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Structure of the Managua graben, Nicaragua, from remote sensing images

A. Frischbutter
GeoForschungsZentrum Potsdam, Potsdam, Germany

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RESUMEN

Como resultado de varias interpretaciones de datos de sensores remotos combinados con datos sismológicos del terremoto de 1972, se llega a la conclusión que la zona de fallas del lago de Managua es una estructura compuesta de importancia regional con dirección norte-sur. El borde este de la zona de fallas del lago de Managua está formado por estructuras de menor orden en que la importancia de movimiento lateral se disminuye hacia el este favoreciendo estructuras de fallamiento normal. Las fallas N-S se presentan en su mayoría como fallas oblicuas con componentes dextrales de movimiento lateral. En combinación con fallas marginales en dirección NW de la depresión de Managua, resulta un régimen de transpresión de la zona del lago de Managua. Movimientos sinistrales en estructuras con rumbos de NNE a NE fueron reproducidos claramente en datos sismológicos del terremoto de 1972 (extensión en substructuras: por ejemplo el graben de Managua, el graben del Aeropuerto). Planos con rumbo N, NW y NE se consideran activados recientemente dentro de la región de interés. Del punto de vista de la amenaza sísmica hay que tomar en cuenta las relaciones cinemáticas. Por su régimen extensional los planos con rumbo NE tienen importancia especial. En los planos bajo compresión en dirección NW son possibles mayores concentraciones de estrés.

Se postula que en el evento de 1972 se activó solamente la parte oeste del graben de Managua. Como consecuencia de esta reactivación - además de otras deducciones - aumentó posiblemente la concentración del estrés a lo largo de la parte este del graben.

PALABRAS CLAVE: Percepción remota, neotectónica, sismología, graben de Managua, Nicaragua.

ABSTRACT

From remote sensing interpretations, combined with seismological data of the 1972 earthquake, the Managua Fault Zone is seen as a N-S - trending, composite structure of regional importance. The eastern margin of the Managua Fault Zone is formed by lower-order, N-S - trending graben structures such as the Managua graben or the Airport graben, which are bordered by oblique faults. The intensity of lateral movements on these N-S trending faults seems to decrease to the east as normal faulting increases. Lateral components on N-S trending faults are mainly dextral in recent times. In combination with the NW - trending marginal faults of the Nicaragua depression this represents a transpressional regime for the Managua Fault Zone. Components of left lateral movements on NNE- to NE - trending structures are clearly indicated from seismological data for the 1972 Managua earthquake (extension within substructures like the Managua graben, Airport graben). N-, NW- and NE - trending planes should be regarded as recently active in the region. These kinematic relations must be taken into account for seismic hazard assessment: NE - trending planes are emphasized because of their extensional regime.

It is postulated that during the 1972 event only the western part of the Managua graben was activated. Higher recent stress concentration along the eastern margin of the graben may be a consequence, among others.

KEY WORDS: Remote sensing, neotectonic, seismology, Managua graben, Nicaragua.

INTRODUCTION

Nicaragua, situated in Central America between the Pacific ocean and the Caribbean sea, became a region of intense geoscientific research after the devastating earthquake (M=6.2) in December 1972 that destroyed Managua, the capital of the country. In the years after the earthquake several seismological, geological and tectonic projects have investigated the causes of the event and the implications for the seismic risk of Managua. In 1975 a seismological observation network was installed, which worked with excellent results until 1982, recording more than 15 000 local and regional earthquakes. It collapsed in the following years, due to economical, political and military crises that struck the country. Similar problems finally inhibited the continuation of geoscientific data collection, the full use of the new data base and of new emergent techniques for the evaluation of the seismic risk of Managua and all of Nicaragua.

In the nineties the seismic network was reestablished on a higher technical level and geoscientific research began to emerge mainly under the auspices of the Instituto

Nicaraguense de Estudios Territoriales (INETER), the leading geophysical institution of the country. Besides trying to improve its own research capabilities, the institute is co-operating with many geoscientific researchers from various countries, especially in the field of seismology, tectonics and seismic hazard assessment.

This paper presents initial results of a project carried out in the context of German activities related to the International Decade of Natural Disaster Reduction (IDNDR). Interpretations of remote sensing images are made, especially with respect to features of the structural pattern, to obtain a part of the basic information required for seismic hazard assessments for the territory of Nicaragua.

REGIONAL GEOLOGICAL SUMMARY

The interaction of the Cocos-, Nazca- and Caribbean plates between the North- and South-American plates produces a complicate structural pattern of the Earth's crust in Central America. Several geotectonic events are superimposed, starting from Jurassic times (but at least since Cretaceous): rifting in connection with the separation of Laurasia and Gondwana, the recent convergence in NW- to WNW - direction between the South- and North-American plates as well as subduction of the Pacific- under the American plates. The triangular Cocos plate is bordered in the west by the East Pacific rise against the Pacific plate, towards the south against the Nazca plate by the Galapagos rift and in the Northeast against the Caribbean- and North-American plates by the Central American subduction zone along the Middle America trench. The territory of Nicaragua represents the southern part of the Chortis block, which is bordered to the NW by the sinistral Motagua-Polochic-Faults (including the Cayman trough) and in the Southeast by the dextral Hess-Escarpment (Figure 1).

The crustal structure of Nicaragua is the result of an interaction of several plates, starting with the breakup of Pangea at 250 Ma (Burke *et al.,* 1984), followed by the collision of the Farallon plate with Protocaribbean crust (primitive island arc tholeiites) in Albian to Santonian times (Seyfried *et al.,* 1991). The crust beneath the Caribbean sea

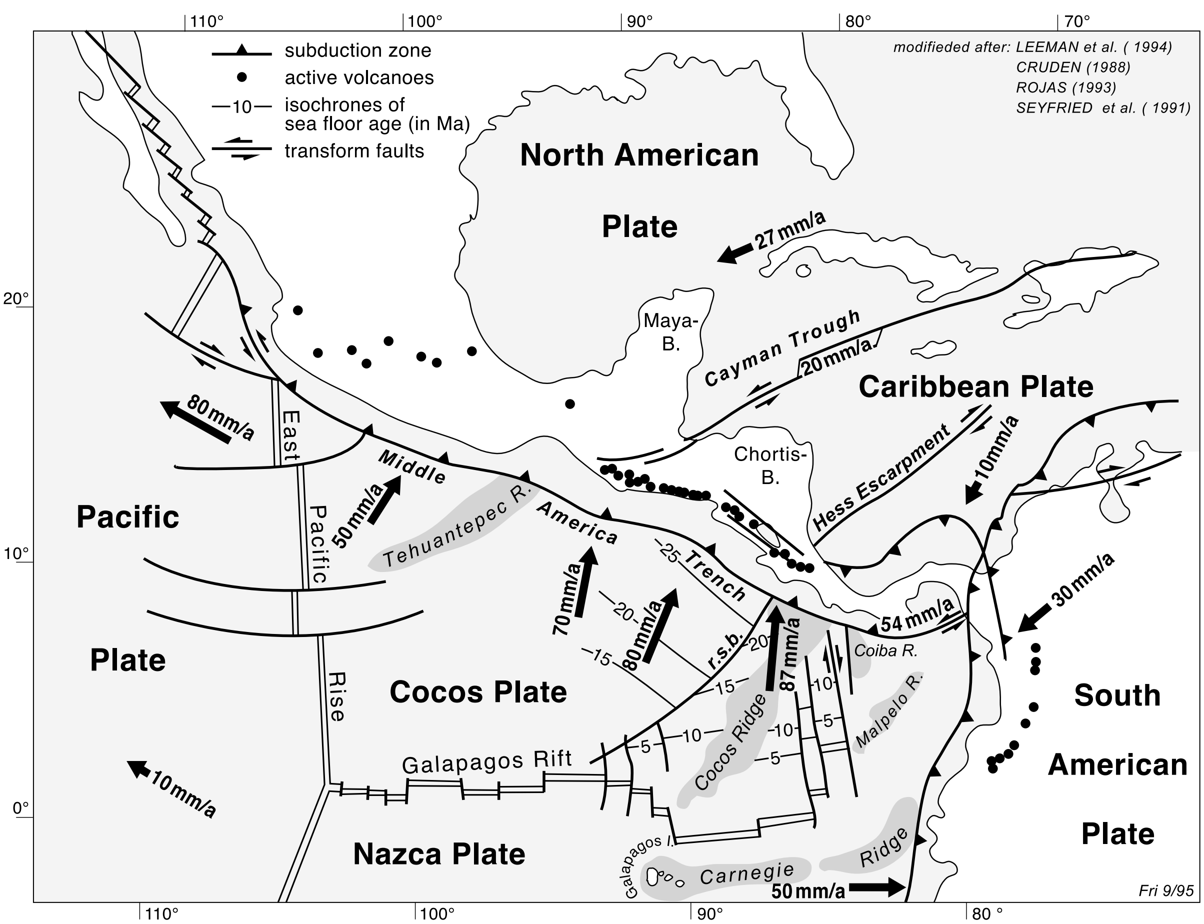

Fig. 1. Sketch of the regional geological setting of Nicaragua. The chain of active volcanoes (dotted line) as well as average drift velocities for different positions are shown.

was considered as a remnant of an oceanic flood basalt plateau, wedged between the North- and South American plates (Sinton *et al.,* 1998). The Farallon plate was broken into the Cocos- and the Nazca-plates in Lower Miocene times. An old medium- to low grade, partly highly deformed metamorphicum of probably Paleozoic age, including granitic to intermediate intrusive rocks (Bermúdez *et al.,* 1992) is involved in the magmatic arc evolution of the crust along the border with Honduras (Figure 2). The Atlantic coastal plain is formed mainly by Miocene to Quaternary up to Holocene deposits, overlying a Tertiary, sedimentary-magmatic succession, which continues towards the east as the Nicaragua ridge under the Caribbean sea. Within the Inner Highlands of Nicaragua are widespread volcanic rocks of Tertiary age, which generally become younger from east to west and parallel to the Middle America trench.

A belt of volcanoes extends over a length of about 1100 km from Mexico to Costa Rica and at a distance of approximately 200 km from the Middle American trench, which is formed by the subduction of the Cocos plate beneath the Caribbean plate. Volcanic activity in Central America dates back to Quaternary times. The magmatic arc consists mainly of basaltic-andesitic volcanic rocks (predominantly pyroclastics with subordinated solid lava sheets). Moreover, the belt follows the axis of the Nicaragua depression. The Nicaragua depression is a morphologically well expressed NW-SE - trending lowland between El Salvador and Costa Rica (up to 50 km wide), which was interpreted as a tectonic half-graben by McBirney & Williams (1965) or a full graben structure due to coast-parallel strike slip faulting (Cruden, 1989). Van Wyk de Vries (1993) explained the depression by isostatic readjustment related to the mass of Tertiary volcanics deposited in the Interior Highlands. The depression is filled with Miocene to Quaternary, predominantly volcano-clastic deposits. The marginal structures of the depression are covered mostly by the youngest deposits. The thickness of Holocene deposits is in the order of 2000 m (Weinberg, 1992).

The Pacific coastal region is composed of a forearc suite of Upper Cretaceous to Tertiary age, with a thickness

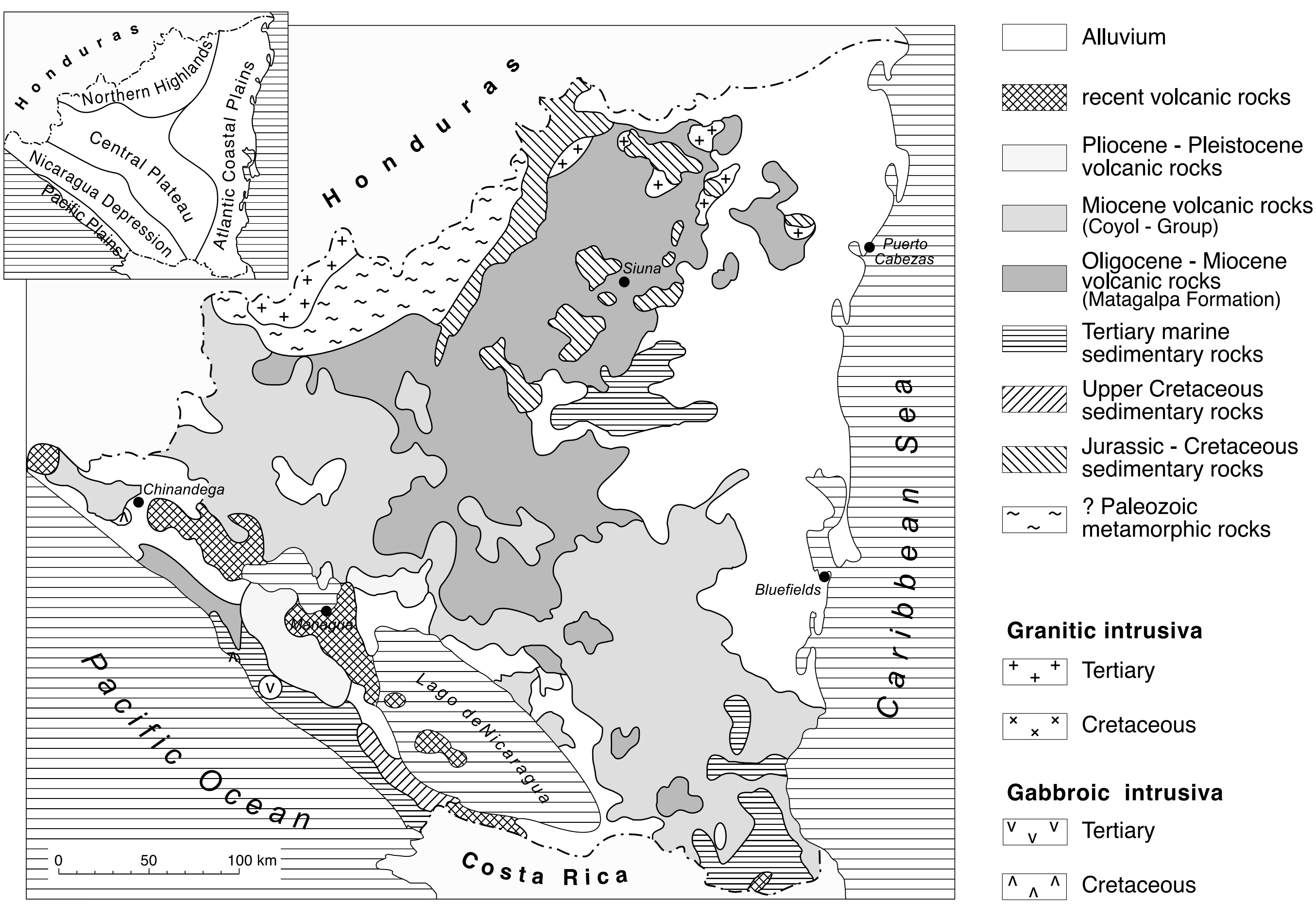

Fig. 2. Generalized geological map of Nicaragua, simplified from the “Geological map of Nicaragua” 1: 500 000, INETER Managua (1995).

of up to 8000 m (Kuang, 1971). The Prepliocene is deformed into open folds with approximately NW-SE - trending, horizontal axes and is unconformably overlain by unfolded, sandy-conglomeratic and calcareous, older Pliocene and andesitic to rhyodacitic younger Pliocene (Andean-tectogene; Dengo, 1985). Thrust- and reverse faults indicate NE- to E - directed transport (Cruden, 1989).

The structural, neotectonic evolution of western Nicaragua, following the deformation associated with upper-greenschist- to amphibolite facies metamorphism of the Paleozoic complex in northern Nicaragua, was subdivided by Weinberg (1992) into three stages:

1. Late Miocene to early Pliocene compression produces the NW-SE - trending fold-structure of the Pacific coastal region, which is associated with volcanic activities of Miocene to Pliocene age in the Interior Highlands.

2. The NE-drift of the Chortis block was related in Pliocene-Pleistocene times to an extensional regime, which in turn resulted in the formation of the Nicaragua depression. Simultaneously, an increasing dip angle of the subducted Cocos Plate caused a SW-migration of the active volcanic belt (Jarrard, 1986). Due to the inverse relationship between the dip and the relative rate of convergence of plates, increasing dip of the subducted slab requires a decreasing convergence (Luyendyk, 1970).

3. Early Pleistocene to present: The formation of pull-apart structures, e.g., the N-S - trending Managua graben, is caused due to N-S horizontal shortening.

THE MANAGUA GRABEN

The N-S - trending Managua graben represents a recently active extensional structure, characterized by numerous lower magnitude seismic events within the city and the surroundings of Managua. Two earthquakes in recent times (1931 and 1972) destroyed the city of Managua disastrously.

The Cofradia fault system in the east and the Nejapa-Miraflores line (Figure 3a) in the west (linear arrangement of calderas and ash cones, combined with a relief drop of about 150 m from west to east) are regarded as the marginal structures of the Managua graben (van Wyk de Vries, 1993). The Managua graben dislocates the structure of active volcanoes within the Nicaragua depression and is characterized by dextral slip of approximately 13 km (Weinberg, 1992). Ward *et al.* (1974) assigned the dextral dislocation of the volcano belt to the Tiscapa fault, which represents an easterly element parallel to the Nejapa line. Following the concept by Martínez *et al.* (1992) the Cofradia fault system on the eastern flank of the Managua graben represents a separate graben structure (Airport-graben) with *en echelon*-like, steeply westward plunging normal faults. A similar graben substructure is described from the western flank of the Managua graben (Tiscapa graben). Between these marginal structures a series of approximately N30°E - trending faults with a sinistral slip component was detected, which reaches to a crustal depth of about 8-10 km and which is believed to represent the main active faults, formed by the earthquakes of 1931 and 1972 also (Brown *et al.,* 1973; Bermúdez *et al.,* 1992).

THE MANAGUA GRABEN ACCORDING TO REMOTE SENSING IMAGES

In the following are discussed indications of the Managua graben, derived by processing various remote sensing images (LANDSAT-mosaic, LANDSAT-TM, SPOT and Radar (SLR)-images) (Figure 3b). The images, except for the LANDSAT-TM scenes, have been generously placed at our disposal by INETER (Managua). A concentrated representation of the methodology used for the interpretation of remote sensing images in geology was edited for UNESCO-training courses by Bankwitz & List (1992) or List & Bankwitz (1993).

LANDSAT-mosaic

The mosaic was produced from LANDSAT 2 and 3 images (1978 and 1979). It covers the Pacific part of Nicaragua between Honduras to the north, the NW-shore of Lake Nicaragua in the east and reaches over the Nicaragua depression in the NE up to the western margin of the Interior Highlands.

The mosaic permits an evaluation of structural elements on a regional scale (Figure 3b, 4). A regionally dominant, N-S - trending zone could be detected between the western and eastern shores of Lake Managua (here called Managua Fault Zone). The zone is characterized by the dominance of roughly N-S - trending lineations. The same lineations cause uniform (always with a southward displaced eastern flank), sharp-edged dislocations of the Pacific coast-line in this region, producing a step-like structuring of the shore-line. The remarkably sharply depicted displacements indicate young or even recent activity of structures related to the lineations. The Managua Fault Zone is characterised by a clearly denser pattern of N-S - trending lineations (approximately 1km in length) compared to the adjoining areas (approximately 10 km). Moreover, the magnitude of displacements on the single elements seems to be smaller there. The structural features of the coast-line west of the Managua Fault Zone are clearly different: West from the estuary of the río El Tamarindo, which is influenced in its lower course by the N-S - trending structures of the marginal zone, the coast-line

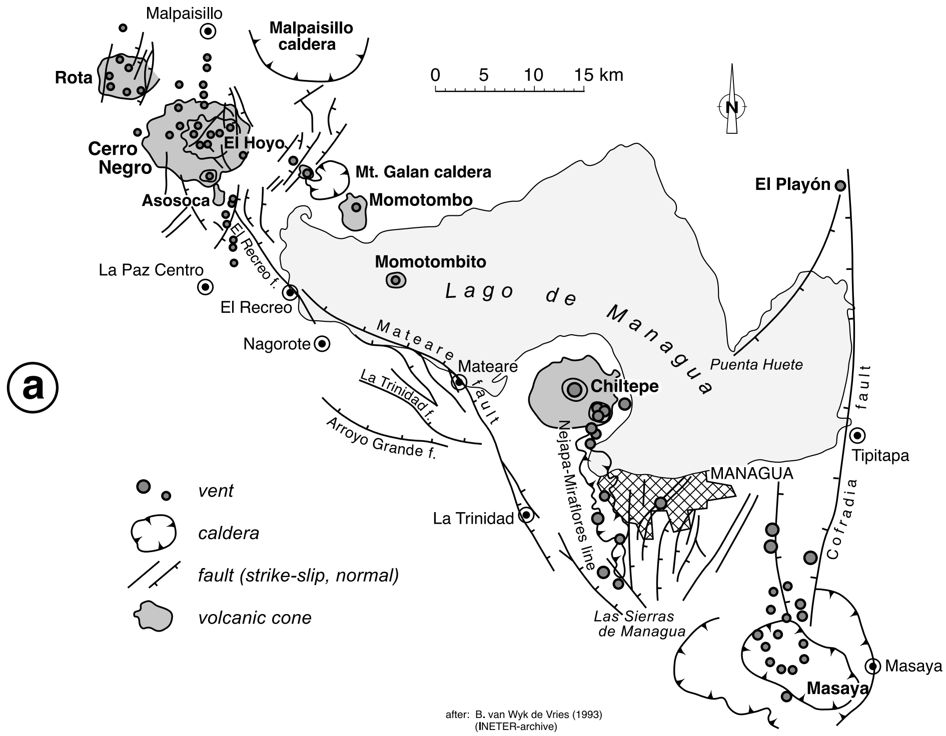

Fig. 3a. Observed structures and subrecent volcanic features in the surroundings of Lake Managua (after van WYK DE VRIES, 1993).

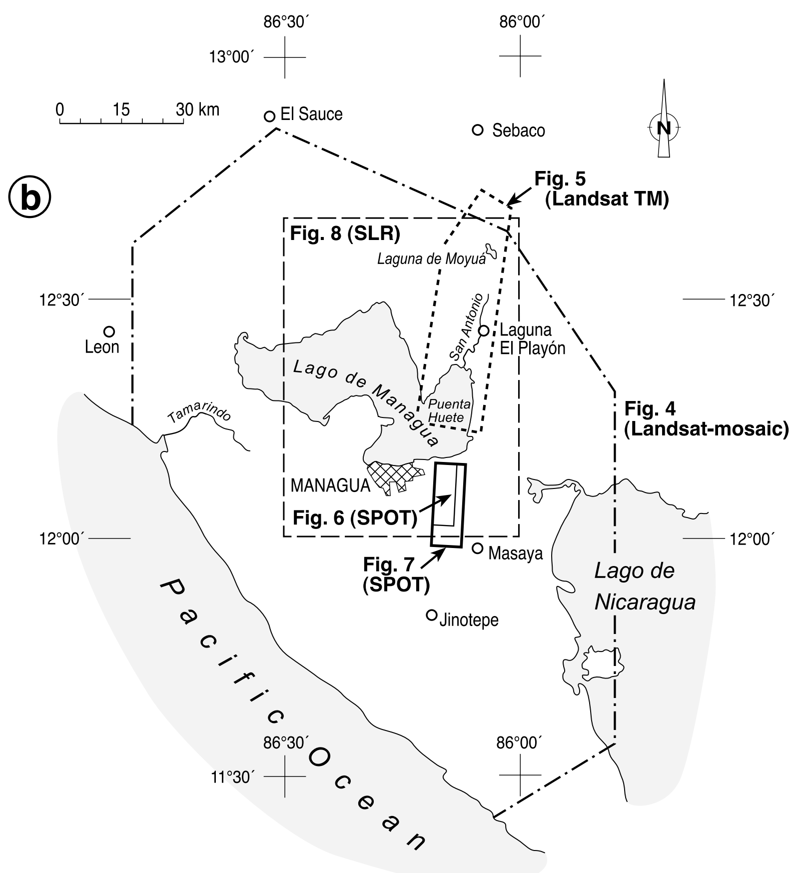

Fig 3b. General view of the areas studied by remote sensing.

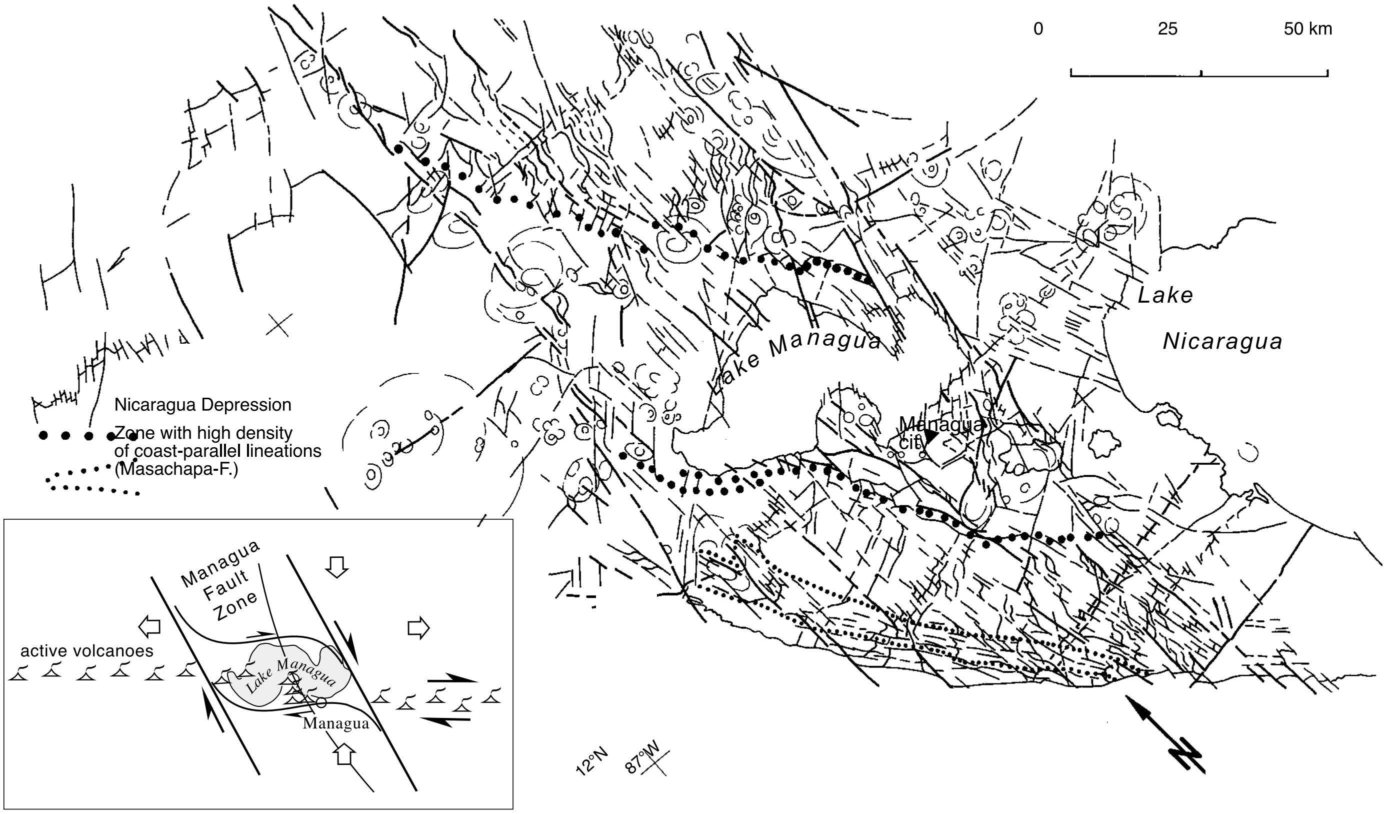

Fig. 4. Interpretation of a LANDSAT 2-3 mosaic (1978/79) for the area surrounding Lake Managua. The inset map shows a kinematic interpretation.

changes to NW and is no longer determined by the distinctive N-S structuring further to NW.

A rhomboidal geometry results from approximately N-S - trending marginal lineations of the Managua Fault Zone and the NW-SE - trending marginal structures of the Nicaragua depression, indicating that the depression may be formed under the additional influence of horizontal movements in the sense of pull-apart structures. The dextral sense of horizontal components, like documented by the satellite images, is above all related to the youngest movements and can be detected by patterns for instance within the Nicaragua depression, along the Pacific coast or by the dextral displacement of the line of active volcanoes. Approximately E-W - and NE-SW - trending, second order lineations are additionally detectable between these first order structures, which are in places characterized by features indicating sinistral components of lateral movements. Simultaneously, lineations parallel to the NW - trending margins of the Nicaragua depression are indistinct.

These observations support a model of an approximately 50 km broad, N-S - trending Managua Fault Zone, which includes the complete area of the Lake Managua. The zone is complex in structure, e.g. subdivided several times in N-S direction (e.g., Airport-graben at the eastern margin). Above all the margins of the zone are emphasised by about 2 km wide zones of some higher density of lineations. These recently active, marginal structures are characterized by a dextral component of recent horizontal movement. The derived sense of movement coincides with the results detected by Weinberg (1992); Bermúdez *et al.* (1992, 1993) as well as for the NW-SE - trending chain of active volcanoes and the N-S - trending Managua graben between the Cofradia- and Nejapa faults. Extensional kinematics under these conditions are only compatible with a structural pattern consisting of sinistral NE - trending- (second order) lineations and dextral N - trending structures and is supposed to characterize the recent state of deformation within the Managua graben. A pull apart-like opening of the Nicaragua depression is supposed to be older, using probably the same faults but under another kinematic regime. The NW - trending borders of the Nicaragua depression may be recently under a state of compression (pop up-structure), which would also explain their indistinct reproduction in the lineation pattern. Nevertheless, a field evidence is still required.

Elliptical stretched ring structures are recognizable especially in the western bordering area of the Managua Fault Zone. The preferred orientation of their long axis is NW- or NE - trending.

LANDSAT-TM

The continuation of the N-S - trending Managua graben (the eastern part of the Managua Fault Zone) within the area north of Lake Managua can be impressively resolved by a LANDSAT-TM image (used channels: 3, 4 and 5). The eastern coast of Lake Managua is formed by the Cofradia fault in a distinctly „straight-line-way“ (Figures 3b, 5) and can be followed to the north without difficulties up to at least the Laguna Moyua. The shoreline of the Laguna Moyua is influenced by these N-S - trending structures too. Indications of volcanic activity, however, are known up to the Laguna El Playón (mineral springs near Las Maderas).

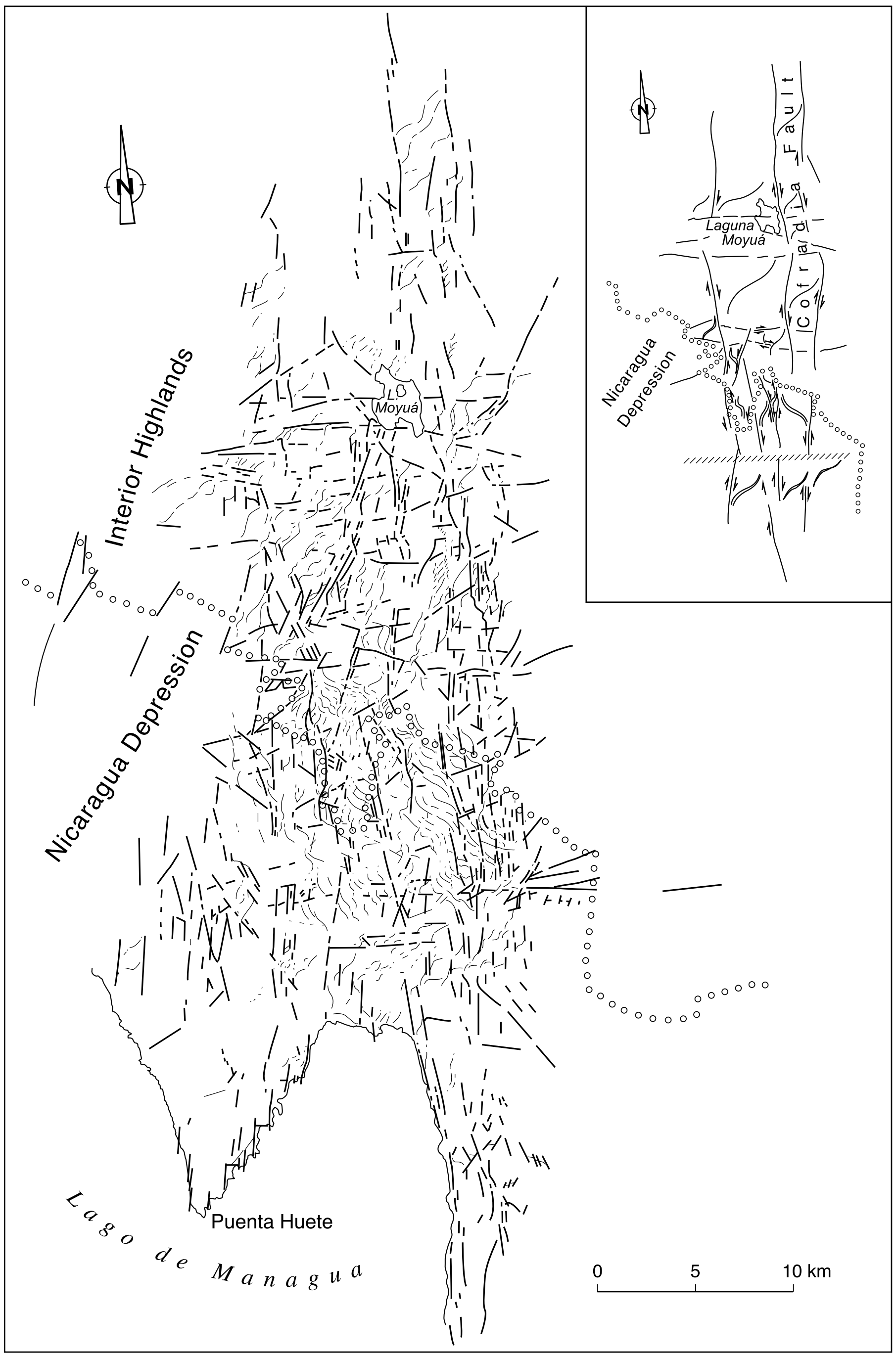

Fig. 5. Interpretation of a LANDSAT-TM - scene for the northern continuation of the Managua graben. The inset map shows a kinematic interpretation.

The Managua graben, which is around 7 km wide near the estuary of the estero San Antonio, narrows northwards. In particular the eastern coast of the triangular peninsula with its southern Cape Punta Huete is divided in a step-like, sharp-edged manner by N- to NE- and E - trending lineations, suggesting an extremely young activity of their structural background.

The Airport graben forms the eastern marginal fault of the Managua graben and in addition - on a regional scale - of the Managua Fault Zone. The inner area of the Airport graben is characterized (in contrast to its marginal parts) by its phacoidal lineation pattern, especially in its northern continuation, where the graben cuts the northern boundary of the Nicaragua depression. Obviously older E-W - trending structures are also important in addition to dominating N-S - trending lineations. They are detectable mainly not as sharp lineations but as broader, less clearly marked zones: These E-W lineations seem to form boundaries of blocks, characterized by different sense of lateral components of movement on the younger N-S - trending structures. This could imply an alternation of compressive and extensive areas following one another along the Managua graben.

SPOT-image

The enclosed interpretation of a SPOT-image (Figures 3b, 6) covers the southeastern-most part of the Managua Fault Zone, that is the region of the Airport graben, immediately south and east of Managua Airport. The marginal lineations of the graben coincide with N-S - trending fault zones, known from field observations and outcropping over a width of about 1.5 km each. The central part of the Airport graben is intensively used for agriculture and - in contrast to the marginal areas of the graben - morphologically less complex. The opposite orientated lineation pattern of the two marginal zones of the graben is obvious: The eastern flank indicates a NNE-SSW system of lineations, relatively straight, uninterrupted and equidistant, in which a system of NNW-SSE - trending, shorter and sigmoidal curved lineations is included. A similar or even the same lineation pattern is to detect mirror-symmetrical arranged at the western flank of the graben. To summarise: the eastern flank of the graben is interpreted as an oblique fault zone with a sinistral component of lateral movement. The western flank may be an oblique fault zone with a dextral component, respectively. That means, the graben centre seems to be apparently pushed relatively southwards on W- and E-plunging oblique faults. The intensity of sigmoidal structuring decreases towards the graben centre, combined with an increasing dominance of N-S - oriented lineations, meaning that normal faulting becomes dominant towards the centre of the graben.

A control of this remote sensing interpretation using relief features of the area shows that the NNE- to NE - trending lineations correspond to steps in the relief, between which a subparallel drainage net is sigmoidally curved. This relation indicates recent activity of the structures, which are the reason for the lineation pattern.

The interpretation of the same SPOT-image for a larger area, covering the Airport graben between Managua Airport in the north and the Masaya volcano in the south (Figure 7), shows that in addition to the already described structural pattern, roughly E-W - trending lineations occur. They are characterized by an equidistance of approximately 2 km and cause obviously the sigmoidal bending of the N-S - trending centre of the graben, which is filled with Masaya pyroclastics. These relations too may be evaluated as a hint to recent fault activity. The inset map on Figure 7 shows an attempt of a kinematic model, derived from the interpretation of the SPOT-image alone.

Radar interpretations

SLR-images were provided by the INETER Managua from a Nicaragua-countrywide survey (1971-1972).

The enclosed interpretation is restricted to sheet “Managua” (Figures 3b, 8) and it is distinguished between linear- and ring-like features. In the SW-corner of this image, SW of the Mateare-fault, the Pliocene to Late Quaternary volcanic and marine-sedimentary formations of the Pacific Plains are separated from the remaining area of the Managua Fault Zone by a completely different pattern of lineations: A pattern consisting of straight lineations cutting ring structures is typical for the area NE of the Mateare fault. South of the Mateare fault a phacoidal and much denser net of lineations dominates. It consists mainly of NE-SW and NW-SE oriented, curved lineations. The phacoidal net of lineations correlates with a dominating compressive folding (Weinberg, 1992), which is in contrast to the extensional character of deformation NE of the Mateare fault. The following age relations may be derived from the lineation pattern within the Managua Fault Zone: younger N-S - trending - and older E-W - trending lineations. Additionally, and in contrast to the interpretations discussed previously, the SLR-image shows numerous lineations with NE-SW- and NW-SE orientations. Data concerning possible components of lateral movements can be derived only for single cases: The SE-shoreline of the triangular peninsula with its southern Cape Punta Huete, for example, is divided in a characteristic manner by a series of left-handed *en echelon*-like lineations. Taking into account the known dextral sense movement on N-S-structures they may be interpreted as transtensional features within a roughly NE - trending sinistral oblique fault zone. Indications to the inner structure of the Managua graben cannot clearly deduced from the radar image.

Fig. 6. Interpretation of a SPOT-image for the area of the Airport graben near Managua, which represents the eastern marginal structure of the Managua Fault Zone.

Ring structures, which are supposed to originate mainly from volcanic activity, are arranged mainly parallel to NW-SE directions. They are mostly stretched, predominantly in submeridional and subequatorial directions. Ring structures occur more rare SW of the Mateare fault.

DISCUSSION

Remote sensing interpretations for geological aims generally require strict constraining by field studies. Such investigations could not carried out in the frame of the project up till now, - there was only preliminary field checking. So the presented results must be regarded as statements of first hypotheses.

Roughly N-S - trending lineations are a characteristic feature found in all remote sensing images used for interpretations of the studied area. N-S - trending lineations coincide partly with structures known also from published field observations (e.g. the multiple dislocations of the NW-SE - trending chain of active volcanoes). They are characterised by a predominant dextral component of lateral movement and in addition partly occupied with volcanic phenomena (thermal springs, ash cones, etc.): - as, e.g., the Nejapa line

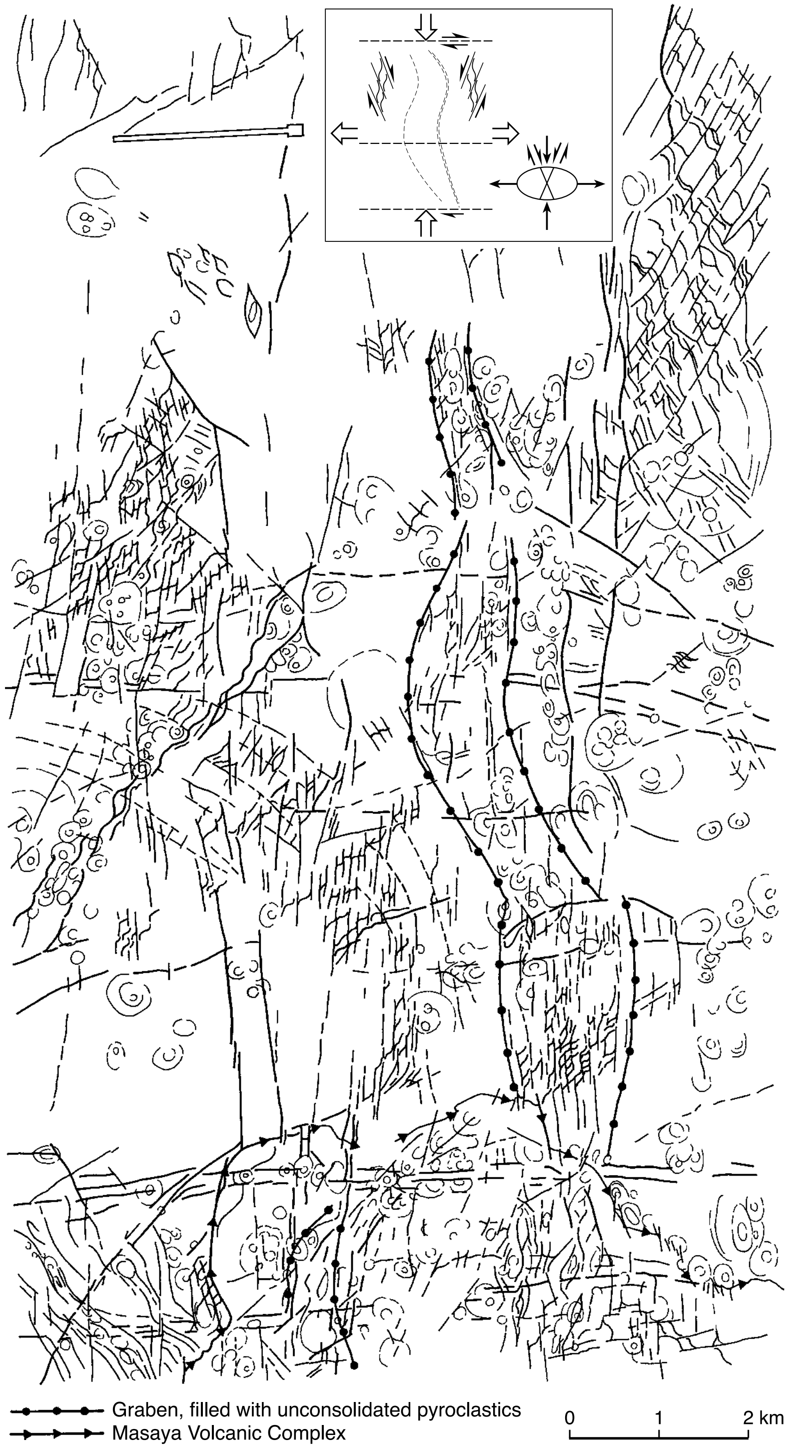

Fig. 7. Interpretation of a SPOT-image for the Airport graben between Managua and Masaya volcano.

or the Cofradia fault. At least two main- (Managua graben, Airport graben) and possibly several N-S - directed, lower-order graben structures can be recognized east of the outskirts of Managua. The Airport graben itself is regarded as the easternmost multi-plane fault structure of the Managua Fault Zone.

Several interesting relations exist between the results of remote sensing interpretations and seismological data of the Managua earthquake in December 1972. The model for the Managua graben, derived from remote sensing interpretations, may be confirmed by the pattern of the distribution of aftershocks, published by Langer *et al.* (1974). A com-

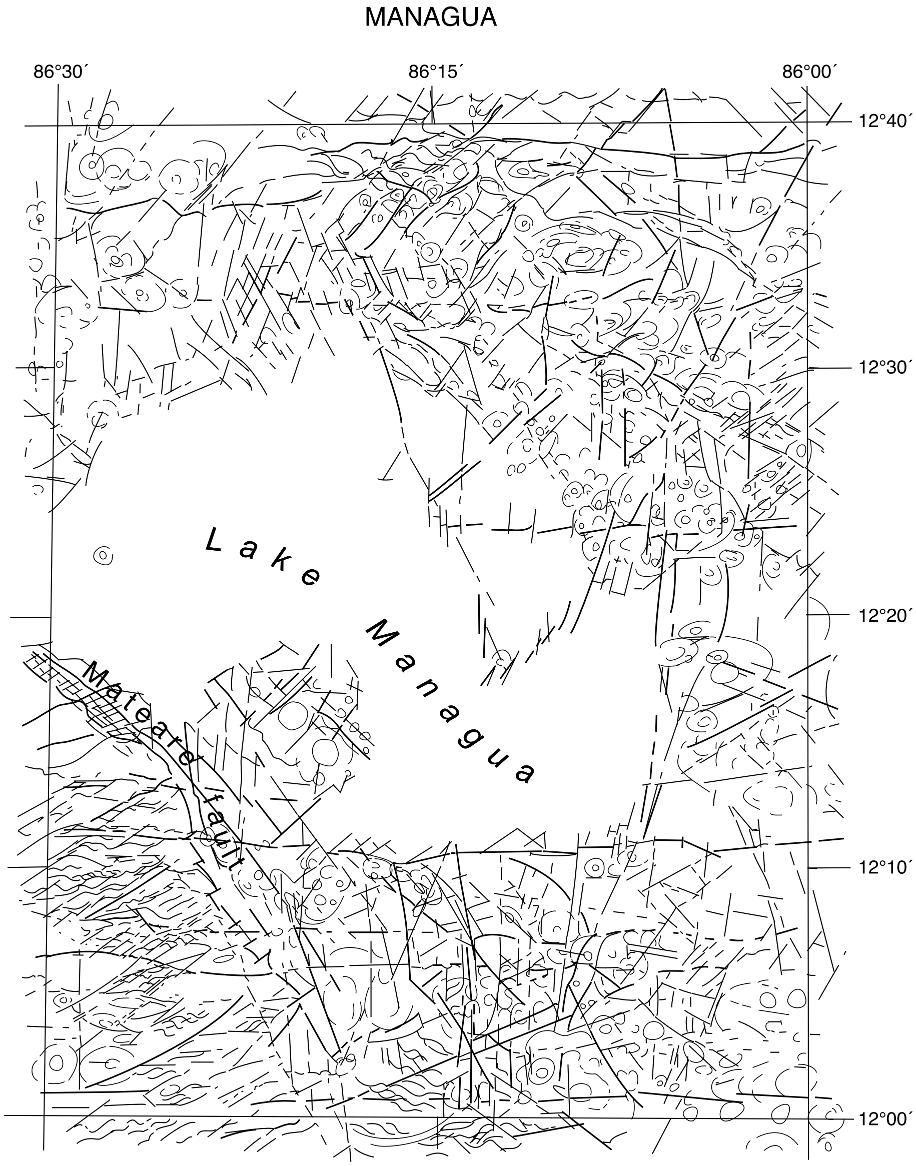

Fig. 8. Interpretation of the radar (SLR) sheet “Managua”.

bined version, considering the spatial distribution of aftershocks and results of remote sensing interpretations, is shown in Figure 9a. From the geological point of view the results by Ward *et al.* (1973), which are derived from a denser observation net (Figure 9b), are similar to those by Langer *et al.* (1974), although - apart from the NE - trending main plane - particularly the N-S - trending elements may be comparatively more indistinctly reproduced in favour of NW-SE - trending structures. Otherwise, there could be no doubt about the neotectonic to recent importance of N-S - trending structures, because they are clearly detectable in all remote sensing materials and they are known from field observations as well and - above all - they seem to be the youngest within the lineation pattern (following cutting relations with one another).

N-S structures (after remote sensing indications) and the NW-SE - trending margins of the Nicaragua depression (Weinberg, 1992) are both characterized by a dextral component of lateral movements, at least regarding the youngest period of deformation. Additionally, on NE - trending structures a sinistral component of lateral movement is proved by the results of the fault plane solution to the 1972 Managua earthquake. From these relations follow a rhomboidal pattern of structures, indicating kinematics characterised by transtensional extension on approximately NE - trending planes within the Managua graben and transpressional conditions for the Managua Fault Zone. This may be a model at least regarding the whole area of the Managua Fault Zone and possibly including the Nicaragua depression as well.

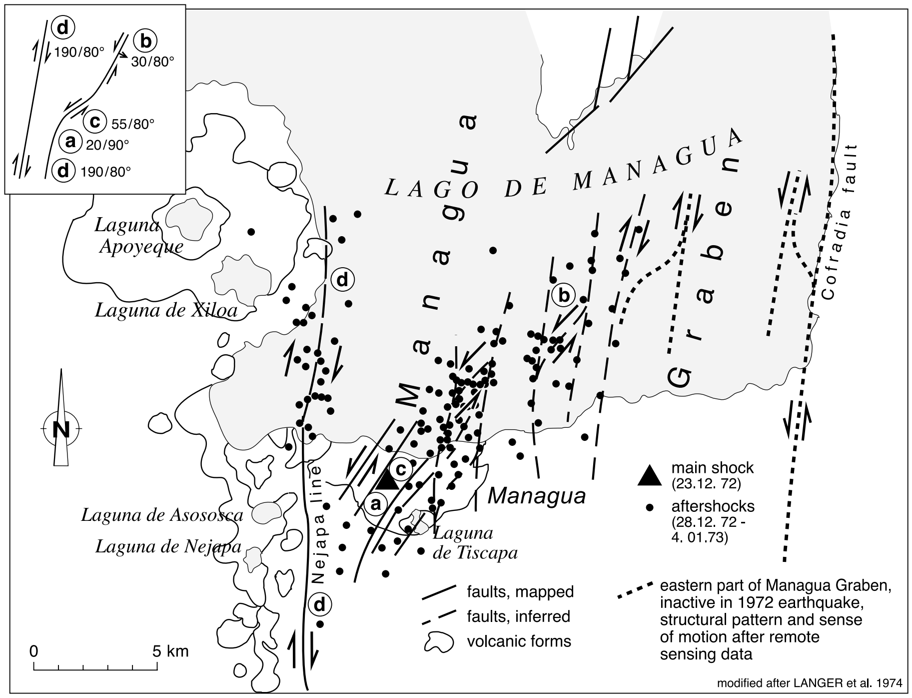

Fig. 9a. The activated fault pattern and aftershock distribution for the 1972 Managua earthquake is shown, completed within the eastern part of the structure after results of remote sensing interpretations. The letters (a) to (d) refer to results of fault plane solutions after Brown *et al.* (1973). The inset map shows their transformation (cf. Fig.10) in a sketch map (compare the aftershock distribution (Fig. 9b) by Ward *et al.,* 1973).

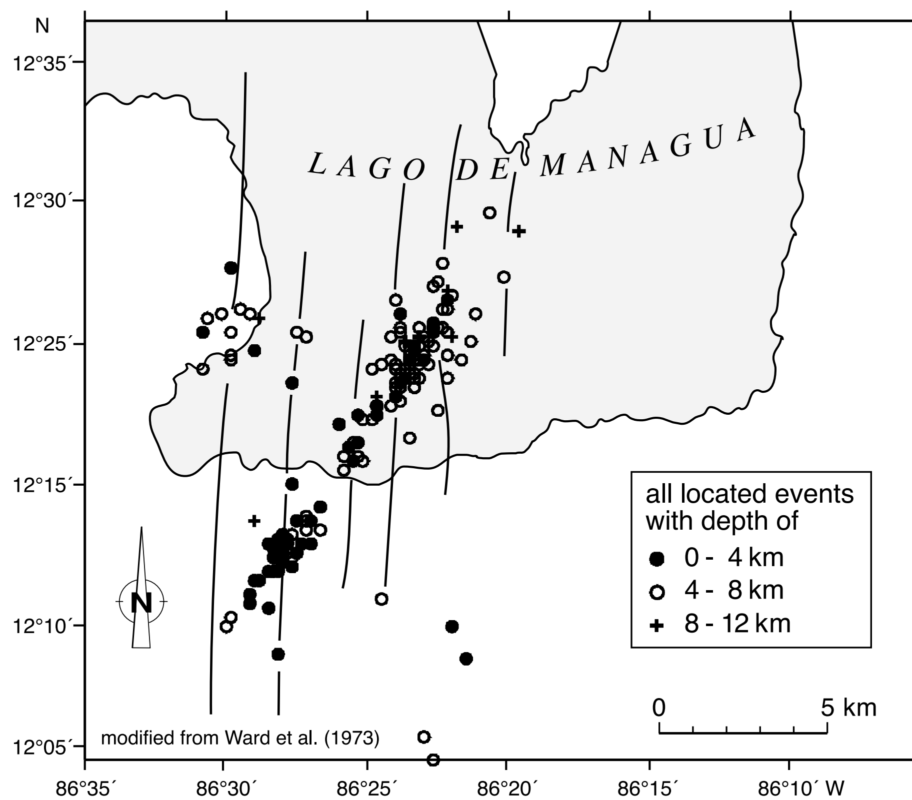

Fig. 9b. Aftershock distribution for the 1972 Managua earthquake by Ward *et al.* (1973).

During the 1972 earthquake a fault pattern consisting of dominating NE- and subordinated N- and NW - trending elements was activated at least in the eastern part of the Managua Fault Zone - in the Managua graben. The aftershocks cover comparatively densely the W-flank of the graben (N-S - trending Nejapa line) and towards east - under decreasing density - parallel elements up to the western border of the Airport graben as well as dominating around NE-, and subordinated NW - trending second order shear planes. The inset map in Figure 9a documents the composite fault plane solution to the 1972 Managua earthquake (Figure 10). The fault plane system activated in 1972 corresponds (with respect to the presented remote sensing interpretations) probably only to the Managua graben as a part of the postulated Managua Fault Zone.

A sinistral component of lateral movement was determined for the NE - trending planes by seismological data (cf. Figure 10). Dextral lateral movement components dominate on N-S - trending elements. The reality of such sinistral components may possibly be supported by block rotations, which may be to expect as a result from differences of drift velocities of the colliding Cocos- and Caribbean plates as well (cf. Figure 1): The recent, approximately NNE - directed drift velocities of the Cocos plate decrease from SE (>80 mm/a) to NW (50-70 mm/a), whereas the SW- directed drift velocity of the Caribbean plate increases in the same direction from 10 up to >20 mm/a. Slip relations along the Central American volcanic arc, due to the recent Cocos-Caribbean plate motions were recently discussed by DeMets (2001) on the basis of GPS-data and seafloor spreading rates .

The Managua graben is interpreted as a complex graben structure, whose western part may have formed under dominating dextral transtension on NE - trending planes and transpression on NW - trending planes, whereas its eastern marginal zone (Airport graben and immediate vicinity) is subjected increasingly to the east under the influence of dominating normal faulting.

During the 1972 earthquake the eastern flank of the Managua graben (i.e., the Airport graben) was obviously not

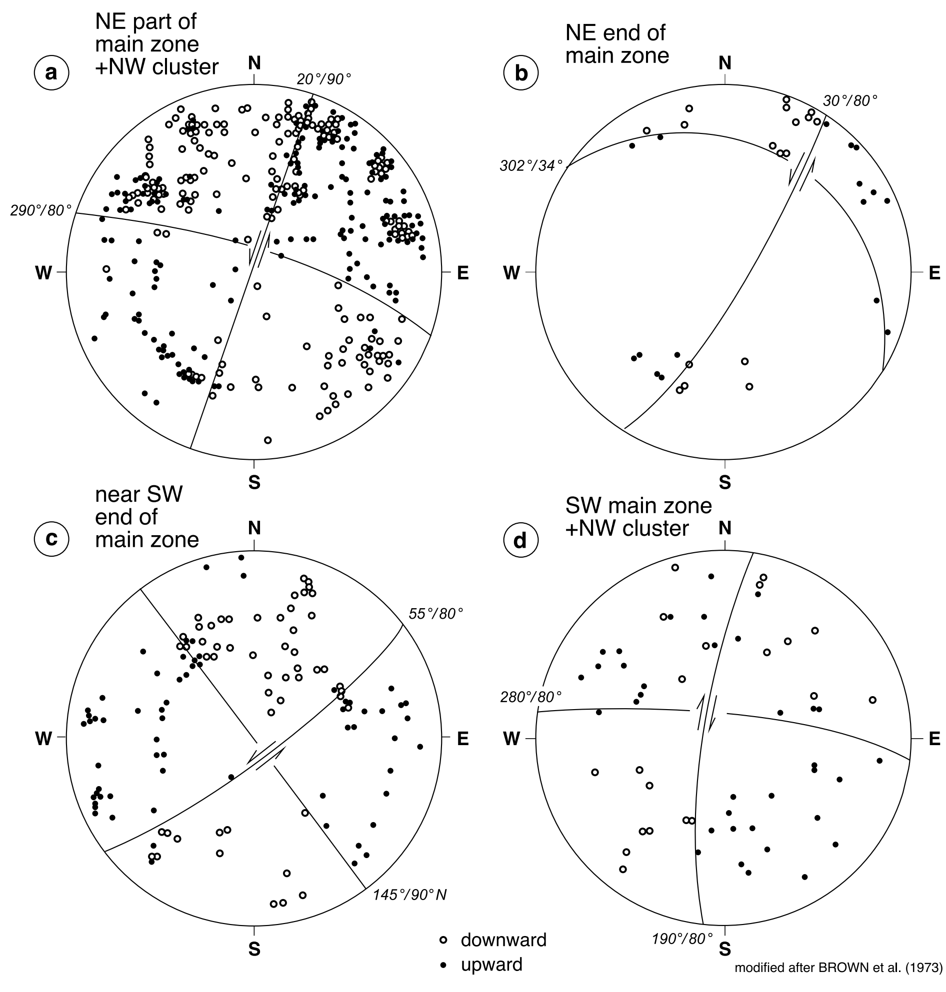

Fig. 10. Fault plane solutions for the 1972 Managua earthquake, modified after Brown *et al.* (1973).

activated, so that - induced by the stress release on the western flank - either an increased stress concentration could rebuild on the E-flank of the graben or a stress concentration may be impossible at all there because of an already existing high level of cataclastic deformation, possibly in combination with a high pore fluid pressure (indications of active volcanism also in N-S!). Additionally, important may be that with the Airport graben follows a structure of different kinematic type, which is characterized - in contrast to the activated W-flank of the graben with a distinct component of lateral movement - by an towards east increasing tendency of normal faulting.

The distribution of aftershocks, shown by Ward *et al.* (1973), is characterized by a distinct concentration on a NE-trending lineation. In combination with an increase in focal depths from SW to NE in the order of 4 km the seismic activation of the lineation comes to an end without reaching the eastern margin of the Managua graben (Figure 9b, 11). The pattern may be controlled by stress redistribution, triggered within the fault system by the single events, changing stress-strain relations within the fault pattern or even by petrologic reactions (fluid output/input as a result of metamorphic reactions). In addition, the aftershock distribution is characterised in an obvious way by a tendency towards a spot-like pattern, which may reflect the locations of maximum stress concentrations within the individual NE-SW - orientated transtensional wedges.

Especially N-, NW- and NE - trending planes must be regarded as recently active - at least with respect to the Managua Fault Zone. Their kinematic relations must be taken into account from a seismic hazard assessment perspective. NE - trending planes are of special interest because of their extensional character, which is combined with oblique faulting. NW - trending planes have recently come under compressive conditions, permitting higher stress concentrations. A sketch of the resulting kinematic relations is given in Figure 11 for the area of the Managua Fault Zone.

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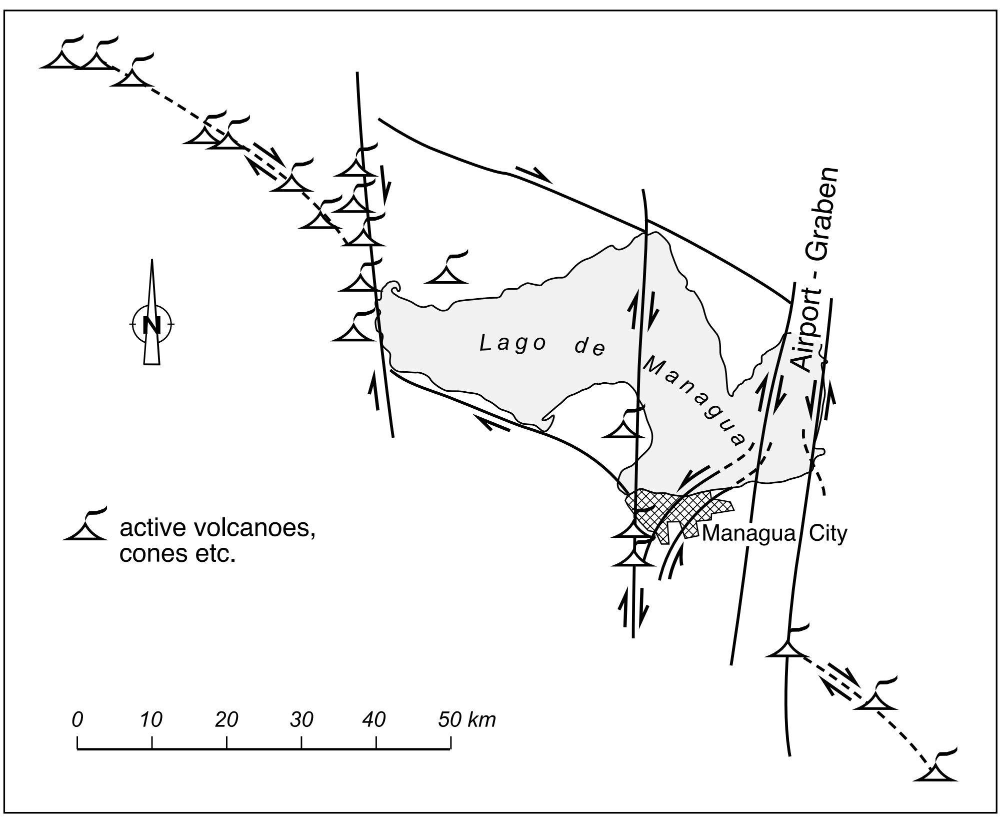

Fig. 11. Combined kinematic model for the Managua Fault Zone. The internal structure of the marginal zones of the Airport graben is indicated with broken lines.

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Frischbutter, A.
GeoForschungsZentrum Potsdam, Telegrafenberg,
D-14473 Potsdam, Germany
Email: fribu@gfz-potsdam.de