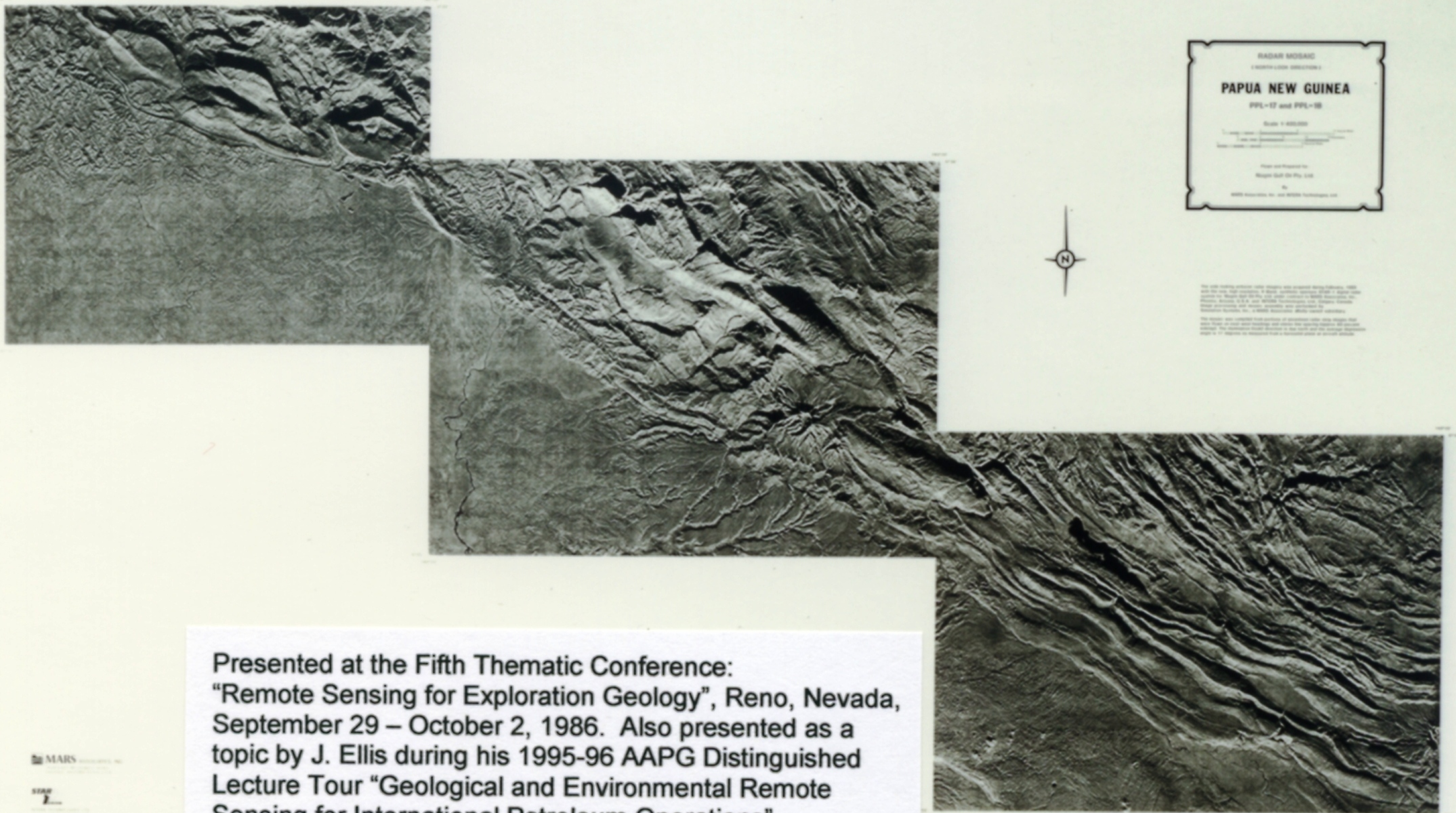
THE SAR MOSAIC (1:400,000) OF SOUTHERN FOLD AND THRUST BELT



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ABSTRACT

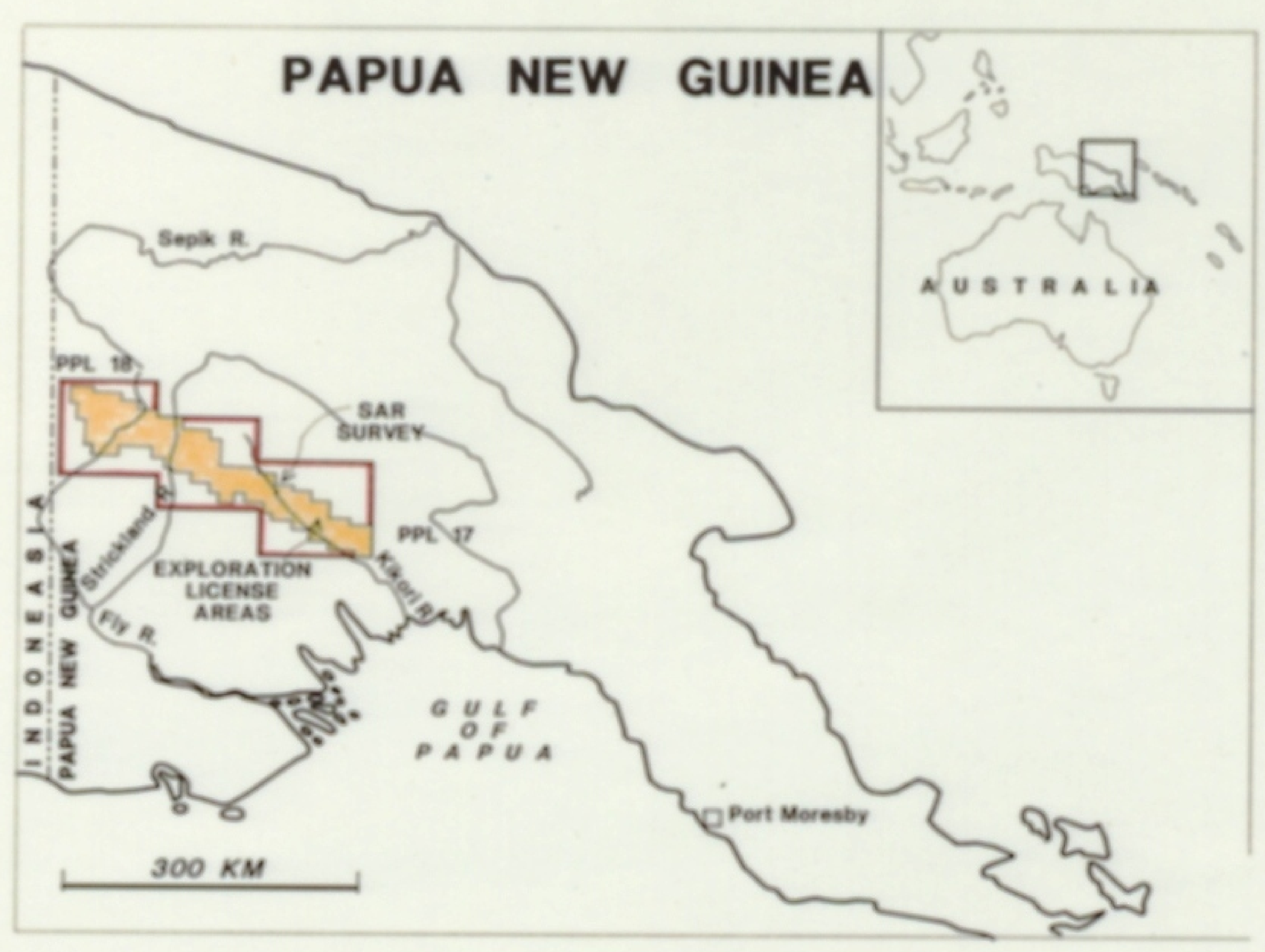
Niugini Gulf Oil Pty. Ltd., a Chevron-owned company and operator for two exploration licenses within the southern Papuan Basin fold and thrust belt, has successfully used synthetic aperture radar (SAR) to map surface structure, stratigraphy, and to help in planning a hydrocarbon exploration program.

Rugged karst topography developed on massive Tertiary limestone causes the region to be exceedingly dangerous, if not impossible, to traverse on the ground. The area is seldom cloud free, is covered with tropical rain forest, and geologic field studies are limited. The region is ideally suited to geologic analysis using remote sensing technology. Landsat images and vertical aerial photographs complement SAR but provide subdued structural information because of the jungle cover and minimal shadowing (due to high sun angles). SAR provided our explorationists with an excellent data base because (1) structure is enhanced with low illumination, (2) resolution is 6 x 12 m, (3) digital reprocessing is possible, and (4) clouds are penetrated by the SAR.

Exploration evaluation, including drilling, is underway within these isolated licenses in search of liquid hydrocarbon reserves which may be trapped in economic quantities in some of the large structures. Hydrocarbon traps within most exploration provinces are usually defined with seismic technology prior to costly drilling; however, deep karst weathering of surface and near surface limestones prevent acquisition of interpretable seismic data at reasonable cost. Typical subsurface information that is required prior to drilling (depth and configuration of reservoir rock, thickness of stratigraphic units, fault attitudes and throw) can only be interpreted and modeled from imagery, surface observations and sparse well data.

SAR imagery revealed significant mass wasting that has led to re-evaluation of previously acquired field data. Lithologies were recognized on the radar imagery by textural and tonal changes in spite of the near-continous canopy of jungle. Typically the anticlines have been formed as the structurally competent Darai Limestone was moved southward above a decollemont surface and thrusted over the younger Ourabadi shale. This limestone is relatively more resistant to erosion and forms the surface outcrop over most of the anticlinal structures. Volcanic cones began to form during late Pliocene time. Most are steep-sided, conical, strato-volcanoes with deeply dissected slopes and central craters; they are thought to be dormant or extinct.

The characteristic radar signature of karst topography enabled some limestone-capped, fold and thrust structures to be interpreted beneath volcanics. Reprocessing and contrast stretching of the digital radar imagery allowed additional geologic information to be extracted from the survey in oversaturated (bright) or flared zones.



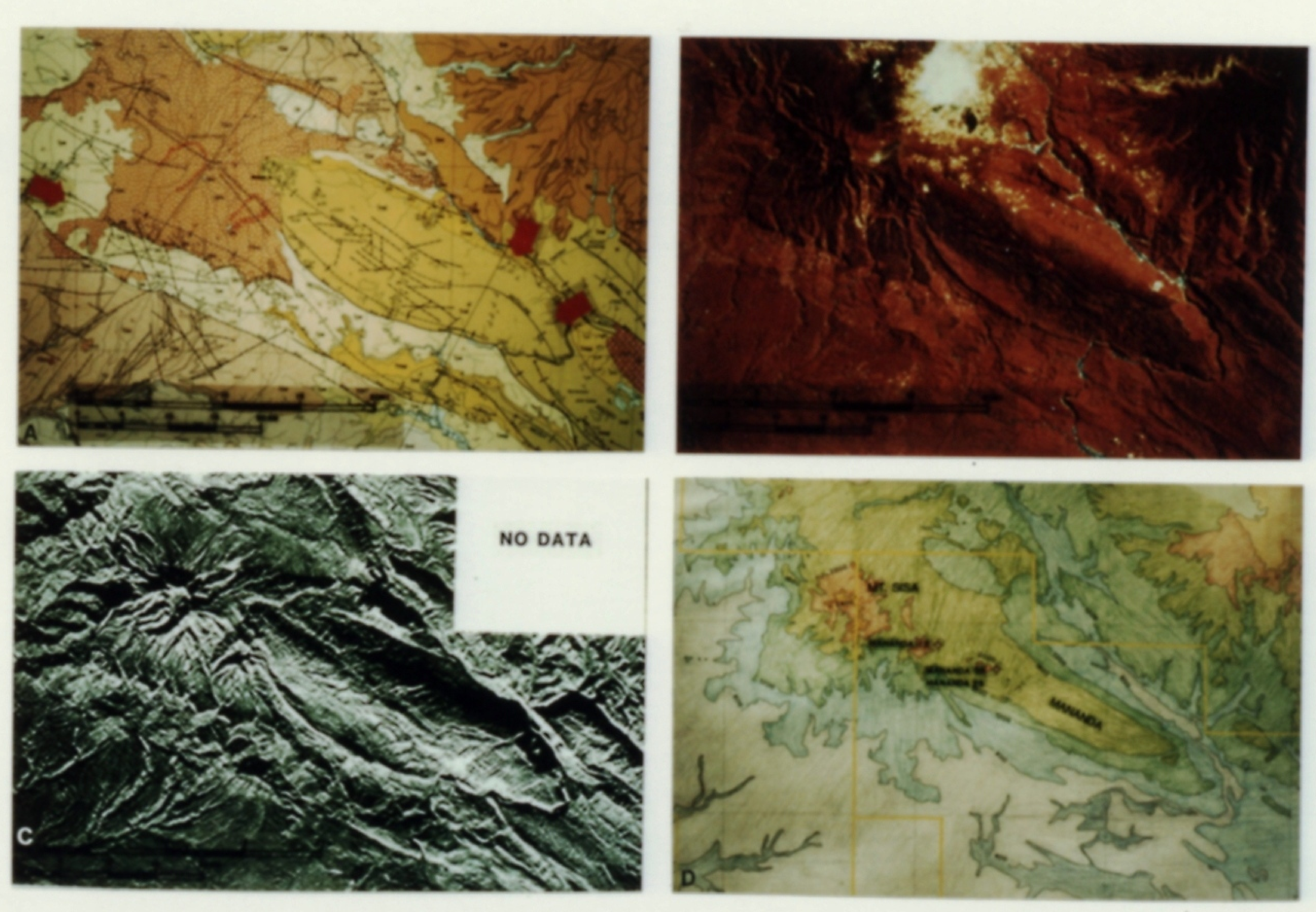
INTRODUCTION

Synthetic aperture radar (SAR) imagery was acquired over an area covering Petroleum Prospecting Licenses PPL-17 and PPL-18 during February 1985. More than 26,000 km^2 was surveyed with airborne radar. Individual flight strips side-lapped by ~60%, permitting stereoscopic analysis of the terrain. The imagery was recorded digitally and then plotted at a scale of 1:250,000. A mosaic at the same scale was also constructed.

The region is mostly uninhabited, and it is covered by a dense rain forest that approaches 30-40 m (+) in height. The rocks are folded and thrust into large anticlines. Several exceed 25 km in length. The height of some of these anticlines approaches 1500 m.

The photograph on the left shows the Darai Limestone dipping steeply on the flank of Kutubu anticline. Small huts can be seen along the shoreline for scale. Topographic relief from lake to crest of anticline is 500 m. The rugged karst topography makes seismic technology impractical.

DATA BASE COMPARISON



GEOLOGIC DATA AVAILABLE

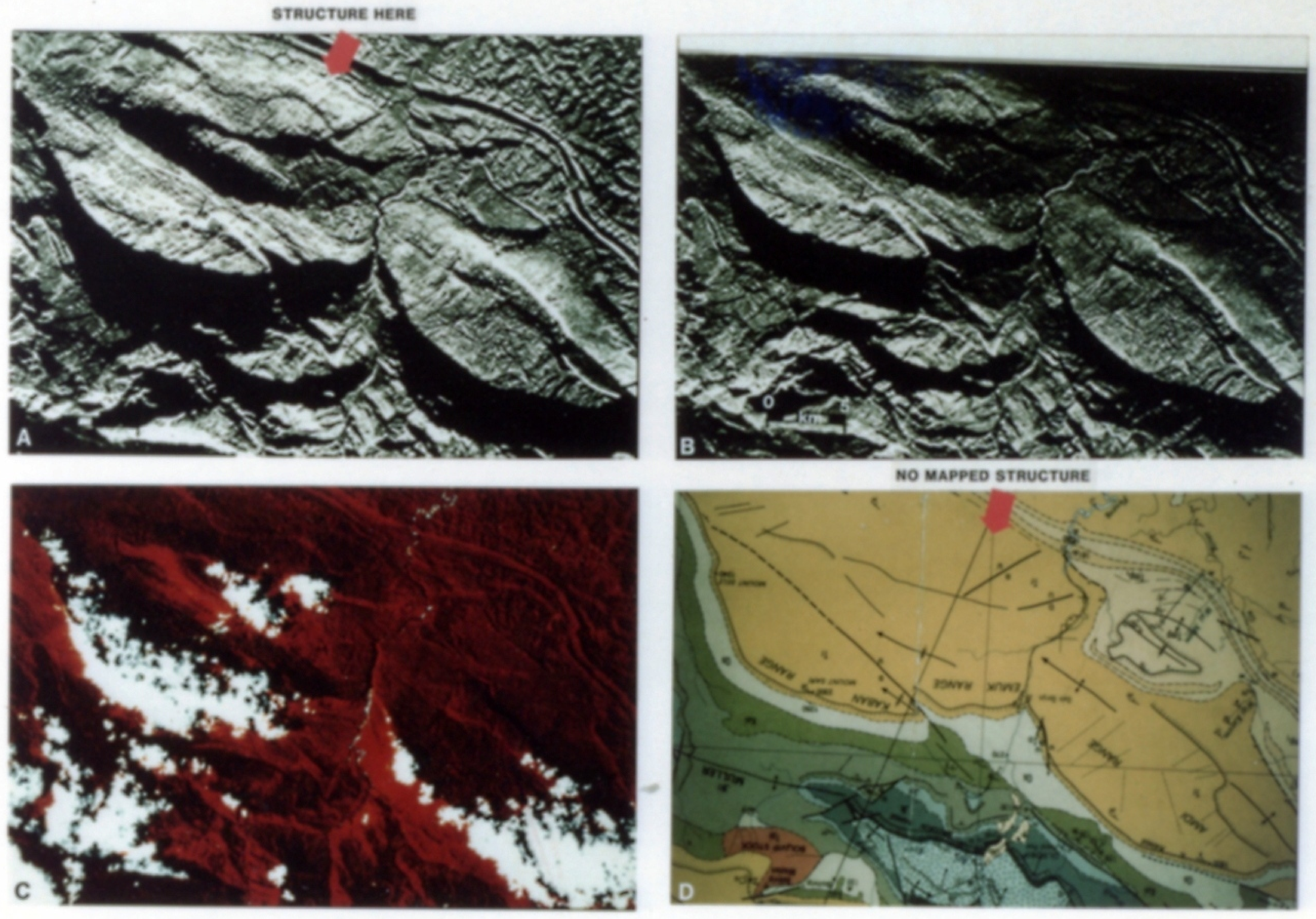
Example of data set available for the exploration effort, set at the same scale: (A) published geologic map, (B) Landsat MSS imagery, (C) SAR imagery, and (D) simplified topographic map (400 m contour interval). Arrows on map point to topographic scarps that are best evaluated with Landsat and SAR. SAR reveals widespread surface instability along the illuminated (south) flank of Mananda anticline, encouraging re-evaluation of previous field measurements.

Geologic MapsThree geologic maps (scale 1:250,000) with explanatory notes that cover most of the exploration area have been published by the Australian Bureau of Mineral Resources and the Papua New Guinea Department of Lands, Surveys and Mines. These maps are the Blucher Range (or Ok Tedi), Wabag, and Kutubu sheets (Sheets SB/55-7, -8, and -12, International Index, respectively). The three sheets are compilations of arduous field work and careful photogeology carried out since the 1940's.

Topographic Sheets Excellent topographic sheets were generated from stereoscopic aerial photographs by the Royal Australian Survey Corps (scale 1:100,000; 40 m contour interval). Inherent distortions in the radar imagery due to layover in the high relief areas were minimized by transferring the SAR interpretation onto these topographic sheets.

Landsat Imagery Landsat MSS imagery is available with <20% cloud cover over the southern foldbelt of Papua New Guinea. As of this date, no TM imagery has been acquired over the southwestern Pacific because no data relay satellite (TDRS) is available for the region. Color IR composites (BGR = 457) of the MSS data are almost completely red because of the extensive forest cover.

SAR SURVEY DESIGN AND SHADOWING

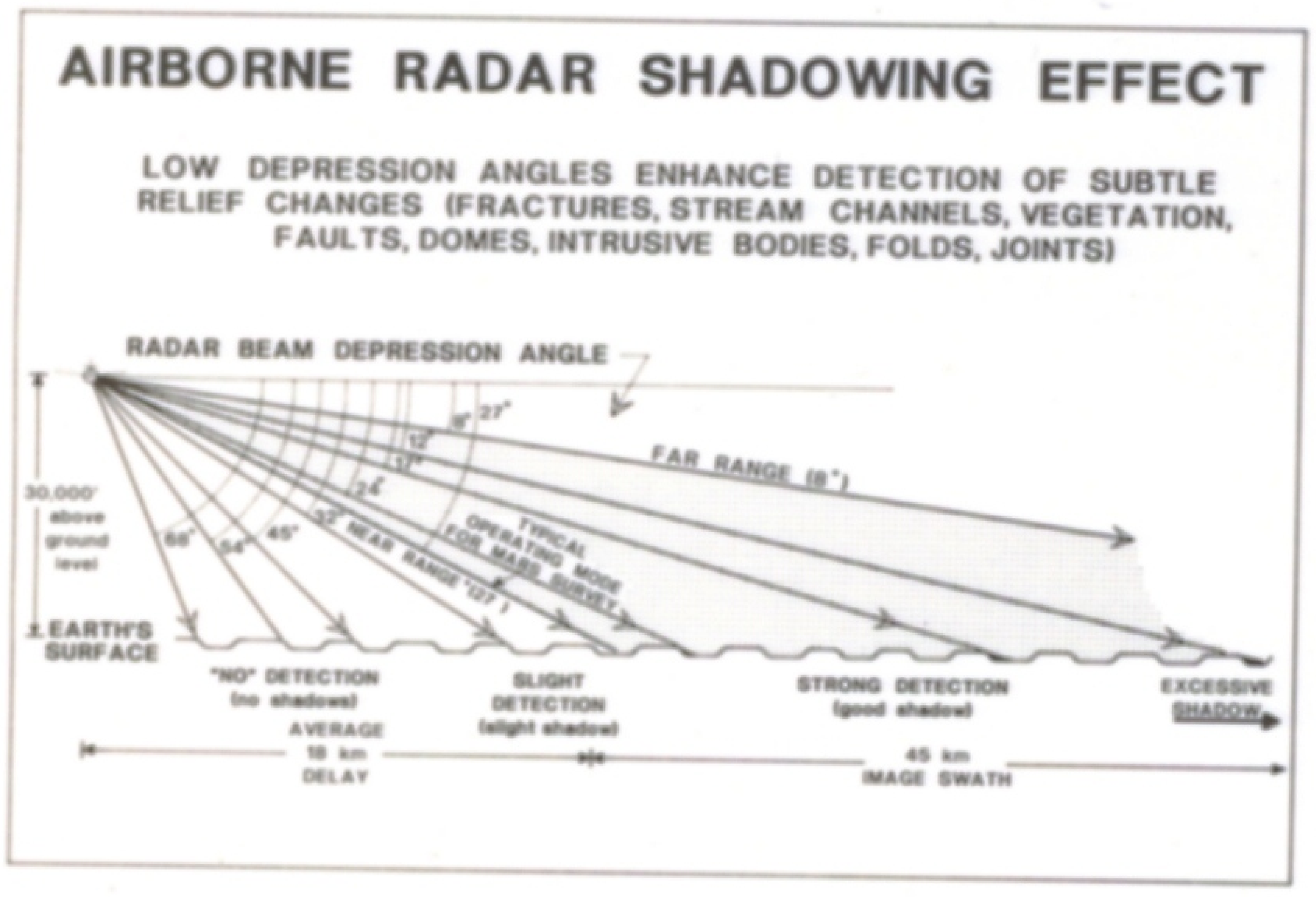


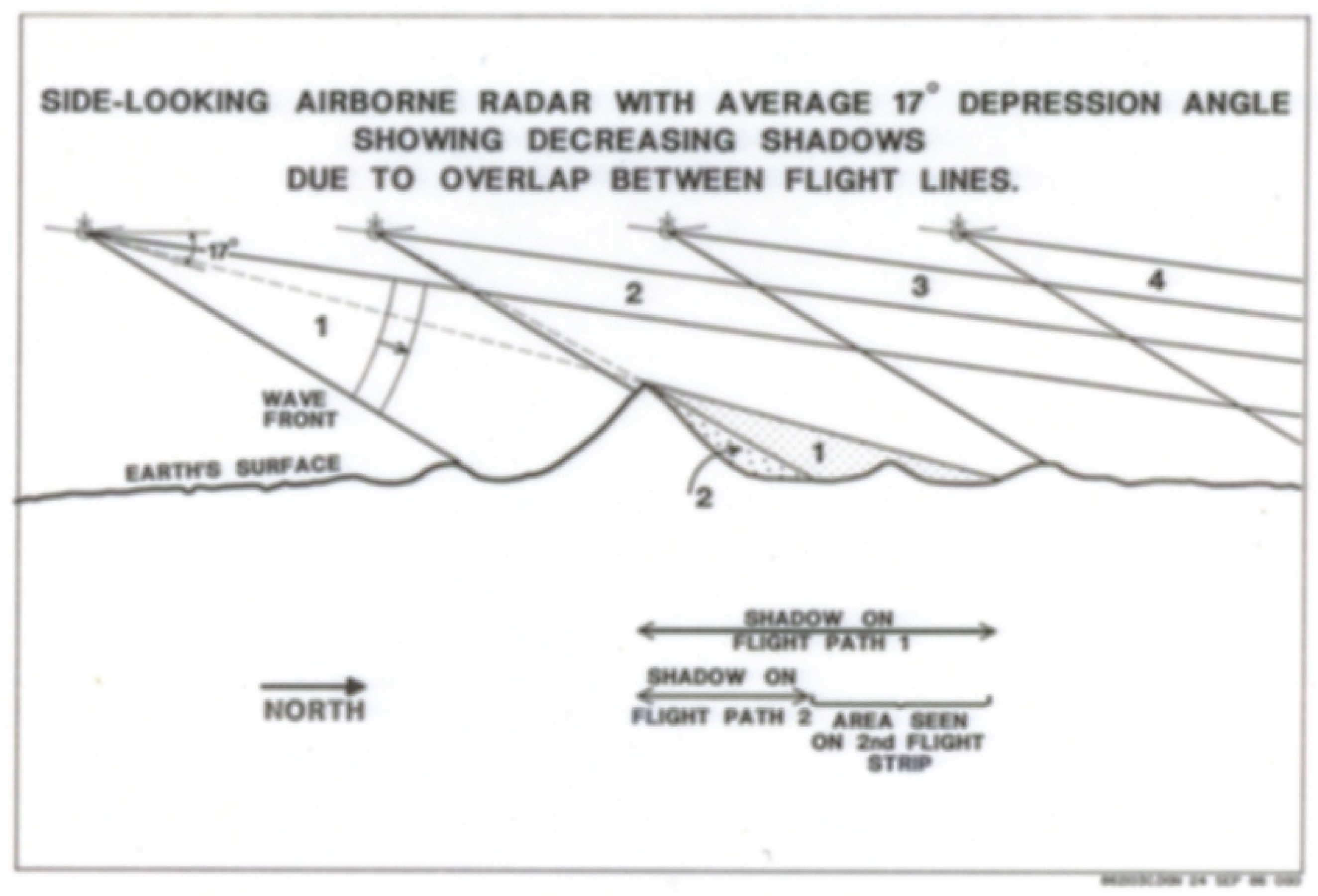
SAR SURVEY DESIGN

Topography rises steeply toward the north, structure trends northwest-southeast, and thrusting is predominantly directed toward the southwest. Flights paths were east-west with the microwave beam directed northward to minimize shadowing and enhance detection of south-facing bedding and thrust fault traces. Also, by directing the beam at an acute angle to the structural grain, excessive signal returns (signature flare) caused by the many slopes and cliffs that face southwest were reduced.

Although this survey design provided for the most economical and complete data acquisition, viewing the imagery with north up (shadows directed toward the top margin of the image) typically results in topographic inversion. The radar imagery in this paper is arranged conventionally with north up. The reader may need to rotate the imagery 180° so that north and the shadows are projected downward in order to see the topography in proper perspective (ridges as highs and valleys as lows).

The figure above shows a profile of airborne radar beam with various depression angles and shadowing of subtle topographic relief. This survey's depression angles ranged from 27° in the near range to 8° in the far range; an average of 17° was used in the mosaic.





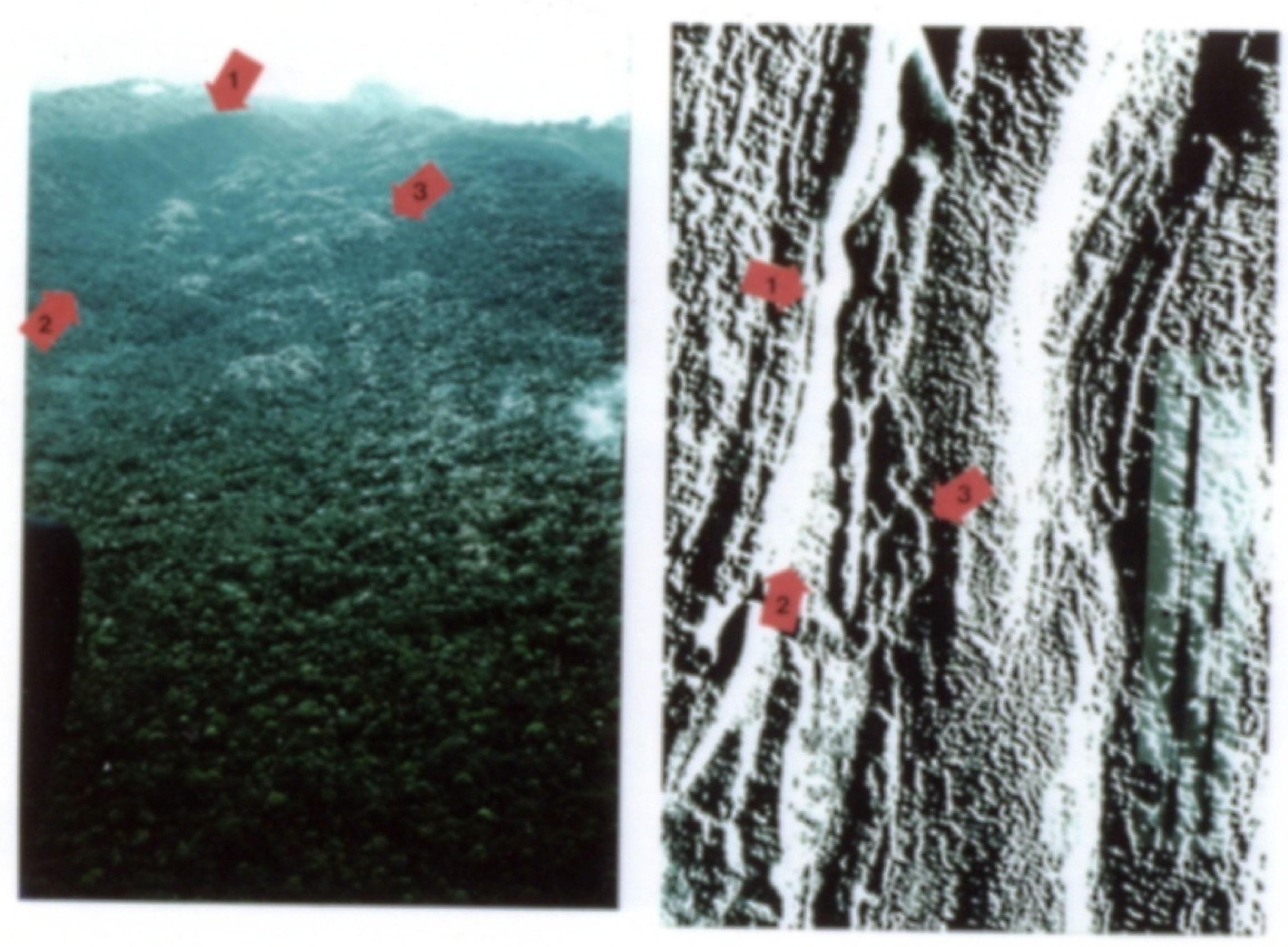
MINIMIZING RADAR SHADOW

On the radar mosaic, which utilized the mid-range portion of each flight strip (~17° depression angle), shadowing on the north side of major topographic highs obscures terrain. However, in the near range portion of the strips much more terrain is illuminated by the steeper depression angle (see figure above). The detrimental effects of shadowing due to topography was minimized by mapping in the near-range portion of the stereo flight strips.

The Amdi, Emuk, and Kaban Ranges are shown to the right on same-scale (A and B) SAR stereopair , (C) Landsat MSS image, and (D) published geologic map. The crests of the ranges are obscured in cloud cover on Landsat and lack detail on the published geologic map. However, the SAR imagery reveals a major fracture pattern that cuts across structure, provides a sense of displacement on many faults, and shows at least two anticlines not shown on the published geologic maps. We contoured the previously unmapped structures on the topographic maps of the area to generate a detailed, surface-structure map from the SAR stereoscopic imagery. Information on karst is more evident on SAR imagery.

COMPARISON OF RADAR IMAGE AND COLOR FILM

A



B

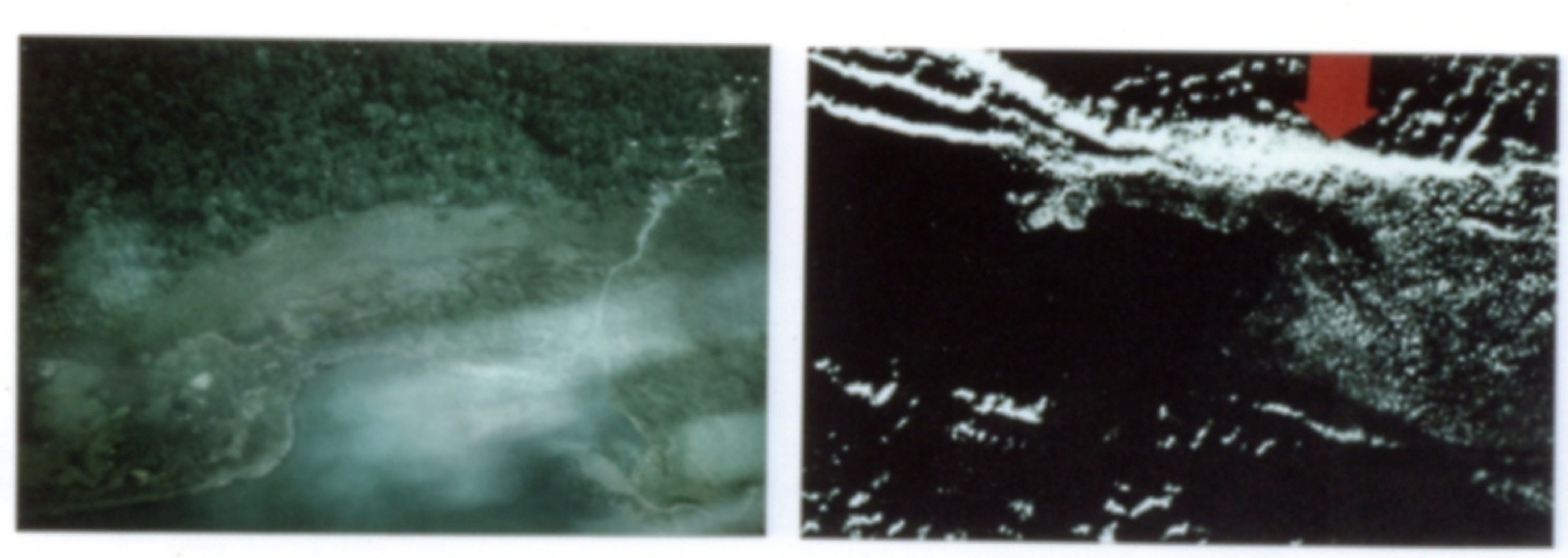
COMPARISON OF RADAR WITH COLOR PHOTOS

The color photos demonstrate that the jungle canopy conforms with the relief of the underlying terrain; however, the top of the canopy is smoother than the underlying relief. The radar imaging process further "smooths" the terrain even more because it averages the returned energy into synthetic 6 x 12 m ground-size cells. The resultant enhancement of longer wavelength features appears to reveal fundamental geologic features better than the color photos.

A. View looking southeast along northern side of Mananda anticline. Resistant Darai Limestone bed crops out along southeast trend as shown by two arrows; this subtle outcrop is best seen on the SAR image. Mananda 3X is evident in a clearing just dipslope of this resistant strata.

B. Comparison of radar image with color photo of a (1) thrust fault carrying Darai Limestone over shales, (2) stratigraphic contact between shales and resistant limestone, and (3) outcrop pattern of Darai strata folded into an anticline. Pitted and irregular radar signature of deeply weathered limestone contrasts with smooth, medium-gray signature of shales.

C. View of southeast end of Lake Kutubu showing radar detection of various vegetation/water content zones along the shoreline. Huts can be seen in the color photo for scale.



C

APPLICATION OF SYNTHETIC APERTURE RADAR (SAR) TO SOUTHERN PAPUA NEW GUINEA FOLD BELT EXPLORATION

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CHEVRON OVERSEAS PETROLEUM, INC.

STRUCTURAL ANALYSIS WITH SAR

STRUCTURAL ANALYSIS WITH SAR

SAR, especially when viewed stereoscopically, is superior to Landsat and aerial photographs for interpreting geologic structure. SAR clearly reveals more geologic information than shown on the published geologic maps. With SAR, strikes and dips, anticlines and synclines, and structural plunge can be mapped across terrain where little or no field work has been done.

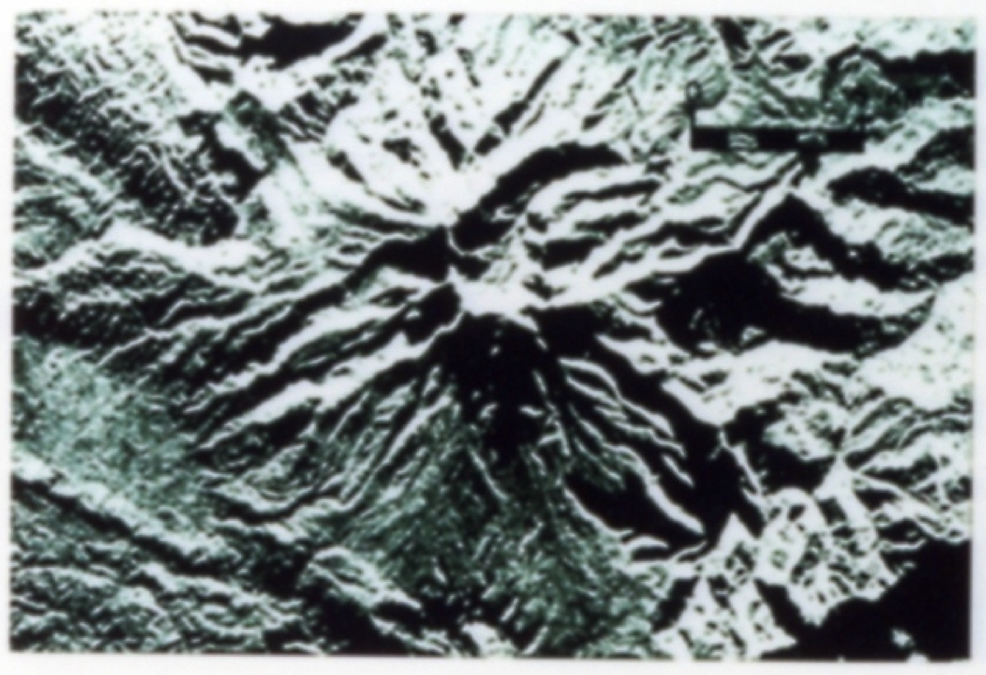
A. Suspected faults mapped on geologic sheet as trending NW-SE through craters can be interpreted with SAR as part of a larger zone of NW-SE trending fractures or faults. With SAR, valleys that trend NE-SW are seen as deeply eroded into flanks of Mt. Sisa, suggesting a major zone of structural weakness at depth.

B. A band of resistant, upturned Darai Limestone (Tr) is highlighted with 2 arrows on the SAR image (NE is toward the upper margin of the same-scale image and map). A thrust fault is mapped only along the SE base of this strata.

The radar image reveals the complex nature of this mapped fault and the surrounding terrain. The upturned strata appears to be topographically higher toward the northwest (left arrow on the radar image), and the Darai Limestone dipslope (Tr) smoothly grades into the plunging nose of the Juha anticline. There is no sharp topographic break here at the Tr/Tma stratigraphic contact as there is farther east where the fault is mapped at the surface. The radar image can be interpreted with the mapped fault losing throw toward the northwest and becoming a blind thrust fault (not reaching the surface).

Two geologic sheets are joined along a north-south line. The SAR image helps extrapolate the greater detail of the eastern sheet onto the western sheet and enables smooth continuation of geology across the boundary.

A



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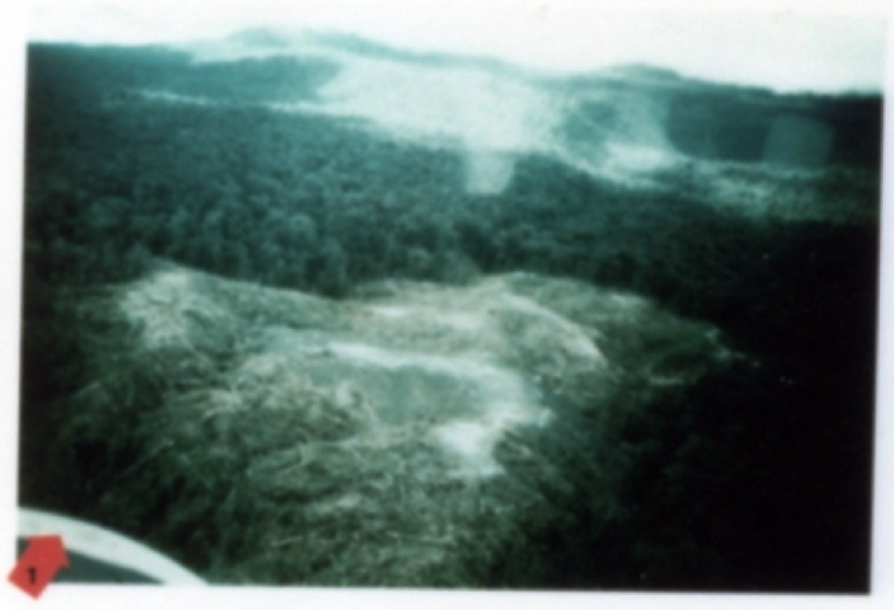
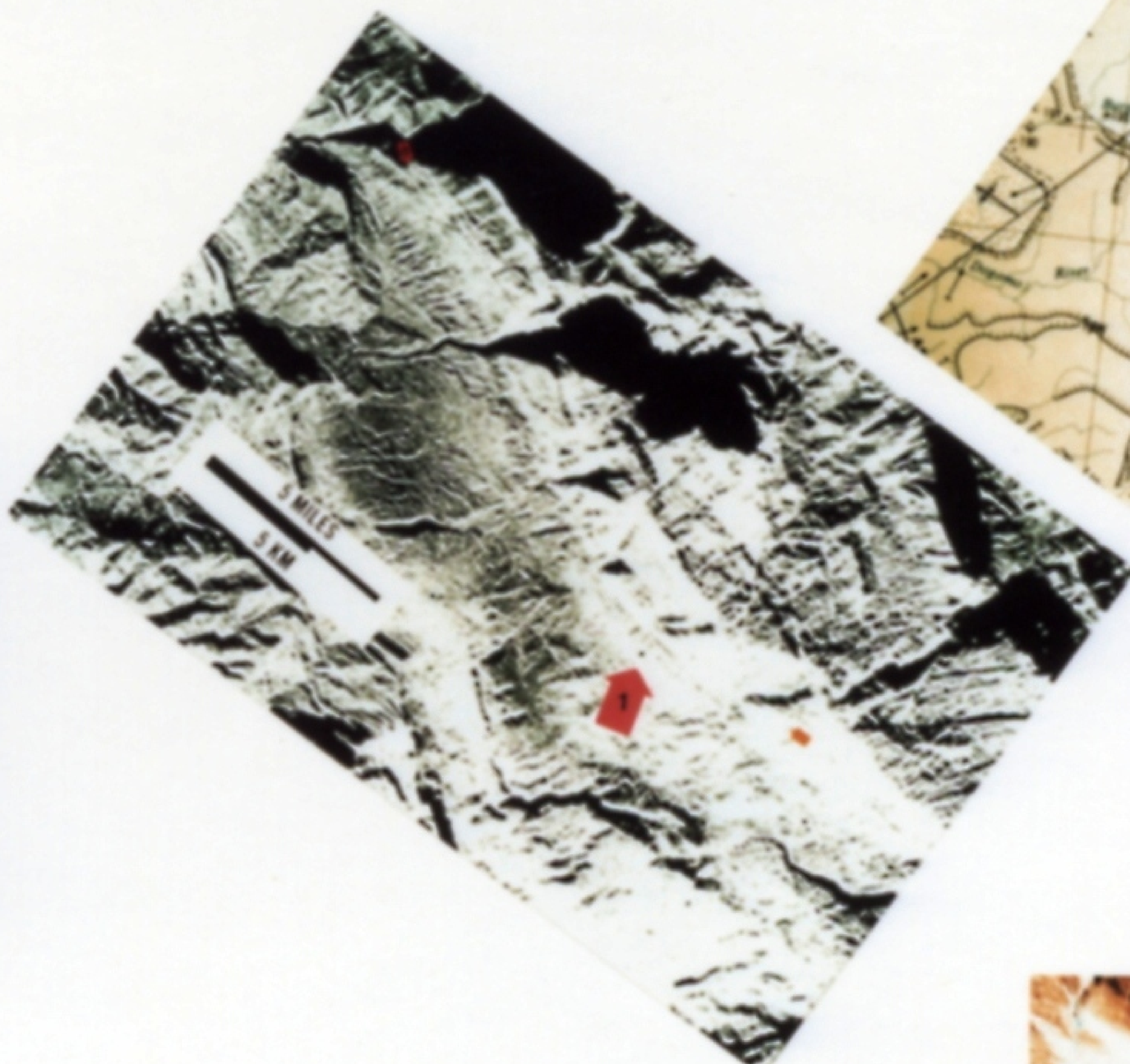
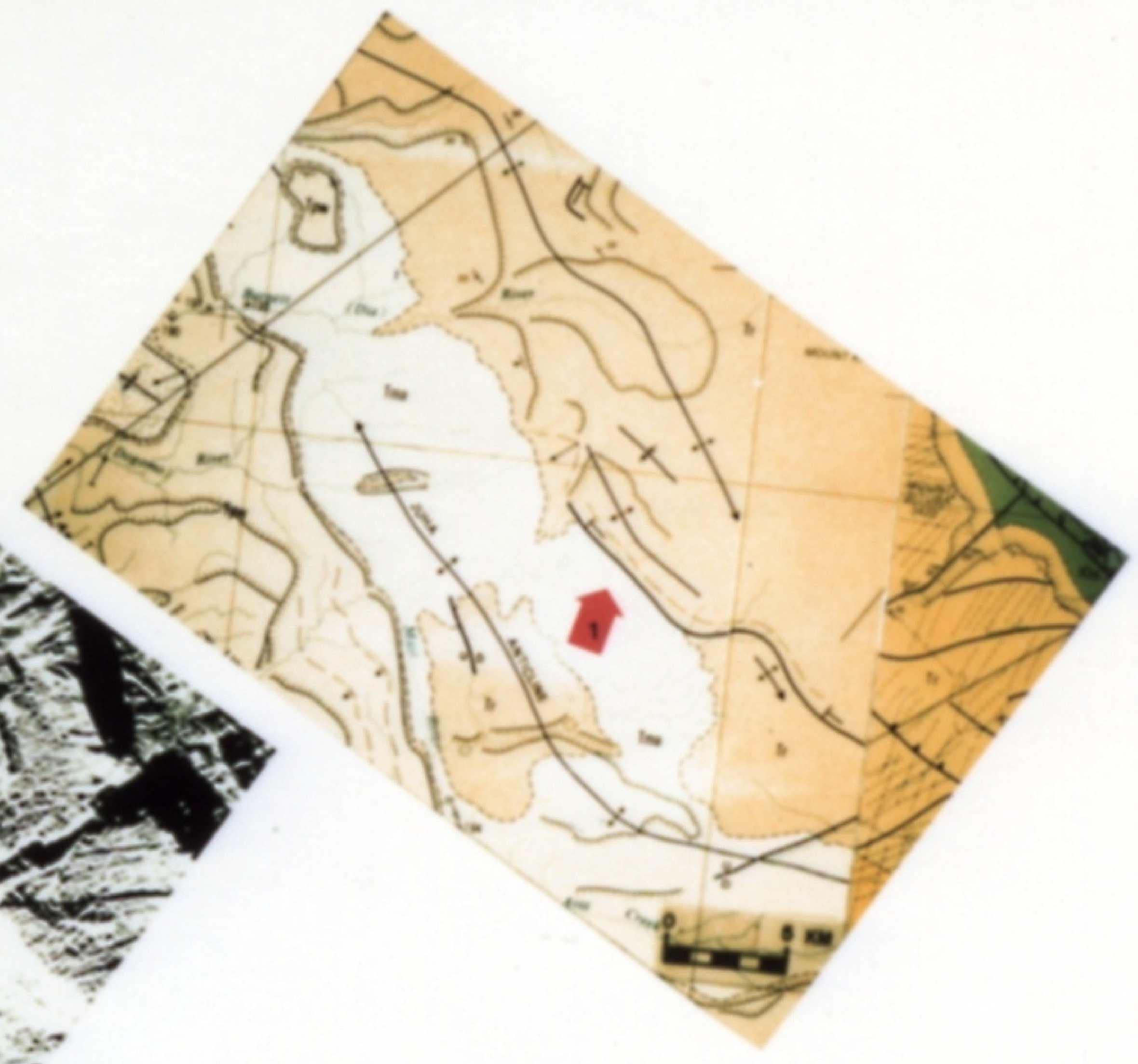
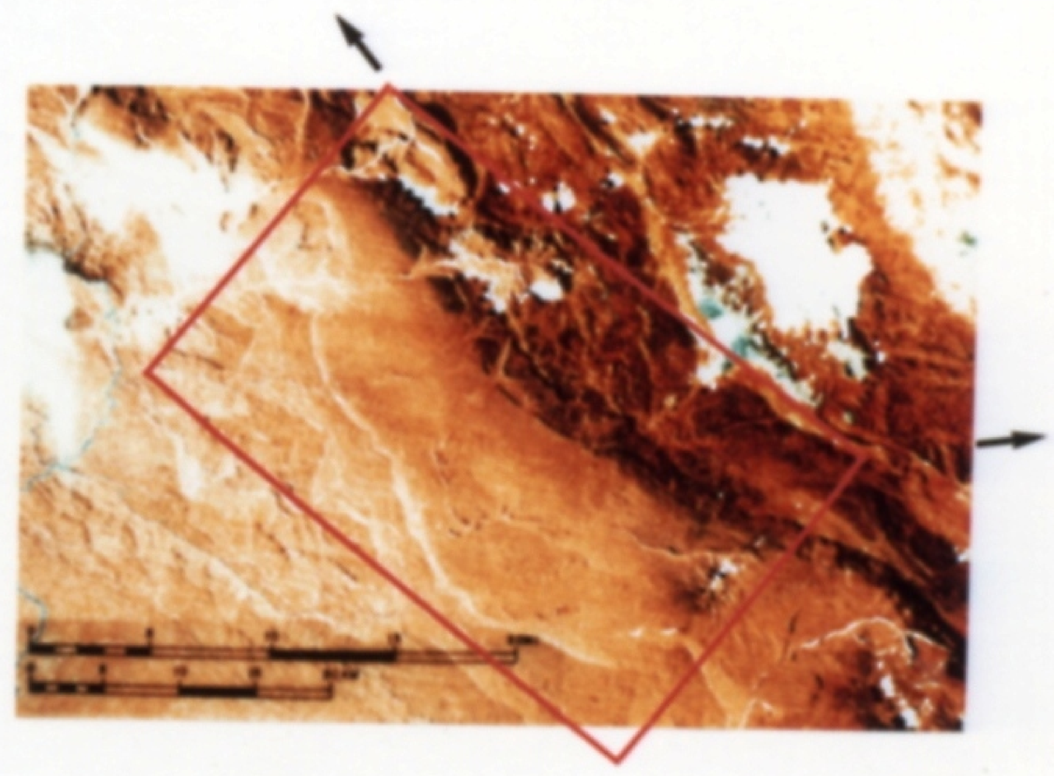
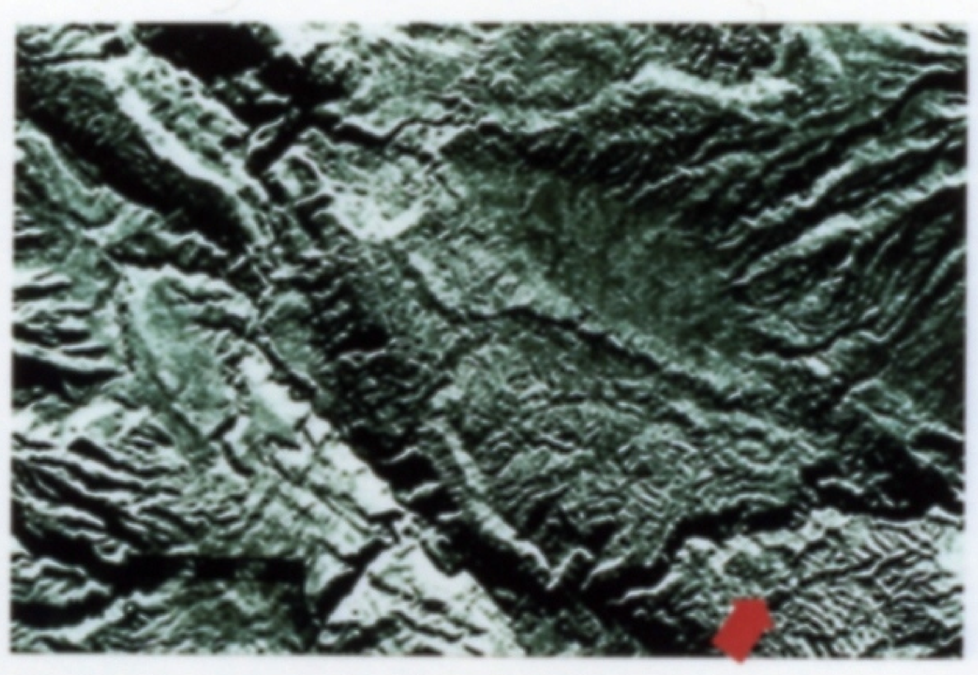
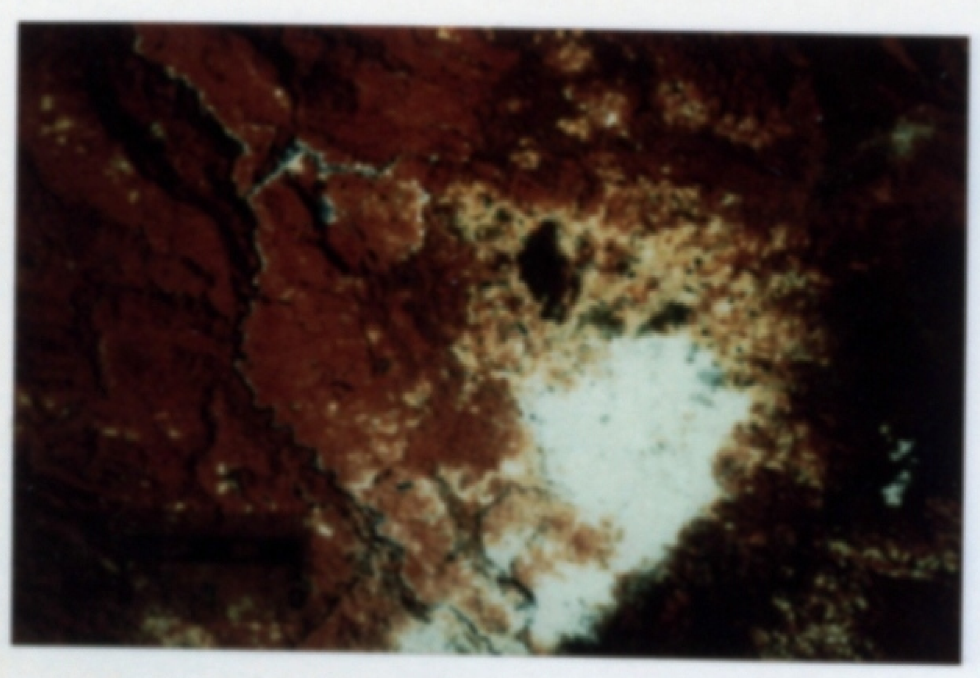





STRUCTURES BENEATH THIN VOLCANICS

STRUCTURES BENEATH THIN VOLCANIC FLOWS

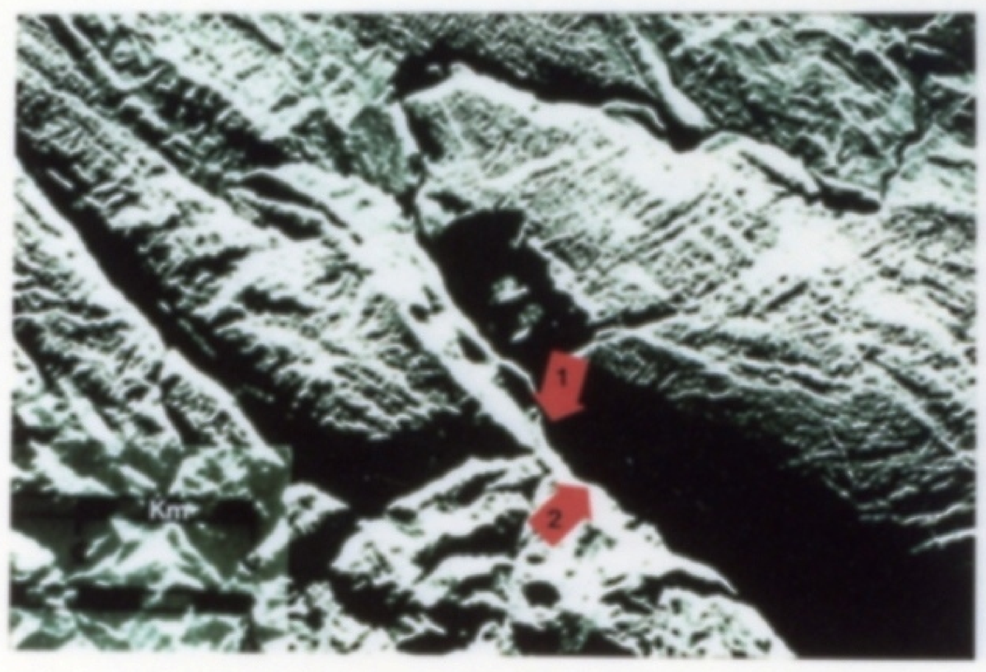
The widespread Darai Limestone weathers to rugged karst topography that has a characteristic radar signature. Resistant limestone pinnacles over 40 m high, sinkholes with surface openings in excess of 100 m, and deeply weathered fractures dominate the surface of the Darai. Resistant strata within the Darai Limestone crop out with an irregular pattern due to the rugged surface morphology.

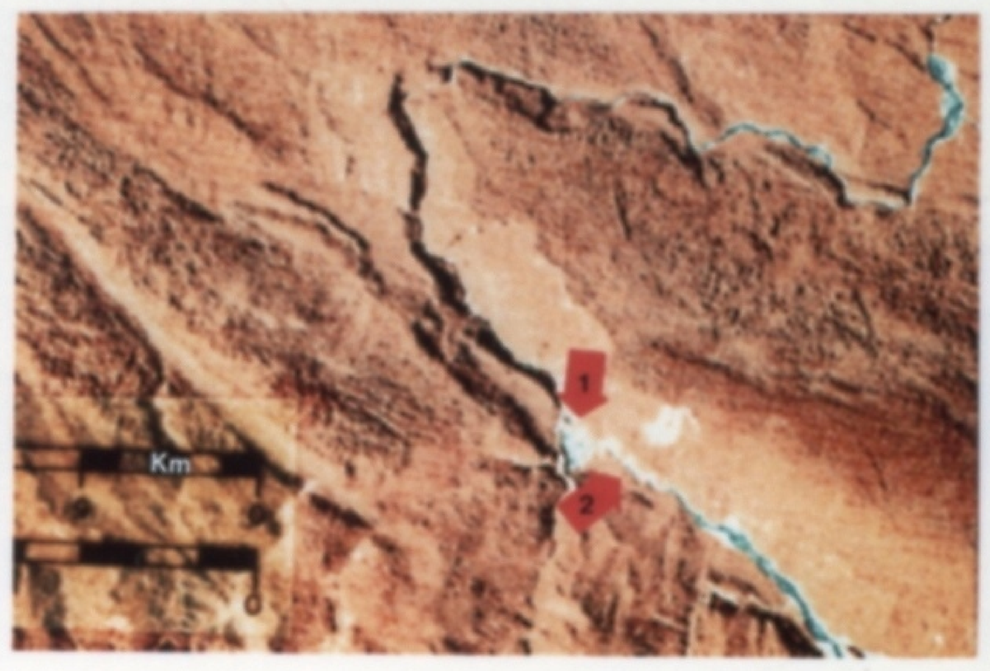
Pliocene to Pleistocene volcanics cover large portions of the fold and thrust belt. On the radar imagery, the surface morphology of some of the volcanic deposits can appear as a karst terrain with well-developed sinkholes, pinnacles, and linear troughs. Here it is inferred that the Darai Limestone is buried beneath the volcanic cover. The radar is reflected from the jungle canopy that covers the surface of the volcanics, generating a subdued but characteristic radar signature for the Darai Limestone .

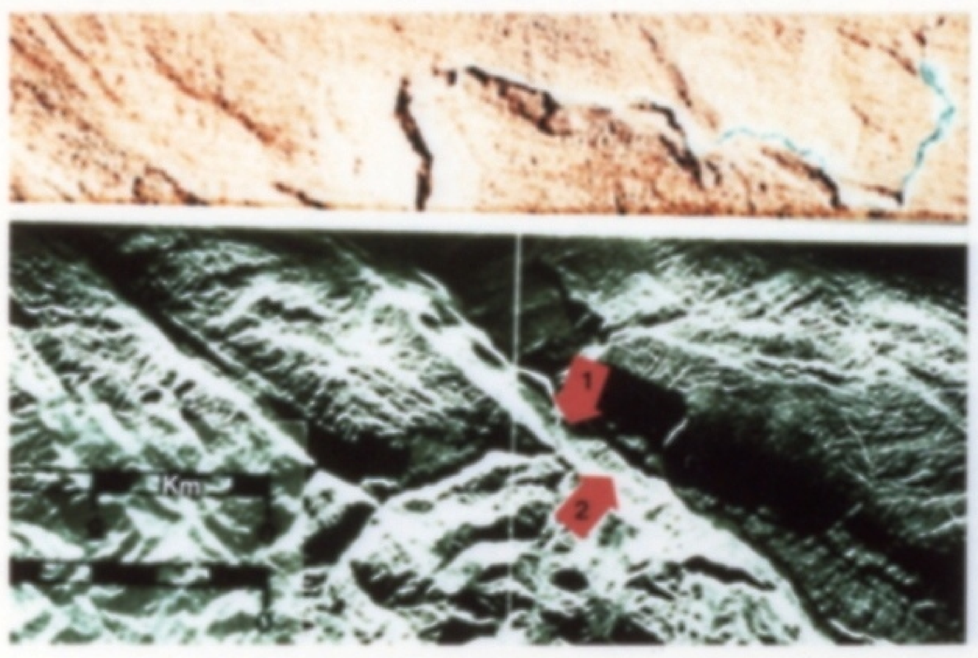
The geologic map above shows two faults, trending NW-SE, that converge toward the southeast, near "Landslide Mountain" . The Darai Limestone (Tmd) caps an anticline (seen toward the northwest), mapped with a anticlinal-axis symbol that terminates at the edge of the volcanics. With the accompanying SAR image, this axis can be extrapolated southeast under the volcanics (TQsl, TQvs), and the plunge of the anticline can be interpreted. The geologic sheet properly shows volcanics at the surface; however, for hydrocarbon exploration the buried structure evident on SAR is of paramount importance.

MOST RADAR IMAGES ARRANGED WITH NORTH AND SHADOWS POINTING DOWN TO MINIMIZE TOPOGRAPHIC INVERSION
MAPS ARE ARRANGED ACCORDINGLY

MASS WASTING







MASS WASTING

The high relief, heavy rainfall, pronounced undercutting of steep slopes by surface rivers, and extensive subsurface erosion caused by karst phenomena (solution and sapping) has resulted in much mass wasting in the fold and thrust belt. The radar images enabled us to recognize numerous mass-wasting zones and alerted us to re-evaluate published dips and strikes in the affected areas. If the zone was hidden by radar shadows, satellite imagery, aerial photographs, and/or field work must be employed.

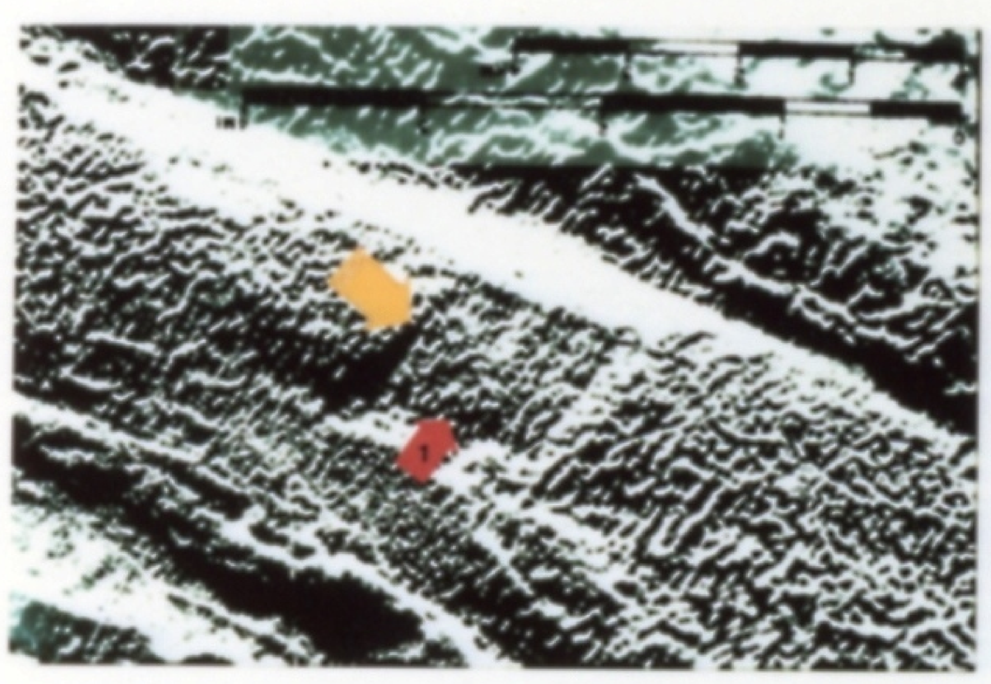
A. One of the largest anticlines in the subject area has significant mass wasting along its flanks. The topographic slope along the northeastern nose is extreme, vertical relief changes >1000 m over a horizontal distance of <4000 m. Here the Hegigio River is cutting a steep gorge. Rock slides are readily seen on the Landsat image. The bright white patch on the Landsat is a recent rock slide that exposes ≈1 km of fresh Darai Limestone. The limestone strata are steeply dipping and unvegetated. These rock slides are evident but partially hidden in shadow on the radar mosaic, and they are not mapped on the geologic sheet.

On the radar image, large WSW-ENE faults (?) are recorded that cut the eastern nose of the anticline; these are very subtle on Landsat and unmapped on the geologic map. The downward extent of these breaks is unknown. They may affect reservoir continuity at depth or they may be restricted to the Darai Limestone cap and represent giant blocks moving downslope toward the down-cutting Hegigio River. The anticline steps down hundreds of meters toward the southeast across these blocks.

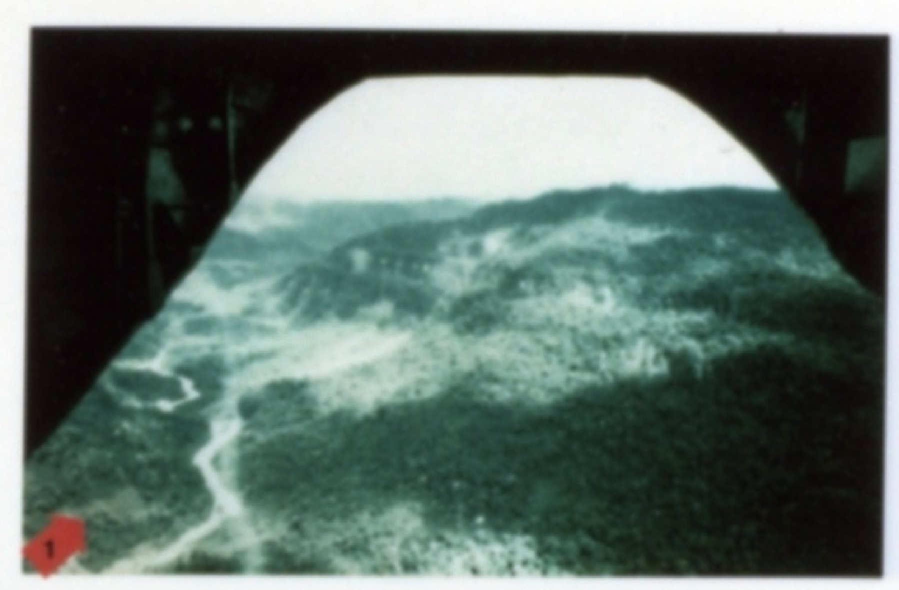
MASS WASTING?

B. Down-dropped blocks of Darai Limestone (to 2 x 2 km in area) along the extended crests of anticlines are detected with SAR. Such depressions may reflect (1) structurally controlled, downdropped grabens due to crestal extension during folding, (2) zones of thinner limestone created by increased subsurface erosion (water, solution, and sapping concentrated by associated fracture systems), (3) incipient rock slides caused by fluvial erosion at the base of the anticline's flanks, or (4) the surface expression of a deep fault and fracture system that has major exploration significance. Only field work and drilling can determine what geological process(es) control the development of crestal depressions.

The large, downdropped block of limestone caprock along the crest of Iagifu anticline is clearly shown on the radar image to the right, but unmapped on the smaller-scale map.



LITHOLOGIC MAPPING



LITHOLOGIC DISCRIMINATION

Although the terrain is covered with a jungle canopy, many lithologies can be recognized by their characteristic radar signatures. Localized field work in the area shown to the left differentiated Tertiary sedimentary rocks into 4 units. Northeast is toward the upper margin of both the map and the image. The accompanying radar image has arrows pointing to areas where the field work confirms the type of rock cropping out beneath the jungle canopy. The arrows are labelled with the SAR identification as follows:

V stratified volcaniclastics (generally Tpw on the geologic map)
Si siltstones
L nonresistant limestone (generally Tma on the map)
D tough Darai Limestone (Tr or Tmd on the spliced map)

Inspection shows that the radar imagery and the geologic sheet contain significant mapping differences. Volcaniclastics (V) are imaged north of the Juha anticline. The Darai Limestone (D) has a more limited outcrop pattern on the radar imagery. Along the crest of the Juha anticline the radar records a grainy, coarse texture that is seen in the field as a siltstone (Si). A weak limestone (L) is imaged by SAR with a lighter tone and sightly smoother texture than the siltstone.

The radar image is from a mosaic composed of 1:50,000 enlargements of the near- and mid-range portions of two flight strips. The splice lines can be seen intersecting near the center of the SAR image. It can be seen that radar signatures for the same lithology vary across the east-west splice line. The northern and the southern strips have 8° and 17° depression angles along the east-west splice line, respectively. Differences in the intensity of radar returns and; therefore, the resulting image signatures (Sabins, 1983) may result from the different depression angles.

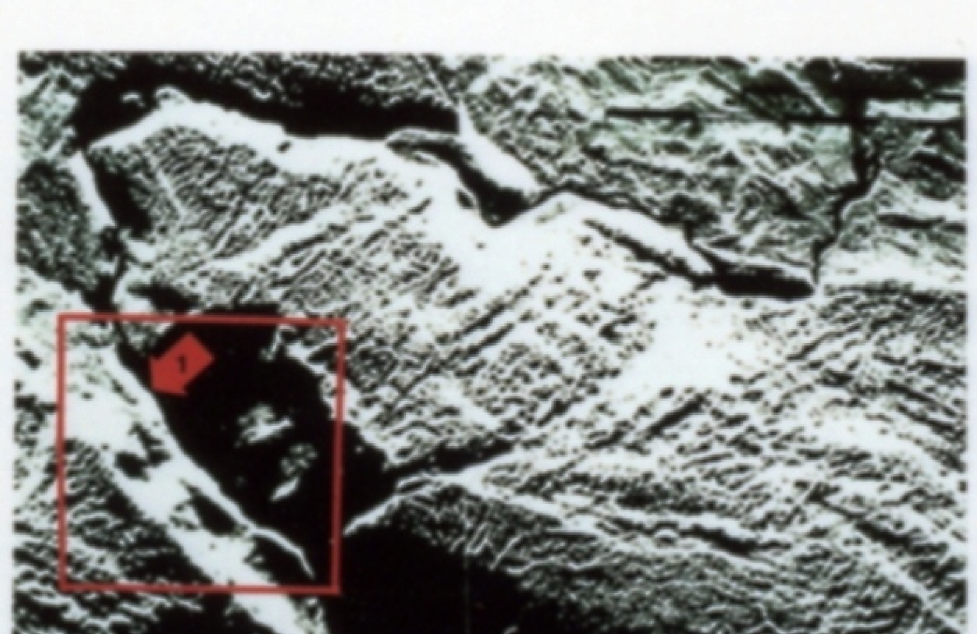
DIGITAL REPROCESSING OF BRIGHT CLIFFS

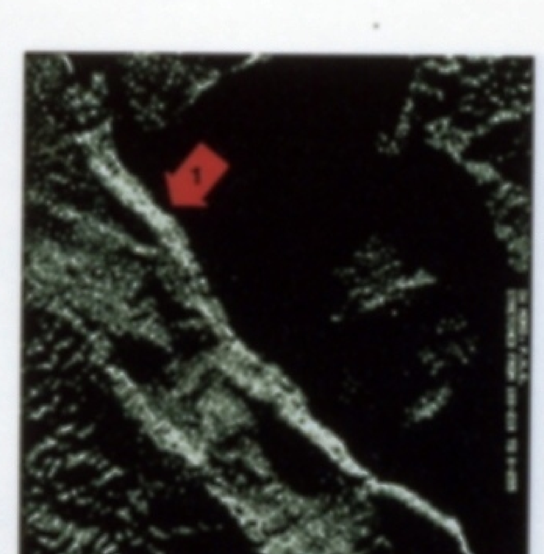
DIGITAL REPROCESSING OF SAR IMAGERY

Reprocessing of the digital data allowed additional geologic information to be extracted from the survey. The original photographic strips were contrast-balanced for the entire scene. However, cliffs that faced the radar antenna reflected (as expected) a relatively high amount of radar energy, which resulted in oversaturated (bright) or "flared" zones on the original strips.

The radar digital data shown in A and B was resampled during processing and 10 x 10 m pixels were generated from the original 4.3 x 11.4 m pixels. The subscene in B is a full resolution image of this resampled data as it was displayed on the image processing monitor. The number of pixels in this undecimated subscene is 262,000 (the monitor displays 512 x 512 pixels); therefore, the area displayed is only ≈5 x 5 km^2. This area is outlined in A. Although this contrast stretching was accomplished on a relatively small area, full-resolution stretching was found to be more informative than working with decimated images that covered a larger ground area.

The oversaturated (bright) cliffs outlined on A had reflectances that ranged from 100 to 210 on a scale of 0 (pure black) to 255 (pure white). The subscene (B) was interactively manipulated and the example shown is one where reflectance values below 100 were saturated to pure black (0) and those from 100 to 210 were stretched over the full range of 0 to 255. Contrast stretching of the brightest digital values (at the expense of the rest of the scene) revealed subtle topographic and structural information along south-facing cliffs.





ACKNOWLEDGEMENTS

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Mars Associates, Inc. constructed an excellent radar mosaic and completed the initial interpretation of the SAR data. R. H. Gelnett of Mars Associates, Inc. was especially helpful organizing the survey and ensuring we understood the interpretative aspects of SAR imagery. Intera Technologies Ltd. acquired the outstanding imagery using an X-band, synthetic aperture STAR-1 digital radar system. Rob Inkster of Intera has assisted in improving our understanding of the technical aspects of SAR acquisition.

F.F. Sabins, W.S. Kowalik, and T.F. Battey of the Remote Sensing Lab at Chevron Oil Field Research Company accomplished the digital manipulation of the SAR data. F.F. Sabins also provided timely geological and technical advice, and reviewed our paper.

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