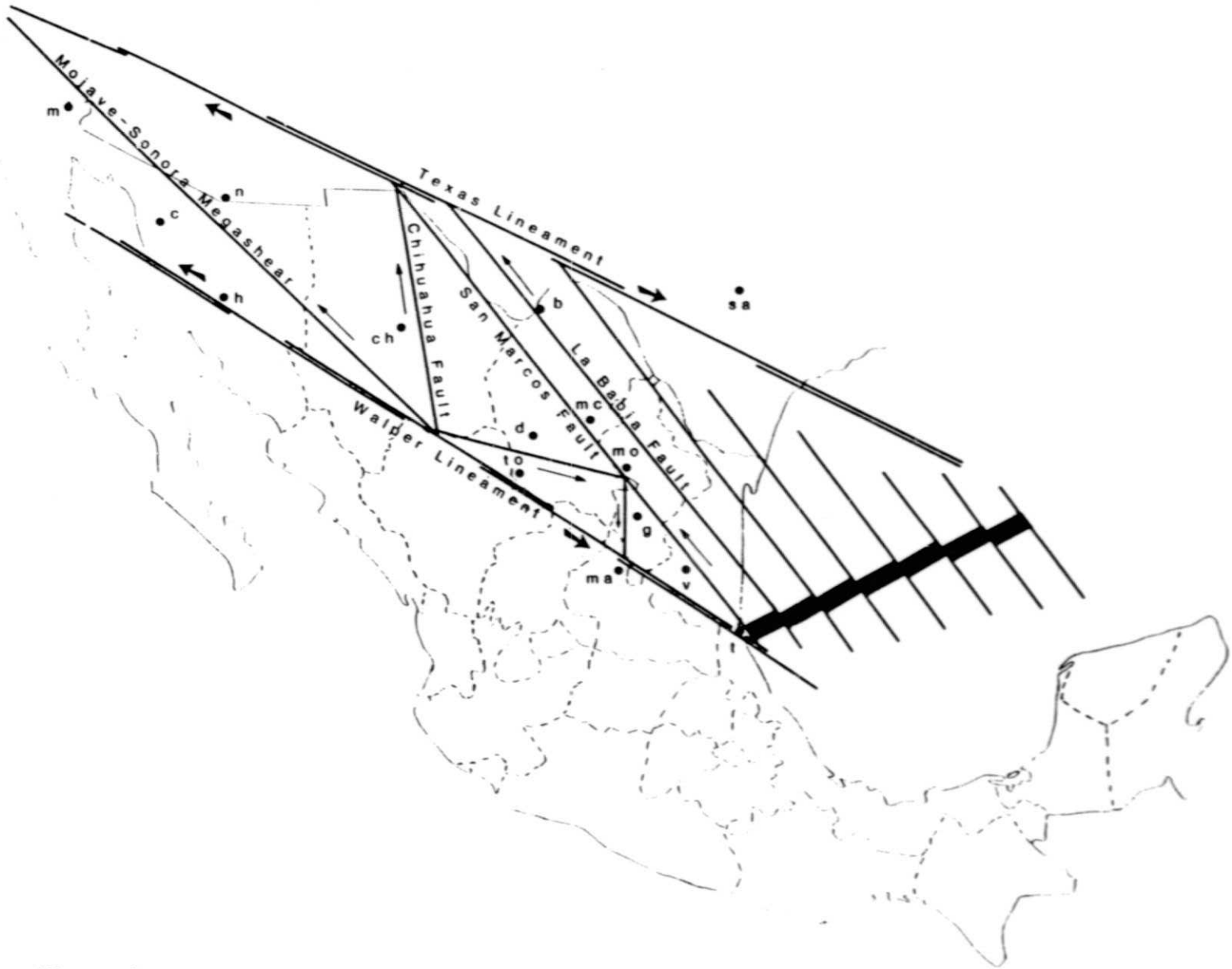

Mojave-Sonora Megashear
Texas Lineament
Chihuahua Fault
San Marcos Fault
La Babia Fault
Walder Lineament
m
n
c
h
ch
b
sa
d
mc
mo
to
g
ma
v
t

Figure 4

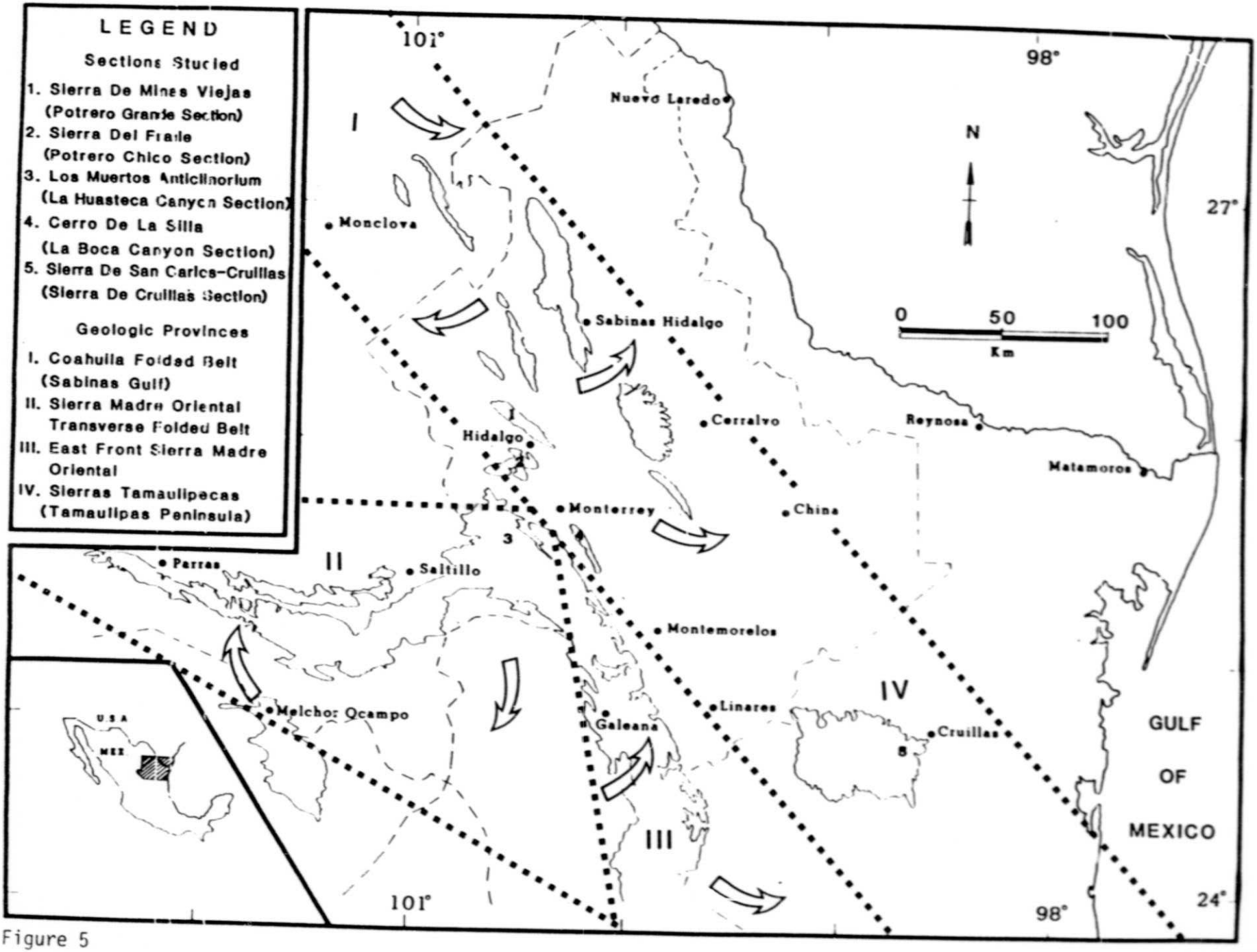

LEGEND
Sections Studied
1. Sierra De Minas Viejas (Potrero Grande Section)
2. Sierra Del Fraile (Potrero Chico Section)
3. Los Muertos Anticlinorium (La Huasteca Canyon Section)
4. Cerro De La Silla (La Boca Canyon Section)
5. Sierra De San Carlos-Cruillas (Sierra De Cruillas Section)
Geologic Provinces
I. Coahuila Folded Belt (Sabinas Gulf)
II. Sierra Madre Oriental Transverse Folded Belt
III. East Front Sierra Madre Oriental
IV. Sierras Tamaulipecas (Tamaulipas Peninsula)
101°
98°
27°
24°
N
0 50 100
Km
Nuevo Laredo
Monclova
Sabinas Hidalgo
Cerralvo
Reynosa
Matamoros
Hidalgo
Monterrey
China
Parras
Saltillo
Montemorelos
Melchor Ocampo
Galeana
Linares
Cruillas
GULF OF MEXICO
I
II
III
IV
1
2
3
4
5
U S A
MEX

Figure 5