MAPPING THE COASTAL PLAIN OF THE CONGO WITH AIRBORNE DIGITAL RADAR*

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ABSTRACT

An airborne radar survey was flown over the coastal plain of the Congo during May 1988 to improve mapping of structure, stratigraphy, geomorphology, topography, and culture in support of petroleum exploration. Fourteen "radar-morphologic" units were interpreted based on texture and drainage pattern. Interpretation of stereo flight strips modified the placement of published structural axes and provided numerous new dip and strike estimates. A fault zone (5 km wide by >100 km long) was interpreted based on an alignment of lakes, swampy terrain, disrupted drainage, and topographic breaks.

The imagery was acquired at different resolutions and look directions to allow for both regional and large-scale mapping. A topographic map with an approximate 10-m contour interval was interpreted using overlapping high-resolution flight strips and a standard mirror stereoscope. Elevation data from surveyed seismic lines and wells served as control. These topographic contours were digitized and a Digital Elevation Model (DEM) was constructed. A digital radar mosaic was draped over this DEM, allowing perspective views of the coastal plain to be generated to enhance planning and interpretation.

1.0 INTRODUCTION

An airborne SAR (synthetic aperture radar) survey was flown by Intera Technologies Ltd. over 7000 km^2 of the coastal plain and bordering basement complex of the Congo during May 1988 (Figure 1). The survey was conducted to improve regional and local mapping of structure, near-surface stratigraphy, geomorphology, topography, and culture. The coastal plain is often covered by clouds and existing, multispectral satellite imagery provided incomplete and limited coverage. In addition, no topographic map existed that was suitable for planning seismic acquisition.

The SAR survey was conducted as a "group shoot" by Intera Technologies Ltd. for Chevron, BP, Conoco (Operator), Elf, HydroCongo, and their numerous partners. Standard resolution (16 x 16 m pixels), 65-km wide-swath radar flight strips were acquired with a low angle of illumination to emphasize regional structure. The area was also flown in a high resolution (4 x 6 m pixels) mode for detailed mapping of culture, terrain, and topography.

A digital mosaic was generated with the standard-resolution data by Intera Technologies using several Global Positioning System (GPS) fixes acquired during SAR acquisition and published maps. These strips and mosiac were plotted at a 1:200,000 scale. A mosaic of high resolution data was constructed by hand to the Congo's standard map projection (Transverse Mercator, Clarke 1880 Spheroid, Zone 32, CM 9° East) at a scale of 1:100,000 by Mars Associates Inc. (see Figure 1). As field work progressed, new GPS fixes were acquired by Chevron. These new fixes were loaded into an in-house, Computer-Aided Drafting (CAD) system and were used to help rectify the northwestern portion of the digital radar mosaic where Chevron and partners have an exploration license (named "Kayes A"; see Figure 1). This updated radar mosaic has become the base map for Chevron's license.

This paper will concentrate on the interpretation and practical application of radar images acquired over the northwest portion of the coastal plain and the adjoining Precambrian basement complex (Figure 2).

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2.0 REGIONAL GEOLOGY

Across the Congo coastal plain, Cretaceous and Tertiary sedimentary rocks with petroleum potential are largely covered by the flat-lying Plio-Pleistocene Serie des Cirques Formation (Bird and Schwartz,1985) and other undifferentiated Plio-Pleistocene sediments (see Figures 2C and 3). Plio-Pleistocene deposits are composed of silty sands with some gravel, clay, and lateritic layers. They support a surface that averages about 50-100 m above sea level and that is mostly covered with savanna vegetation and grasses. The watertable may be too deep within this well-drained landform to support an extensive growth of trees.

The Plio-Pleistocene coastal plain (termed a "piedmont") is being actively dissected by hundreds of steep-sided gullies that have a cirque-like appearance (Figure 4). The slopes of these incised gullies are covered with trees that often attain heights above the surrounding and uneroded piedmont. Broad fluvial channels, rivers, lakes, swamps, and a vigorous northwest-flowing, longshore current characterize the remainder of recent (Quaternary?) deposits across the coastal plain. Rivers are often discontinuous because ponding is relatively common within low-lying valleys. Ponded drainages support dense jungle growth which is almost impenetrable (Figures 2D and 5). Lagune Conkouati dominates the center of the Kayes A license (Figure1), is surrounded by swamps, and is open to the ocean.

Northeast of the coastal plain and about 30 km inland, Precambrian metamorphic and crystalline basement crops out (Figure 1 and 6A). A 1:500,000 geologic map of the coastal plain and the adjoining basement complex was published by the Bureau du Recherches Geologiques et Minieres (B.R.G.M.; Datet, 1966). Ages assigned to the published stratigraphic units were broadly applied to radar-lithologic units interpreted from the images. The Congo coastal plain is underlain by Precambrian basement. Across the area Cretaceous, Tertiary, and Quaternary sediments were unconformably deposited on this basement. Paleozoic and Mesozoic sediments older than Cretaceous are absent.

3.0 LITHOLOGIC INTERPRETATION

Both high- and standard-resolution flight strips were interpreted stereoscopically. Fourteen radar-lithologic units were interpreted across the coastal plain of the Congo based on texture and drainage pattern.

The coastal plain is dominated by Plio-Pleistocene undifferentiated sediments, including the Serie des Cirques Formation. Much of the coastal plain is characterized on radar by a dark, smooth surface (representing an elevated, well-drained surface that supports savanna vegetation) that is surrounded by brighter and more textured terrain (depicting forested, incised stream valleys whose tree canopies often cast radar shadows onto the savanna; Figures 1 and 3). Northwest of Lagune Conkouati, the Plio-Pleistocene surface is seen on SAR differently; here the savanna is limited and instead the terrain is dominated by a bright hummocky signature and medium drainage texture with some straight-stream segments (Figure 1). Quaternary fluvial and swamp deposits are characterized by a uniform, light-gray texture with minimal relief and an obscure drainage pattern (Figure 5). In general, Plio-Pleistocene and Quaternary units interpreted from SAR agree with patterns on the published map.

Radar-lithologic units representing Tertiary and Cretaceous (?) outcrops generally parallel the coastline (Figures 5C and 6D). The folded and faulted Precambrian basement was divided into several units based on texture and brightness (some noted as A-D on Figure 6D). This interpretation is significantly different compared with the published map (Figure 6C), which emphasized metamorphic mineral assemblages across the basement complex. This difference in interpretation is probably due to the difference in mapping scale. SAR imagery provided a consistent regional overview of terrain and outcrop patterns. In contrast, the published map was based on localized field work in a very difficult area. The two interpretations are being integrated with ongoing field work and sampling. Although detail and field verification are lacking, mapping lithology with SAR was effective because it provided a simpler geologic model for petroleum exploration.

4.0 STRUCTURAL INTERPRETATION

Stereo viewing of the imagery altered the placement of structural axes and provided new dip and strike estimates (Figure 6B). Within the basement complex a major anticlinorium and subsidiary anticlines and synclines were mapped. SAR imagery was very useful for resolving a structural pattern of basement deformation. This information has value because the coastal plain sediments with petroleum potential are adjacent to and are underlain by this basement complex.

A fault zone (5 km wide by >100 km long) was interpreted paralleling the coastline based on an alignment of lakes connected by near-continuous swampy terrain, offset stream channels, and relatively sharp topographic breaks (Figure 7). The SAR imagery across the entire Congo coastal plain highlighted several subparallel valleys orthogonal to the coastline that are filled with lakes (i.e. Lagune Conkouati), linear stream segments, and elongated swamps. These valleys have about a 30 km spacing (see Figure 1) and probably relate to small transform faults associated with Atlantic spreading.

Fractures with no apparent offset were interpreted from topographic and drainage alignments. The dominant pattern of these lineations is northwest-southeast and northeast-southwest across the coastal plain (Figure 1). Alignment of streams and ridges parallel to the coastline (northwest-southeast) may indicate stratigraphic contacts, but this could not be determined from the images. A secondary north-south/east-west lineation pattern can also be interpreted from the SAR imagery. This more subtle pattern was highlighted by selectively illuminating a DEM of the coastal plain (see Section 7.0). Only a few drainage anomalies were interpreted across the coastal plain, and these were poorly developed.

5.0 MAPPING CULTURAL FEATURES

The high resolution imagery provided a superb 1:50,000 base for geological field work and seismic-acquisition operations. Swamps, savanna, forest, 4 to 5 orders of streams, and widespread erosional gullies were mapped, forming a reliable and up-to-date base for operations. Individual trees on open savanna were easily identifiable (Figure 3), enabling exact locations to be determined in the field (a necessity for locating GPS fixes on the imagery).

Trails for 4-wheel vehicles were concentrated and easiest to interpret on savanna-covered terrain where they follow the flat drainage divides of the Plio-Pleistocene coastal plain. Here trails were recorded on the images as light gray lines against a dark smooth background (Figure 4). Often trails are abandoned when the tire ruts are too deep for vehicular passage. These abandoned trails are typically easier to see on the imagery than are active ones, due to continued erosion and gullying. Deep tire ruts disrupt the protective root cover, accelerating erosion. In addition, trails that are abandoned but are less worn may be easier to discern than active ones because a more reflective vegetation type becomes established a year or two (?) after abandonment (R. Lowry, 1988, pers. comm.). In jungle-covered gullies and vegetated swamps, the tree canopy almost always cover any evidence of a surface trail.

Rural cultural features (small villages, trials, and subsistence agriculture; Figure 2B) are sparse in northwest Congo and within the Kayes A license (Figure1). They are difficult to interpret on radar imagery because they contrast only slightly with the surrounding terrain. If able to be acquired, a multispectral, color SPOT image would be superior for mapping cultural features in the sparsely populated Congo coastal plain of Kayes A. Urban and industrial features 90 km southeast of Kayes A were easily defined with the airborne SAR imagery (see Figure 8).

6.0 CONSTRUCTION OF A BASE AND TOPOGRAPHIC MAP

A digital radar mosaic provided by Intera Technologies was upgraded and rectified to the company basemap using numerous proprietary GPS fixes. Following this registration, the company CAD files (Lat/Long, seismic, wells, culture, interpretations, etc.) were digitally transferred to an image processing system for integration with digital SAR data. CAD files were selectively embedded into rectified SAR images, producing very useful "image maps" (Figure 9A).

The coastal plain has little topographic relief (<200 m) and the aircraft encountered minimum air turbulence during acquisition. This combination allowed the generation of a topographic map with an approximate 10-m contour interval using overlapping, high-resolution flight strips and a standard mirror stereoscope. Determination of relative elevations is possible when viewing overlapping flight strips stereoscopically because the interpreter perceives "false" parallax because the same ground feature has different radar shadow length and geometric distortion on each strip (R. H. Gelnett, 1986, pers. comm.). Elevation data from surveyed seismic lines and wells served as control (Figure 9A). The contours were transferred from interpretation strips to the basemap. The resulting topographic map provided a simple, quick, and cost-effective base for planning seismic acquisition (Figure 9B). This radar-topographic map was checked while new seismic lines were being acquired. Along the new lines, the map was within 15 m of the surveyed elevation about 85% of the time (see Figure 12C).

7.0 GENERATION OF A DIGITAL ELEVATION MODEL (DEM)

The topographic contour map (Figure 9B) was digitized, gridded, and a Digital Elevation Model (DEM) was constructed on both CAD and image processing systems. The CAD wireline DEM (Figure 10) has the advantages of rapid integration with various CAD map files, easy updating, and quick output as a low cost, large-scale paper print. The DEM as processed on our image processing system has the advantage of being a solid model that can be interactively color-density sliced to simulate some contour interval (Figure 11A) or highlight some range of elevation. In addition, it can also be displayed as a "plastic relief model" and illuminated from different azimuths and elevations to create shadows that accentuate a variety of topographic (structural?) trends (Figure 11B; Kowalik and Glenn, 1987).

A digital radar mosaic with seismic lines embedded (Figure 10A) was draped over the remote sensing DEM, allowing perspective views of the coastal plain to be generated to enhance planning and interpretation (Figure 12A). Proposed lines were transferred from CAD without dots (these represent shot points on existing lines) so that they could be differentiated from existing lines. Interactive work with the perspective-view image on our PC-based image processing system allowed explorationists to zoom-in on problem areas (Figure 12B) and roam across the coastal plain following elevation changes along specific seismic lines.

8.0 SUMMARY

Airborne radar imagery delivered timely solutions to many problems facing frontier exploration along the coastal plain of Congo. It provided a complete basemap of the region that is being continually upgraded and used at scales ranging from 1:25,000 to 1:250,000. As expected, extensive structural information was interpreted from stereoscopic flight strips. In addition, 14 radar-lithologic units were mapped that provided a simpler geologic model for exploration. Special circumstances allowed construction of a reasonably accurate and very inexpensive topographic map using overlapping flight strips and a mirror stereoscope. From this hardcopy, DEM's were generated to assist in visualization of the terrain for planning field operations and interpreting structural trends.

9.0 ACKNOWLEDGEMENTS

We greatly appreciate Chevron Overseas Petroleum Inc., Chevron International Limited - Congo, and our partners in Kayes A (Amoco Congo Exploration Co., Shell, and HydroCongo) granting permission to publish this paper.

Soofie Khalid of Conoco did an outstanding job coordinating the acquisition and processing of the airborne SAR data for the partnership. Image processing and integration of CAD vector files with SAR raster data was accomplished on a DIPIX system. W. S. Kowalik (Chevron Oil Field Research Company) provided the software and expertise on creating a DEM and shadowgram with our in-house system. Chevron Overseas' CAD Drafting group provided the wireline DEM of the topographic map. The 3-D perspective view was generated on our Terra-Mar image processing system. Peter Goodwin, Pat Caldwell, John Granzella, Chuck Clancy, Hattie Davis, Mark Choiniere, and Mike Quinn of Chevron Overseas provided timely and excellent technical support.

10.0 REFERENCES

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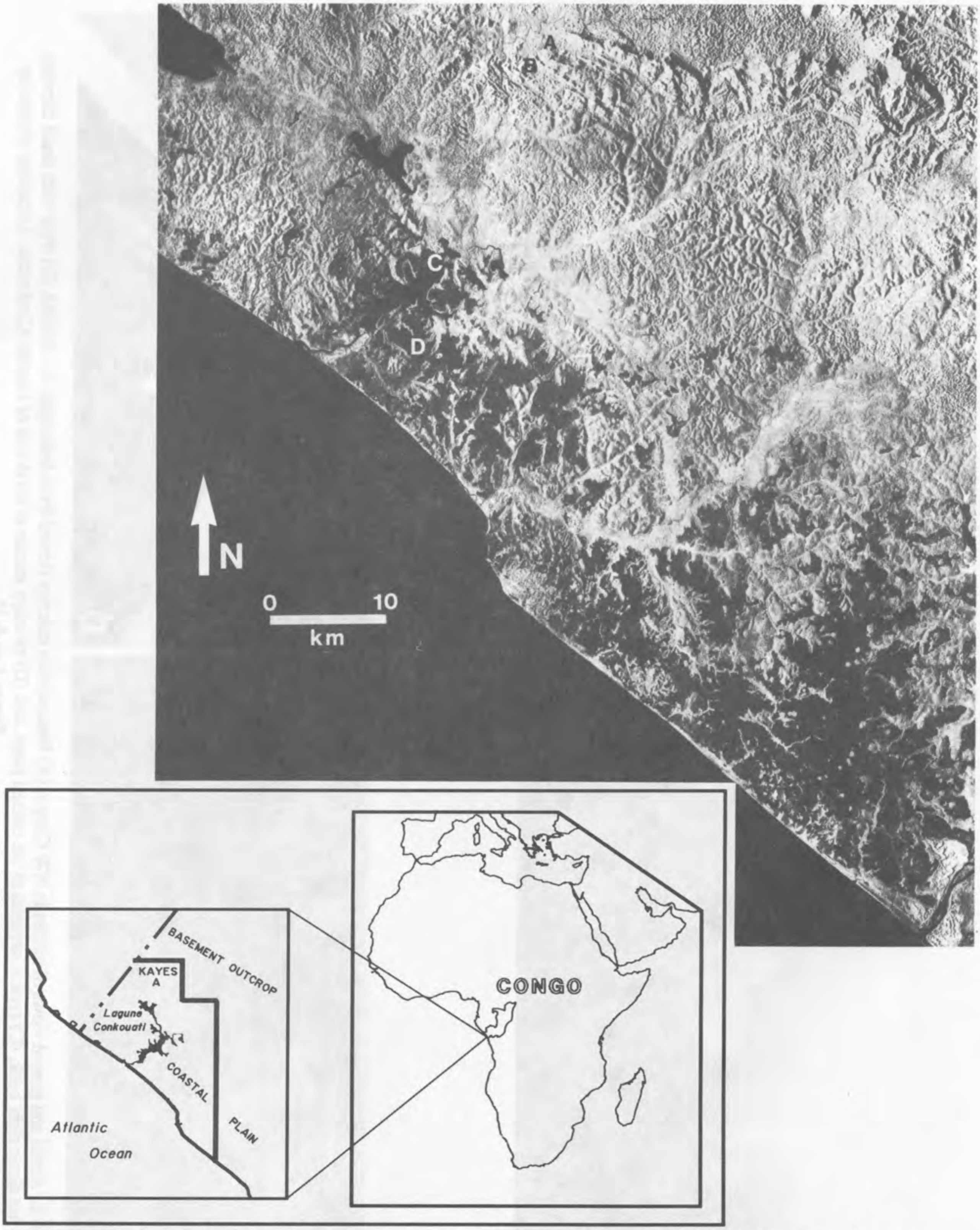

Figure 1. Mosaic of high resolution SAR image of NW coastal plain and adjoining Precambrian basement complex of Congo. Location map provided with Kayes A license outlined. A-D on mosaic refer to locations of aerial and ground photographs in Figure 2.

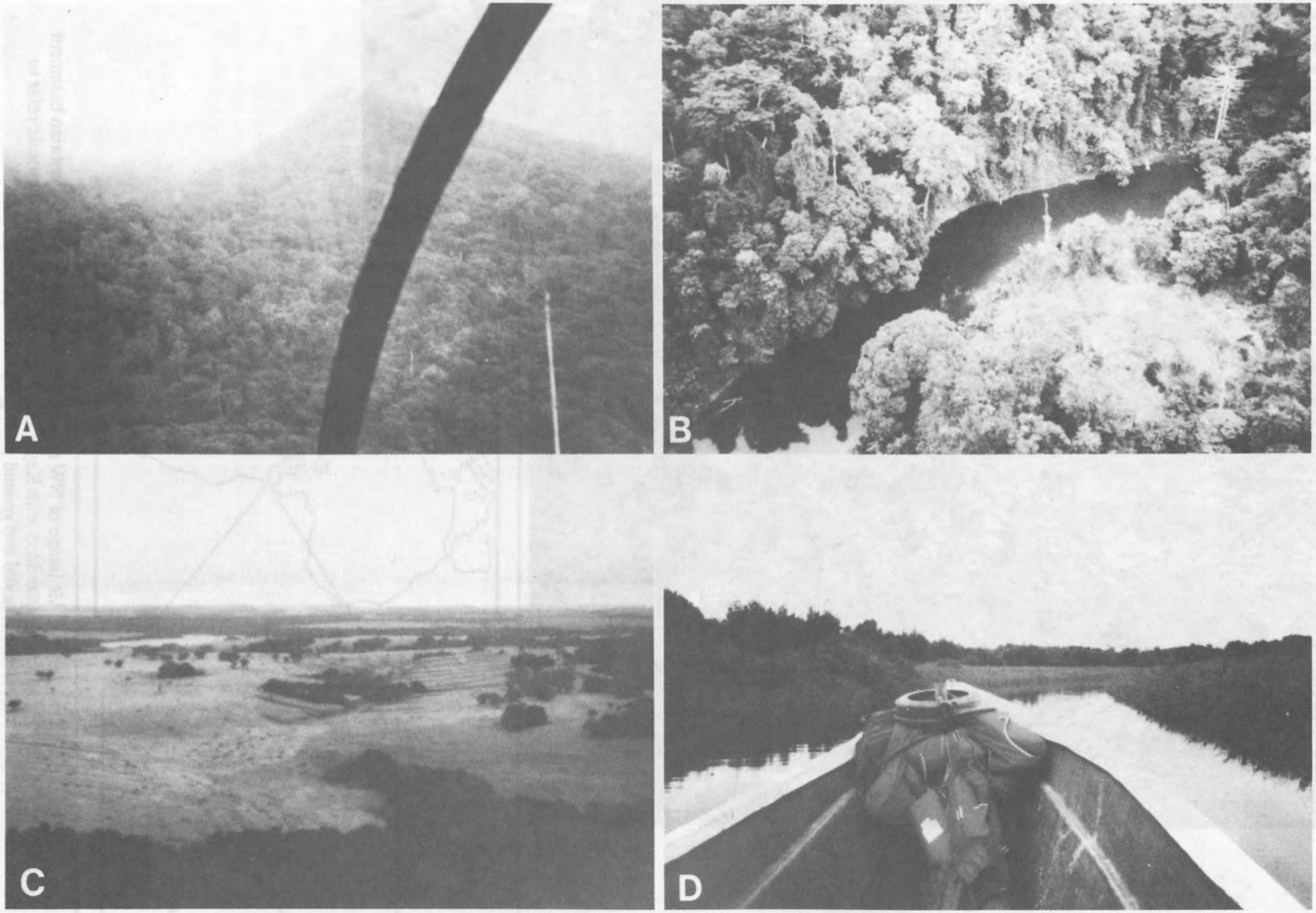

Figure 2. Aerial and ground views of terrain in NW Congo. (A) Precambrian outcrop viewed from helicopter windshield, (B) river with small clearing and hut along right bank, (C) typical savanna of the coastal plain, and (D) swampy terrain at north end of Lagune Conkouati. Locations shown on Figure 1 as A-D.

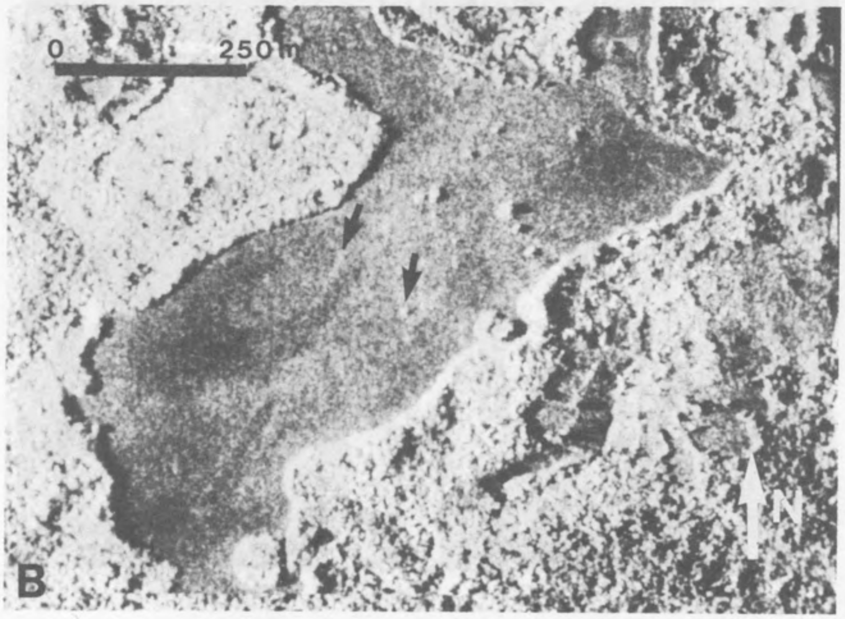

Figure 3. Example of (A) aerial photograph and (B) corresponding SAR image of coastal plain. (A) was taken looking south and shows solitary tree on savanna with abandoned runway on extreme right. Arrows on (B) point to tree and faint trace of runway (photographs provided by R. Lowry of Intera, 1988).

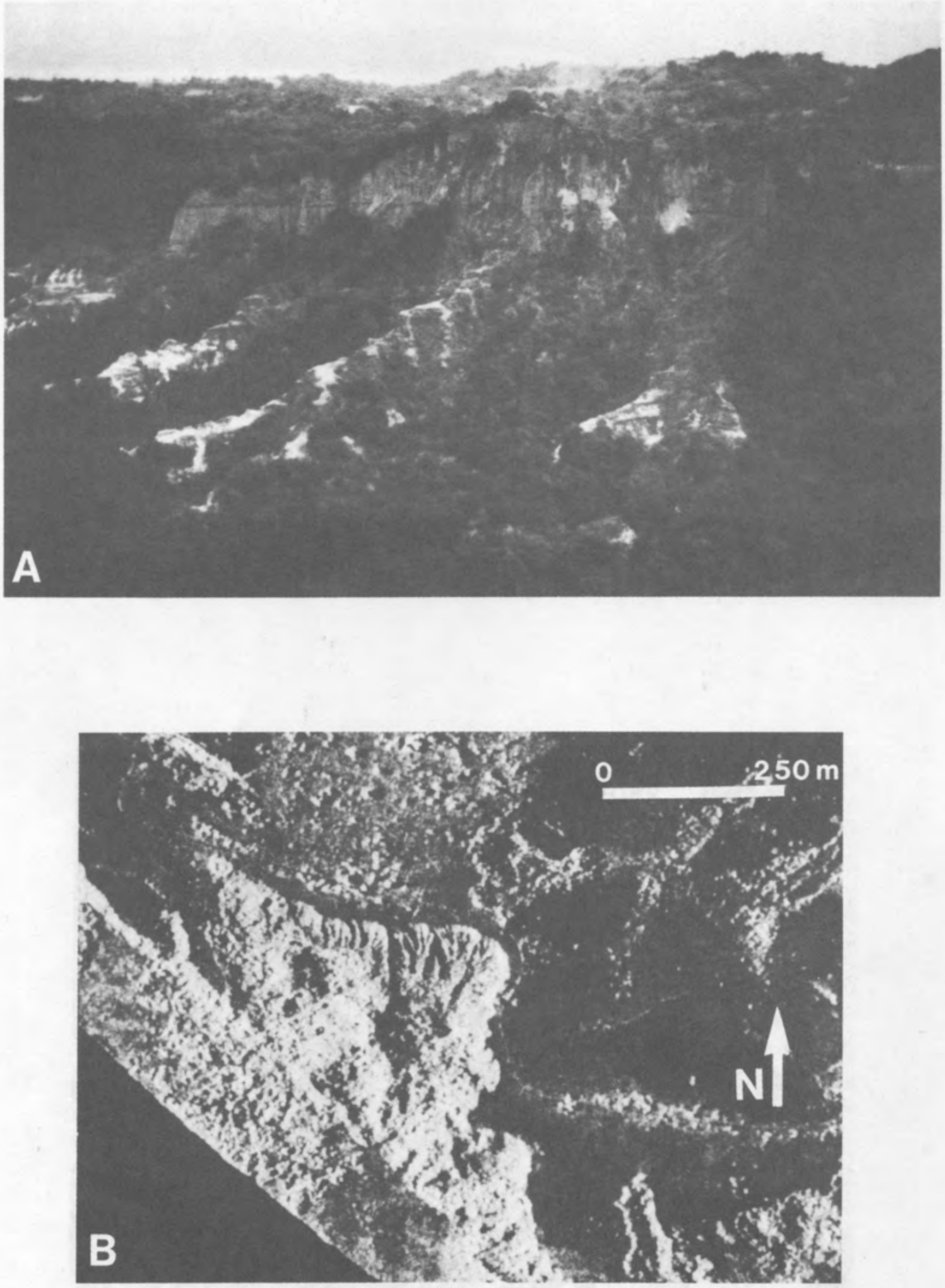

Figure 4. (A) Ground view of incised headwall of gully that is eroding Plio-Pleistocene sediments of coastal plain. (B) SAR image of same area showing typical "cirque" morphology of these erosional features (SAR photograph provided by R. Lowry of Intera, 1988).

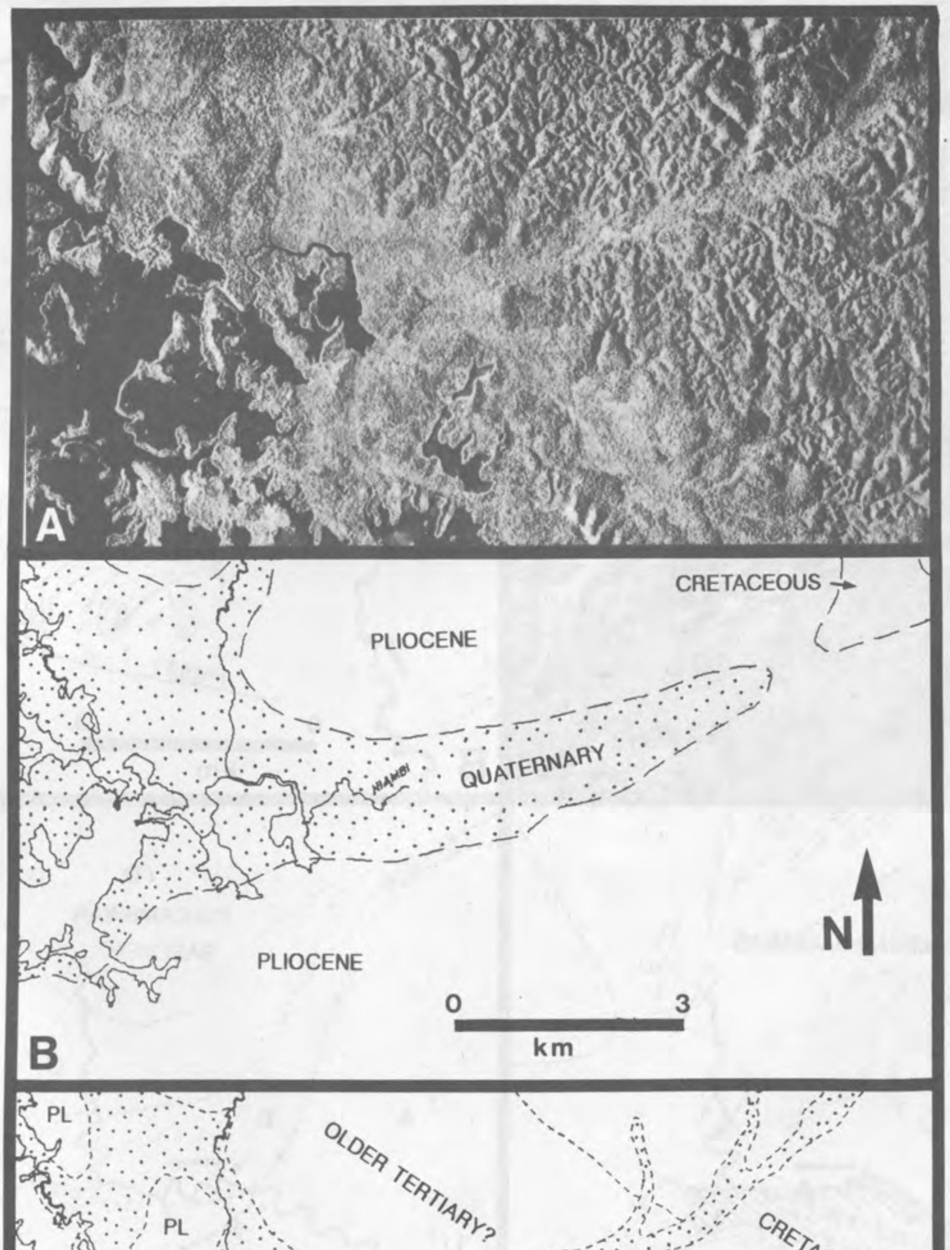

Figure 5. Same-scale comparison of (A) radar, (B) published geologic map, and (C) interpreted radar image of low-lying, swampy Quaternary terrain and older deposits of coastal plain. SAR image allows more accurate mapping of swamps and Tertiary/Cretaceous (?) rocks.

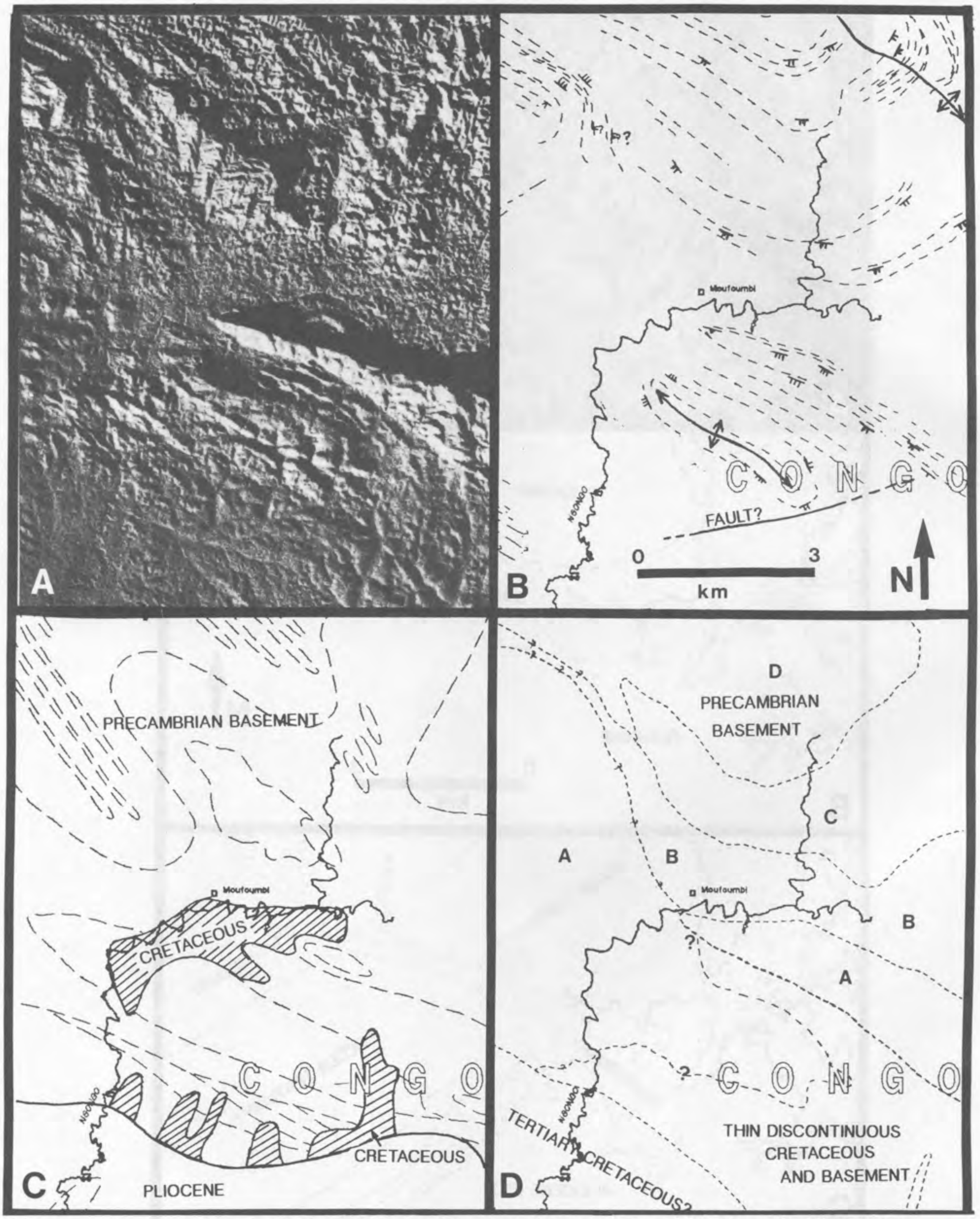

Figure 6. Same-scale comparison of (A) radar, (B) structural interpretation of SAR (axes, bedding planes, dip and strike), (C) published geologic map with Cretaceous highlighted and various Precambrian basement units outlined with dashed lines, and (D) interpreted SAR lithologic units (units A-D are Precambrian basement). SAR simplifies geologic trends and provides new structural information.

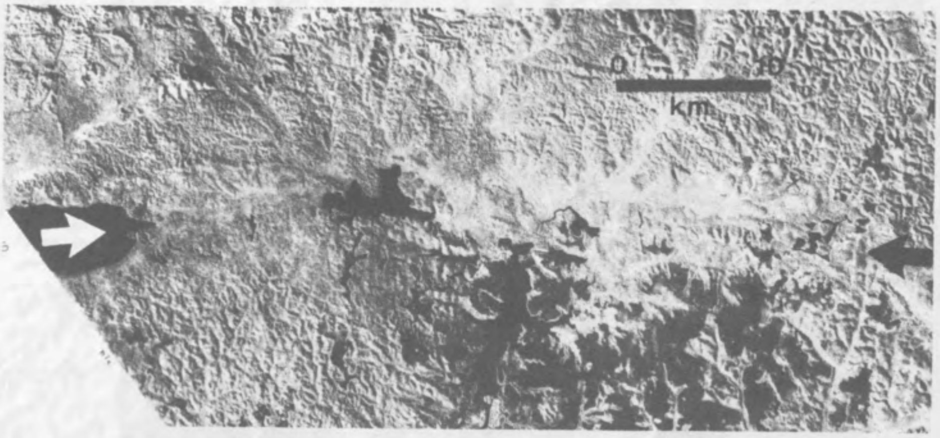

Figure 7. Arrows highlight zone of aligned lakes, swamps, and drainage that represents a fault zone trending northwest-southeast across the coastal plain.

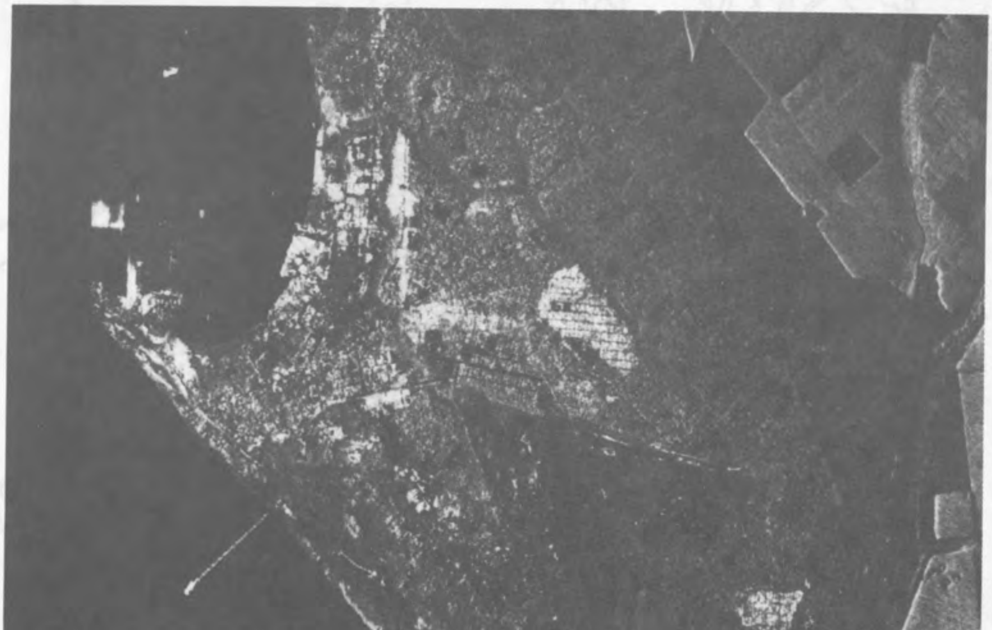

Figure 8. Close-up of high-resolution (4 x 6 meter pixels) SAR image of Pointe Noire (capital of Congo - located about 90 km southeast of Kayes A along the coastal plain) .

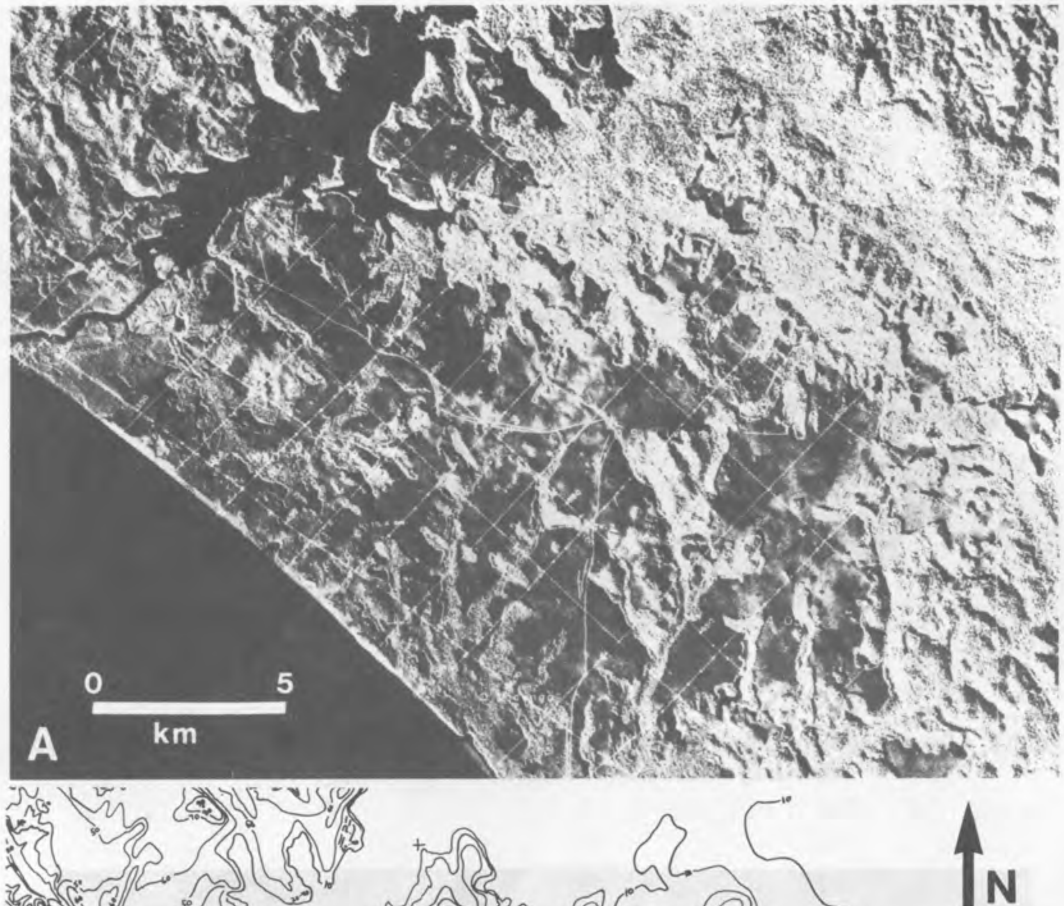

Figure 9. Same-scale comparison of (A) digital SAR mosaic with embedded seismic lines from CAD and (B) topographic map constructed from overlapping flight strips with mirror stereoscope. Existing lines annotated with dots and numbers (representing shot points). Proposed lines are without any annotation.

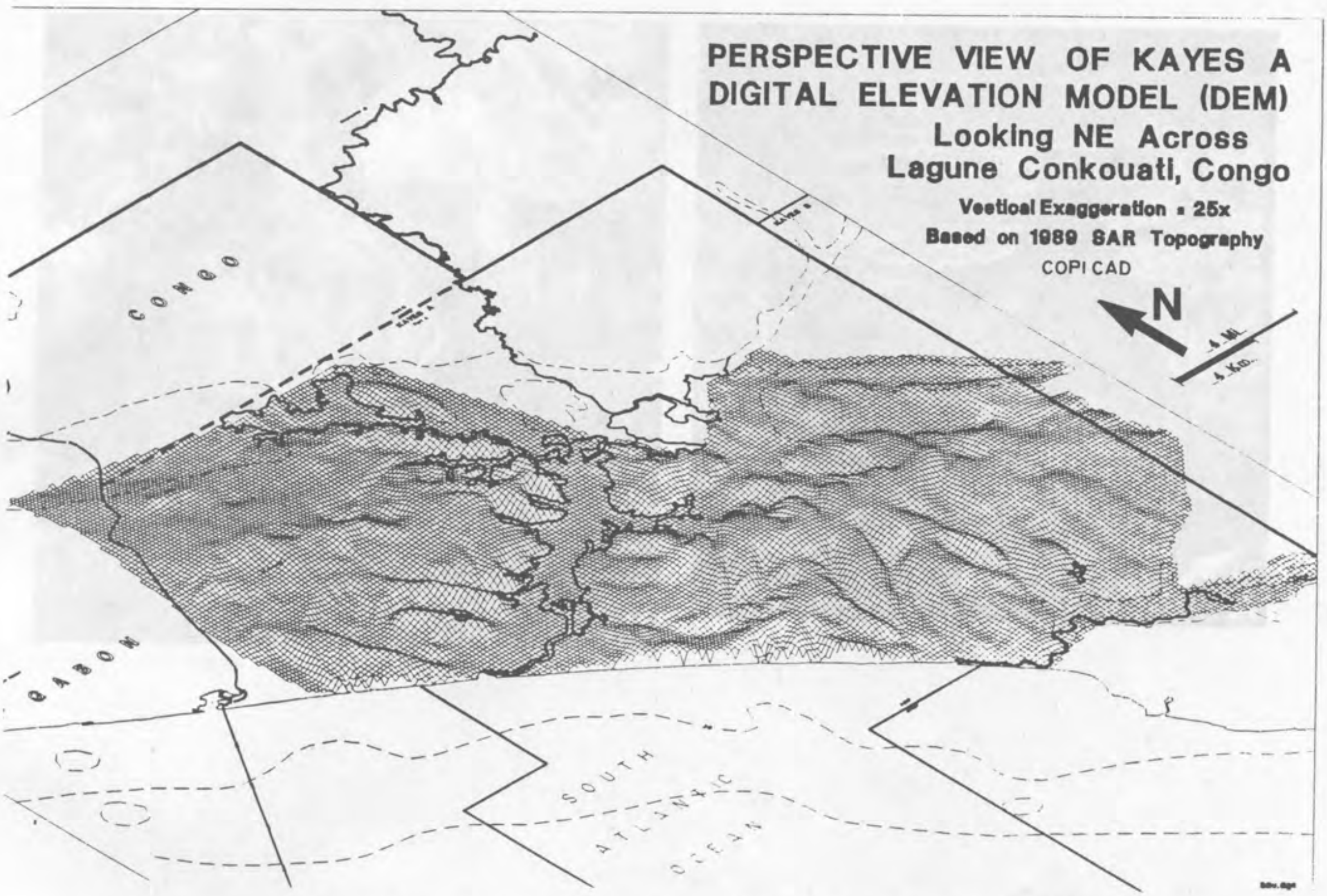

Figure 10. Wireline grid model created by CAD from DEM.

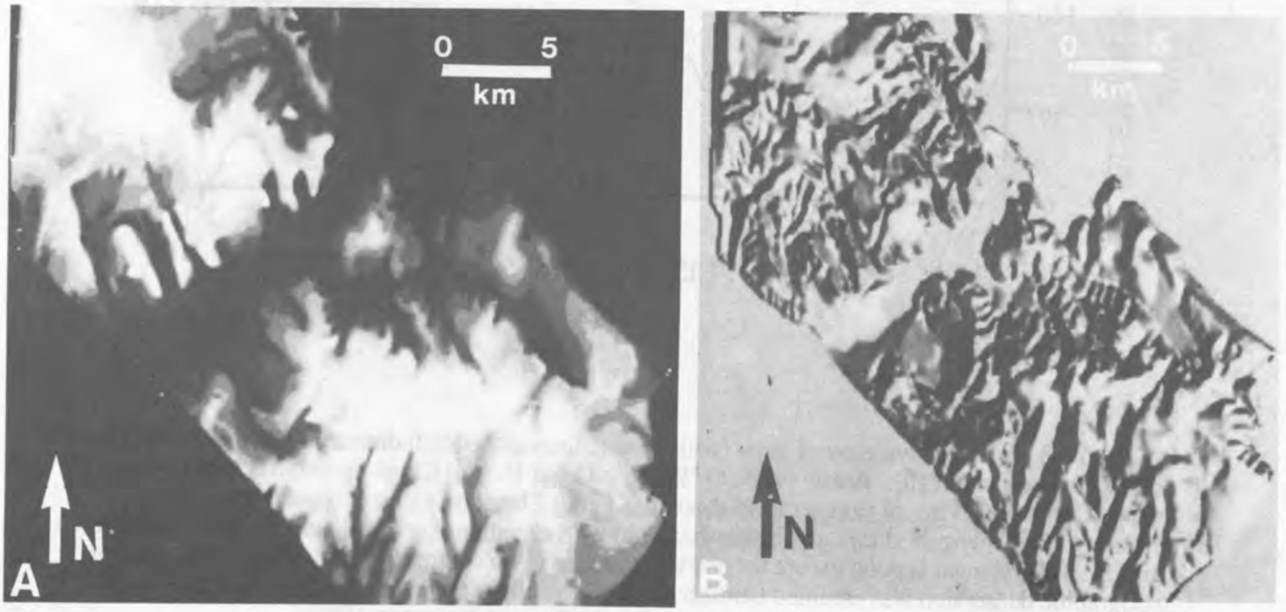

Figure 11. Same-scale comparison of image-processing DEM with (A) density slices representing approximate 10 m contours and (B) DEM illuminated from East.

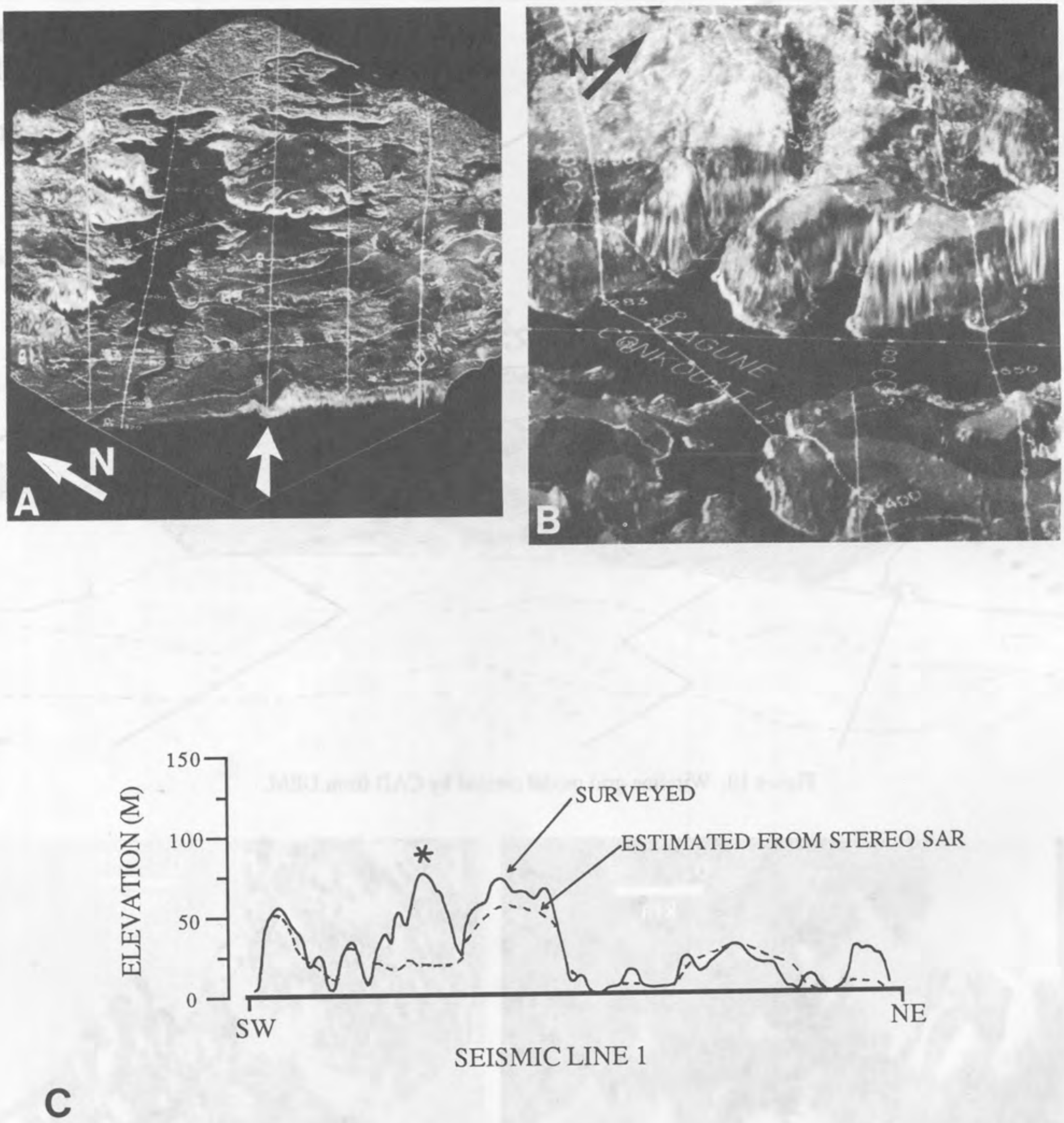

Figure 12. (A) 3-D perspective view of radar (with seismic lines embedded) draped over DEM (view toward NE across Lagune Conkouati). Arrow refers to "Proposed Line 1". (B) Close-up of cliffs along west shore of Lagune Conkouati (vertical exaggeration about 12X). (C) Elevation along Proposed Line 1 comparing before-survey, SAR-interpreted topography (dashed line) with elevations surveyed during seismic acquisition (dark line). Agreement is good except for one wooded area (* on diagram) where during interpretation topographic depression was assumed beneath dense tree canopy (typical situation on coastal plain). Elevation data provided by R. Burk (Chevron Overseas, 1989)