Combination of spaceborne radar interferometry (DEM) and Landsat TM imageries contributing to recent tectonic and geology studies in the Aswa lineament shear zone (Sudan)

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ABSTRACT

Until recently, the Aswa lineament shear zone in Uganda and Sudan was considered to be tectonically at rest but the 1990-1991 seismic events triggered a renewal of interest in this area.
Using ERS1-ERS2 tandem covering the area where earthquakes were observed, we have generated a high resolution Digital Elevation Model (DEM) which provides a good quality reference to analyse the geomorphology and the drainage patterns, in order to extract valuable tectonic information. Then, the combination of spaceborne radar interferometry and Landsat TM imagery contributes to a better understanding of the geological and tectonic phenomena of the studied area.

Keywords: spaceborne SAR interferometry, Landsat TM, Sudan

1. INTRODUCTION

The Aswa shear zone lineament, extending from SE Uganda into SW of Sudan has been considered until recently as tectonically at rest. However, from May 1990 to September 1991, a total of 64 earthquakes were recorded including one of the largest seism ever recorded in Africa (Ms=7.2; [9]); all these seismic events were concentrated in the north of the shear zone itself, nearby the White Nile Valley in Sudan.

Preliminary studies performed on a Landsat-MSS image mosaic have shown various lineaments affecting lithological units dating from Archean to Recent likely to be connected to this activity. This has motivated a more detailed study of the present tectonic evolution of the Aswa lineament and adjacent regions in Sudan.
Due to the lack of accurate topographic and geological maps in that part of Sudan, SAR interferometry was chosen as a powerful tool to generate high resolution Digital Elevation Models (DEM). Such DEM provide good quality reference to analyse the geomorphology, the drainage patterns and geology in order to extract valuable tectonic information.

2. GEOLOGICAL SETTING

In the region of the western branch of the East African Rift, the basement is made of Archean to Upper Proterozoic metamorphic rocks partly reworked during the Pan-African orogenic cycle. During the Pan-African (±550Myrs), East Africa and Arabia were subjected to a regime of mobile belts and subduction zones giving rise to the Mozambique Belt, extending from Mozambique in the south to Arabia in the north.
A striking feature of this belt is the major NW-SE trending Aswa fault zone which, during the emplacement of the Mozambique belt, is considered to have acted as a large lateral ramp [2,4].
During the Mesozoic, an important rift system developed from western to eastern Africa. It is considered as inactive now and devoid of present-day surface expression [1,6].

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The East African Rift System defines a diffuse active plate boundary within Africa, comprising two main branches; an eastern branch running from Afar to northern Tanzania, including the Gregory Rift in Kenya; and a western branch from lake Albert to Mozambique coastal plain. Since the Oligocene–Miocene, the East African Rift has developed a very active zone for which it has been shown that the old zones of weakness along the pattern of Archean cratons and Proterozoic mobile belts played an important role in controlling the location of the rift basins [5]. From structural analysis in the field and fault mapping from satellite images, some authors suggested that the rift is formed as a consequence of a NW-SE movement of the Somalian block, relative to the African continent [3].

Although the Aswa lineament zone is considered to be tectonically rather inactive, a historic seismic activity, concentrated in the Mozambique belt corridor, North of the lineament itself, have been recorded (NOAA World database of seismic epicenters). Between May 1990 and September 1991, earthquakes affected the same region and the largest one caused damage in the southern of Sudan.

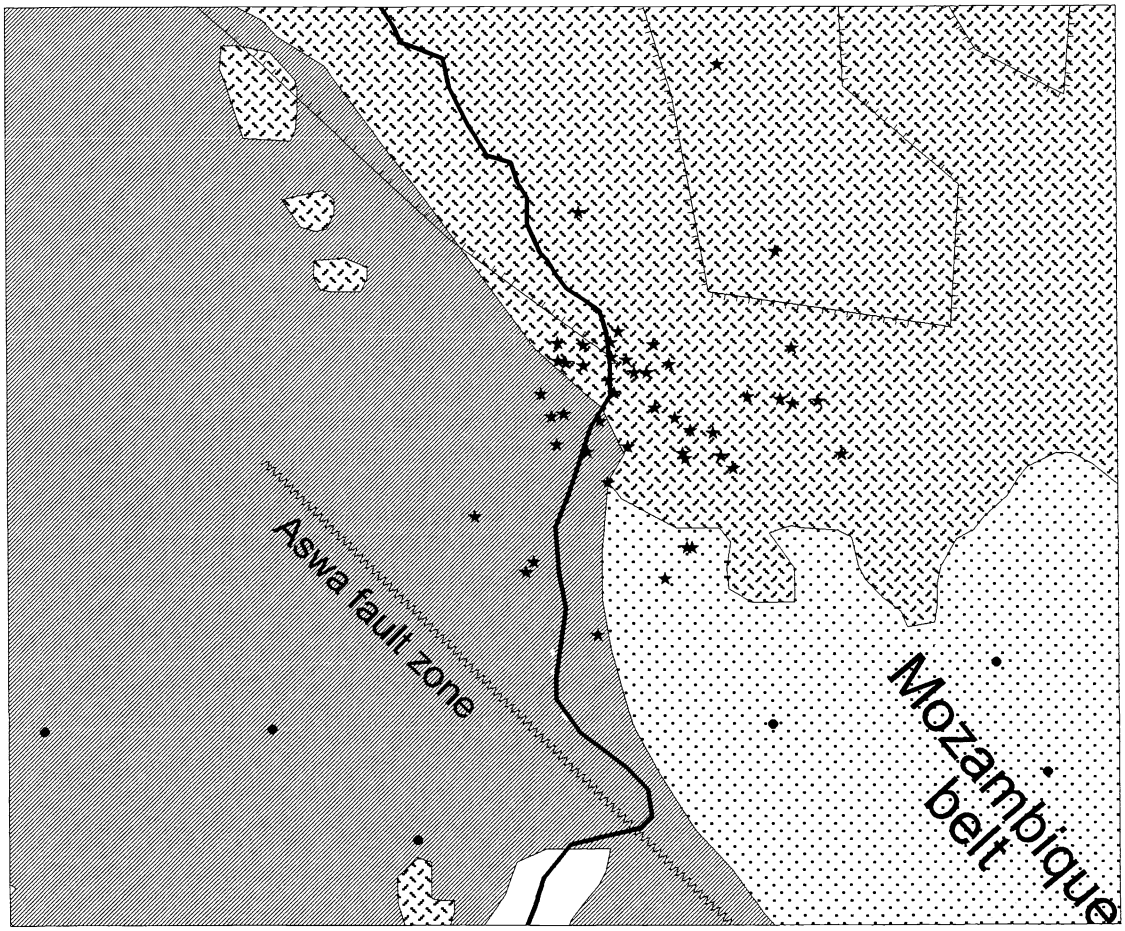


Figure 1: geological map and seismicity of the northernmost part of the western branch of the East African Rift System. The 1990-1991 Sudan earthquakes (black stars) are mostly north of 5°N while historical epicentres (black points) from 1850 through 1963 characterise the Aswa shear zone [9]; [⫽] and [:::] correspond to Archean Craton and [/ \ /] corresponds to Mesozoic and Cenozoic deposits.

3. DATA AQUISITION AND IMAGE PROCESSING

3.1. ERS1–ERS2 imagery

Taking benefit of an ESA research project AOT.B304, 12 ERS1-2 tandem pairs (24 full scenes) have been acquired in order to produce a mosaic covering the NW-SE oriented Aswa lineament and the adjacent areas, nearby the Nile valley (an area located between 3°N and 8°N and 30°E and 34°E). The geographic location near equator, the semi-arid environment (except in the Nile Valley itself), the short period between acquisition of ERS1 and ERS2, and the baseline which are maintained in the range 120 to 300 meters, are optimal conditions for use of this technique.

A this time, a total of six tandem couples ERS1-ERS2 (12 full scenes SCLI; fig. 2) covering the Aswa lineament and the adjacent areas characterised by recent seismicity (1990-91;[9]) have been processed in our laboratory using Earthview software's developed by Atlantis Scientific Inc. (Canada). This software generated geocoded product files such as intensity images (slave and master), interferograms, coherence maps, and interferometric DEM images which have been projected in UTM E001 zone 36 (Clark 1880 ellipsoïd).

One of the main objectives of the research is the construction of a high resolution SAR interferometric DEM in a ground range projection for the whole studied area. Thus, as two tandem couples (scene 2 and 3) covered the Sudan-Uganda border area, we decided to control the accuracy of these interferometric geocoded products by comparing these with the six existing accurate maps (scale: 50000) of the Uganda northwest part. A cartographic digital terrain model (DTM) of the Sudan-Uganda border was created with ArcInfo. The combination of the cartographic DTM with the interferometric DEM products of the Sudan-Uganda border area (zone 2, 3) showed a mean error about 50 seconds westwards and 20 seconds southwards. This shift (in latitude and longitude) have been minimized in superposing the contour lines of the interferometric DEM with the cartographic DTM. Then by extrapolation, we rectified the geocoding of the whole studied zone using the overlap area existing between the two georeferenced tandem (scene 2 and 3) and the other scenes (1, 4, 5 and 6).

The interferometric products of each ERS1-2 tandem provide qualitative information such as relative elevation values. To calibrate these in absolute values it would be necessary to have a good cartographic DTM for the whole studied area or to make a ground control field survey with a GPS. But none accurate topographic maps exist in this part of Sudan and due to the political conflicts in the South Sudan it is now impossible to organise any survey in the studied zone. Finally, we create a relative topography model for each tandem which can be used to analyse local topography variation due to tectonical features and geomorphological processes.

To increase the relief effects of the interferometric DEM imagery we have used an application of PCI software's which consist of illuminating the interferometric DEM with a virtual sunshine source of variable angle in azimuth and in elevation. The shaded relief imagery provides a better tool for analysing faults, drainage patterns and geomorphological features. All major and minor (secondary) lineaments can be easily digitised on-screen and stored in georeferenced vector segment in order to extract valuable tectonic and geomorphology information.

3.2. Landsat TM imagery

To cover the Aswa lineament and the adjacent areas of observed earthquakes, 4 Landsat TM images were acquired from EROS data centres' archive (fig. 2). These data have been recorded in January 1986 (path /row 172/56, 172/53, 173/56, 173/57). The image processing was executed using PCI's EASI/PACE software on an Unix station. The four image have been mosaiqued and georeferenced with the interferometric products in a common UTM E001 zone 36N projection (Clark 1880 ellipsoid) using geographic features (roads, rivers,...) as ground control points. After geometric correction, the Landsat TM imagery was easily compared with the interferometric products. The spatial resolution of the interferometric products and the Landsat TM imagery combination is 30 by 30 meters while the height resolution is expected to approach 5 meters. The result of the merging contributes to a better understanding of the geological and tectonic phenomena of the studied area.

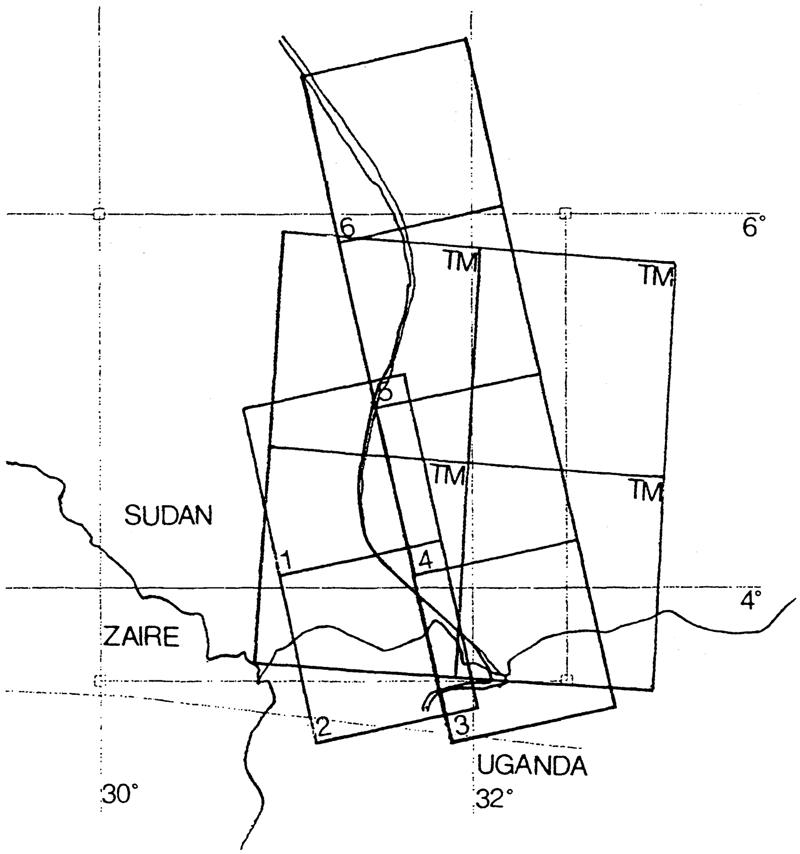


Figure 2: location of the six tandem ERS1-ERS2 (12 full scenes) and the four Landsat TM images processed which cover the Aswa lineament area and the adjacent regions characterised by recent seismicity.

4. GEOLOGICAL INTERPRETATION OF THE IMAGERY AND DISCUSSION

The interferometric products of each tandem ERS1-2 provide a relative elevation model of the local topography which shows that the whole studied area can be divided in two different topographic districts described as:

- the Aswa lineament itself covering the Sudan-Uganda border (zone 2 and 3; fig. 3a) and mostly characterised by high relief which coincide with the Archean Craton and the Proterozoic mobile belt;
- The northern area of the Aswa lineament (zone 1, 4, 5 and 6; fig. 3b) characterised by low relief which coincide with Mesozoic and Cenozoic deposits of the 'African platform'.

4.1. The Aswa lineament area

The Aswa shear zone (zone 2 and 3), delimiting the Mozambique belt from the Zaire Craton is clearly visible on the shaded relief imagery (with a virtual sunshine source of 60° in azimuth and 35° in elevation; fig. 3a). This area is emphasised by a long crest zone and is characterised by a 'high' relief with a total relative elevation difference close to 2000m. All visible major and minor lineaments have been digitised (white colour in fig. 3a).
In this fault zone, all of major features are oriented NW-SE and span diagonally an area between 3°N and 4°N and 31°40'E and 32°15'E. Some minor NE-SW oriented lineaments, crossing the main Aswa lineament can also be observed in the south of it. The upper left part of the scene is characterised by NW-SE and NE-SW features in a landscape of relative high altitude.

The major NW-SE lineaments consist of a succession of left-lateral shear zones which during the emplacement of Mozambique belt, interpolated as having acted as a large lateral ramp [2,4].
The features oriented NE-SW in the upper left part of figure 3a and these, located south of the Aswa lineament itself, must be related to the original structures in Archean and lower to Middle Proterozoic [8].

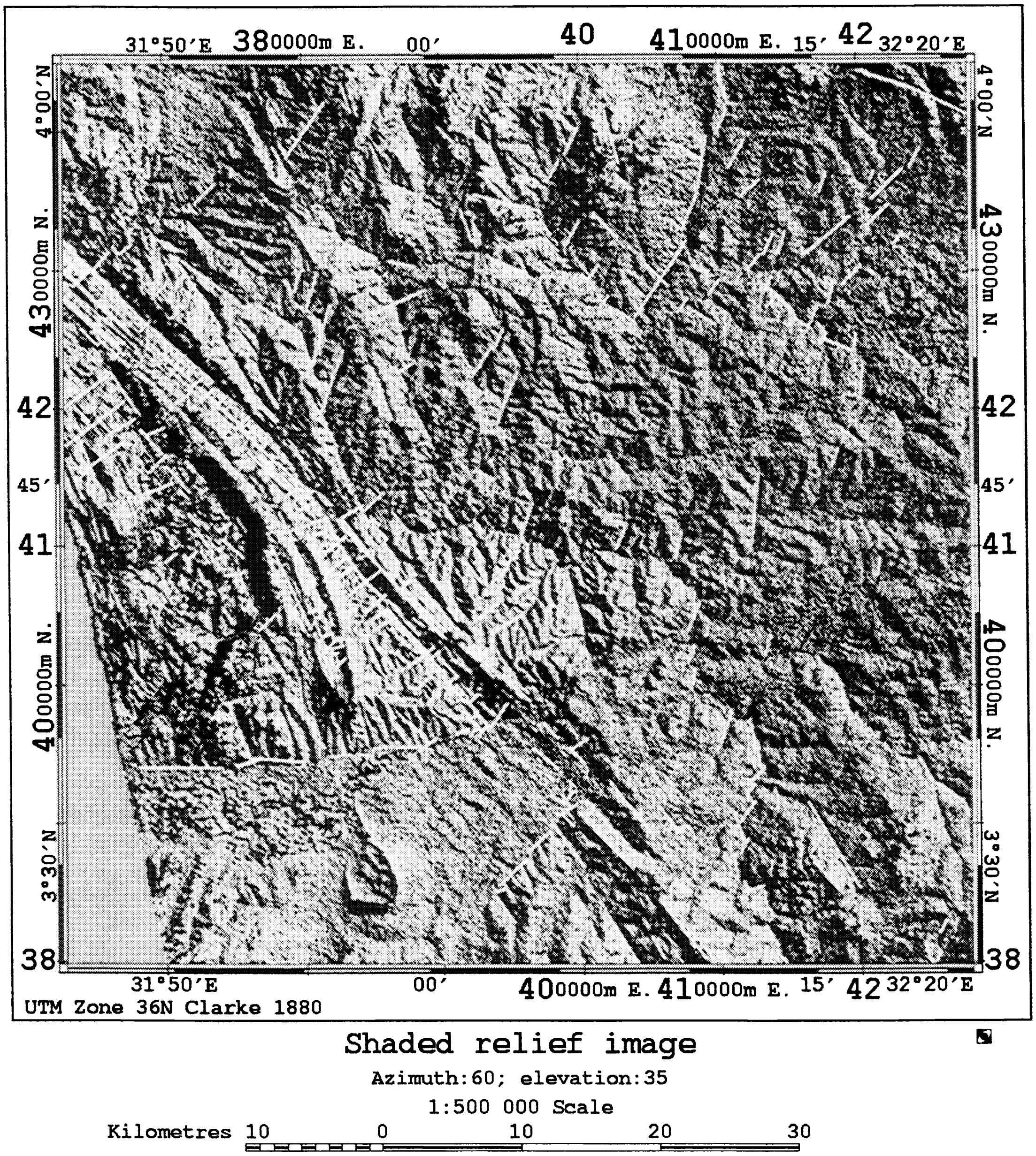


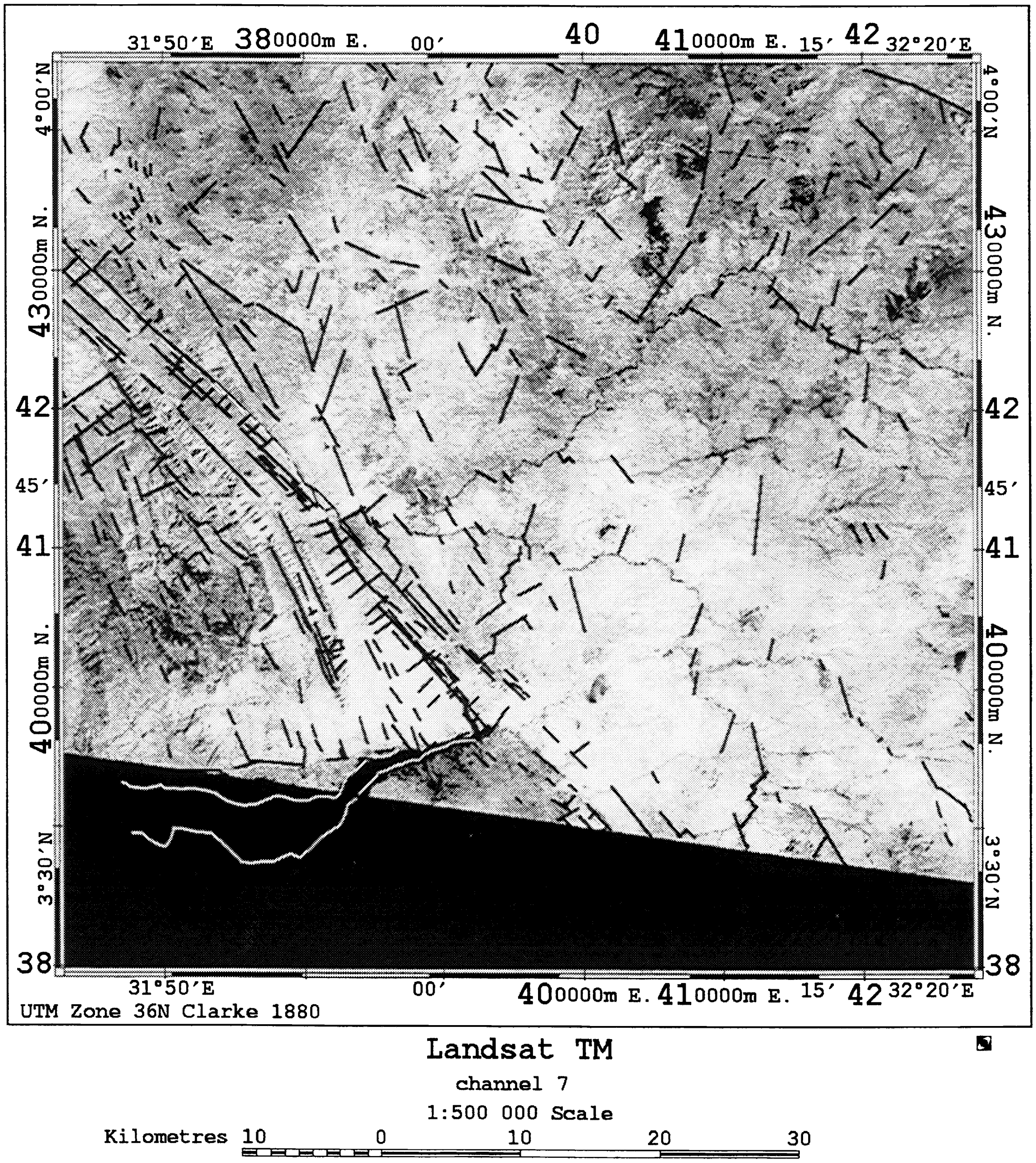
Figure 3a: a shaded relief image of the Aswa lineament area (zone 2 and 3) illuminated with a virtual sunshine source of 60° in azimuth and 35° in elevation. Major and minor lineaments, which have been drawn on-screen, appear in white color.

The combination of the lineaments drawn on the shaded relief imagery with the Landsat TM imagery of the Aswa lineament area shows (fig 3.b) that some of the major and minor features are not visible by using conventional optical sensors. But

nevertheless, a Landsat TM imagery provides complementary spectral information, which can be used, for classification of the different rock types and vegetation.
The merging of the Landsat TM imagery and ERS1-2 images displays clearly that the White Nile river (or 'Bahr El Jebel') is deflected by and follows the Aswa lineament zone in a 'rift valley'. The river flows with rapids confined in a narrow channel extending 50km to the NW.

Recent seismic epicentres [9] can be plotted to the spaceborne radar interferometry and to the Landsat TM imagery with their respective geographical co-ordinates. It appears that they are not directly relate to the Aswa lineament itself but positioned about 100 to 200km northwards of it and mainly out of the white Nile alluvial plain.

Figure 3.b: Channel 7 of the Landsat Thematic Mapper where major and minor lineaments have been drawn using the shaded relief imagery (colored in white).



4.2) The adjacent regions

The ERS1-2 tandems of Juba area (scene 5 and northern part of scene 4), located 100km to 200km northwards of the Aswa lineament, displays the large White Nile alluvial plain globally oriented NS. The coherence image is characterised by lower values due to water presence such as in rivers, small lakes and wet grounds and also abundant vegetation along the White Nile river. The interferometric DEM products of the same area shows a very flat topography typical of an alluvial valley with a total relative elevation difference close to 400m.

The shaded relief imagery (fig. 4a) illuminated with a virtual sunshine source of 60° in azimuth and 35° in elevation provides a good tool to observe the tectonic and geomorphological features of this alluvial plain. All major and minor (secondary) features were digitised on-screen and stored in georeferenced vector segment which is drawn in white colour.

Two main lineament populations can be observed (see also in figure 5):

- the first major lineaments are oriented NW-SE and are located on the eastern bank of the Nile between 4°30'N and 5°40'N and 31°30'E and 32°20'E. These are parallel to the Aswa lineament shear zone but with a shift of 100km to the north;
- the second major lineaments are oriented NW-SE and characterise the western bank but along the Nile valley and extend between 4°20'N and 5°50'N and 31°20'E and 31°45'E.

Most earthquakes which have been recorded in 1990-1991 are dispersed either to the east of the river or to the west but along the Nile valley. The largest seismic epicenter (event 1, Ms= 7.2) is located 50 km east of the Nile in the area of the observed NW-SE features using the shaded relief imagery (fig.4a). According to Girdler (1994) this earthquakes resulted from left-lateral shear along a fault with azimuthal 136° and dip 86° southwest. As most of major and minor lineaments oriented NW-SE observed on the interferometric products have a similar northwest trend we think that those can also be originated from a left-lateral movement parallel to the Aswa lineament.

Two other important seisms (event 37, Ms= 5.9 and event 48, Ms=5.2) affecting the west side of the valley have also be plotted (fig. 4.b). They are associated with dominantly normal faulting (with azimuth 28° to 44°) with dips southeast (43°;^{9}). As for event 1, these two recent epicenters are located in a area where major features oriented NE-SW have been drawn using shaded relief imagery. Thus, there is enough evidence to attribute the NE-SW lineament to the same tectonic mechanism (normal faulting) which seems to be parallel to the Albert rift to the South but narrower.

Some minor NE-SW and NW-SE oriented lineaments also appear along and in the river White Nile bed itself; these features are probably responsible of the local flow orientation changes of the river course and also of the small adjacent effluents (Fig.5). These minor features oriented NE-SW and NW-SE seem locally to constrain the White river bed.
The colour composite Landsat TM (red, green, blue for channels 7,4,2) over the Juba area reveals a dense vegetation cover in the Nile river bed and mainly recent alluvial deposits along the river valley.

As seen on the merged of Landsat TM and ERS1-2 imagery of this area, Upper Nile river shows a 'Z' shape which suggests that the course is fault-controlled (see fig. 5). In the Aswa lineament area, the river is narrow and deflects Northwest along the shear zone. At 4°N, the orientation river course changes abruptly to NNE and the river becomes larger, meandering and braided in a welldefined valley until south of Juba. Then after juba (5°50), the course change abruptly to the NW and becomes parallel the Aswa lineament

Note that the shaded relief image of the Juba area (fig. 4) is characterised by large transverse features oriented NE-SW visible on the eastside of the White Nile valley. These features display topographic steps with an mean relative elevation difference of 10m. They are also crossed by other smaller features which are similar to dune morphology. At this time we have not yet real explanation for all these structures but we think that these linear features probably result from geomorphological phenomena such as eolian processes. As they seem to be present on optical imagery is well, it is not likely that they could result from problems with the radar signal acquisition.

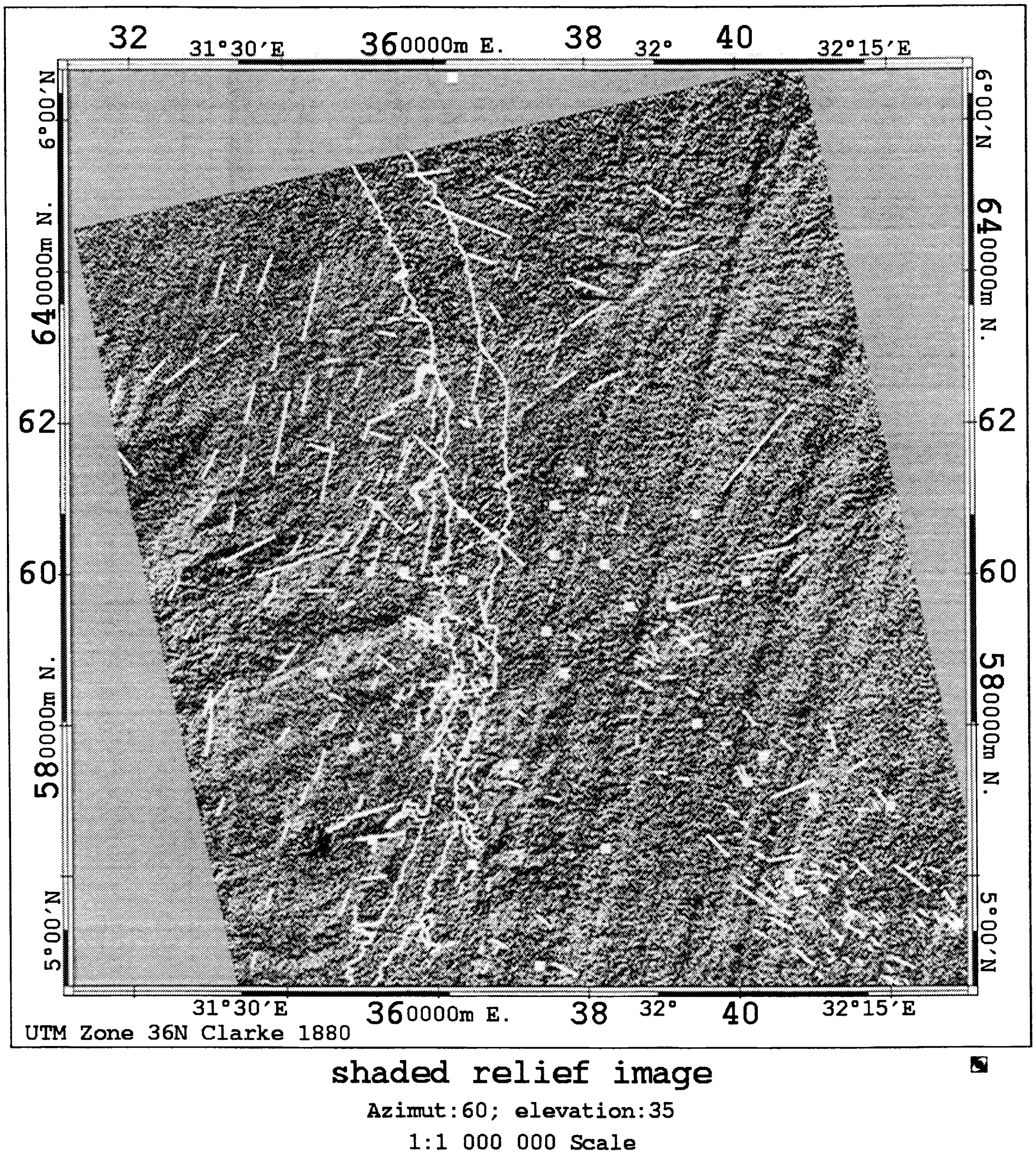
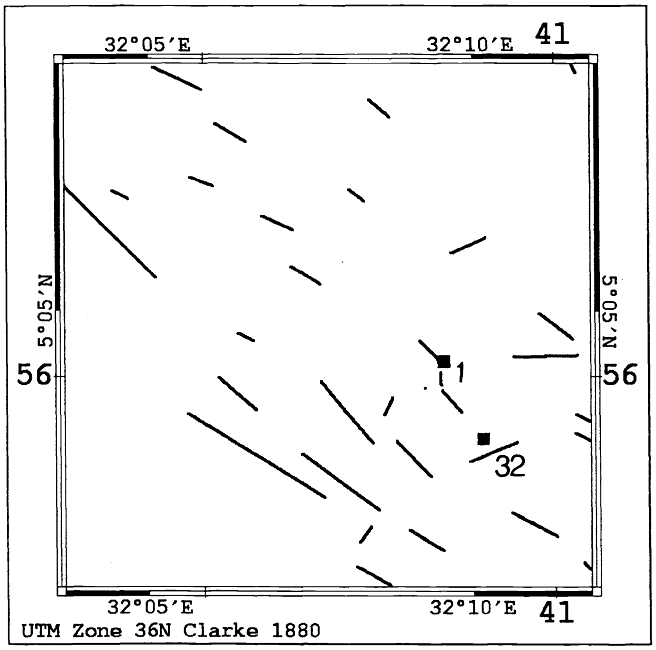
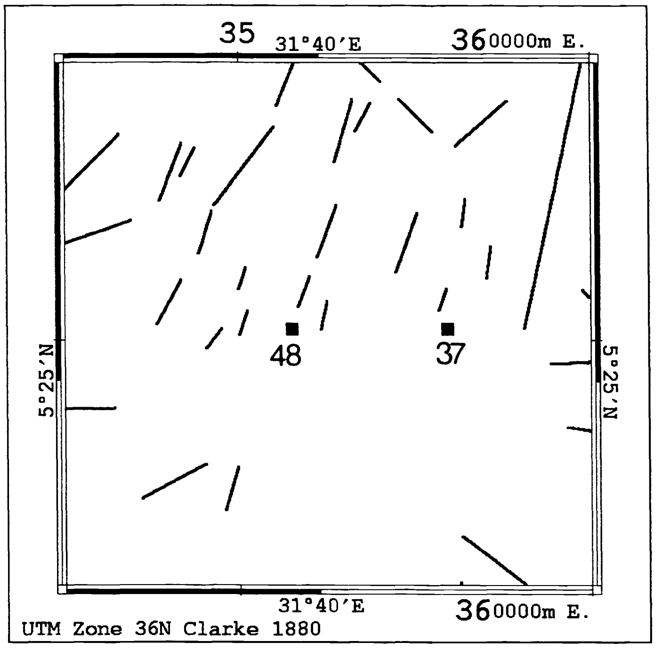


Figure 4: the shaded relief imagery showing of the Juba area (zone 5 and north of zone 4). The lineaments digitized on-screen, the White Nile valley and the recent seismic epicenters[9] are depicted in white color.



satellite lineaments + seisms
1:200 000 Scale



satellite lineaments + seisms
1:200 000 Scale

Figure 4: a) zoom of NW-SE lineaments showing the southeast part of the Juba area where seism event 1 have been recorded; b) zoom of NE-SW lineaments showing the northwest part of the Juba area where seism events 37 and 48 have been recorded..

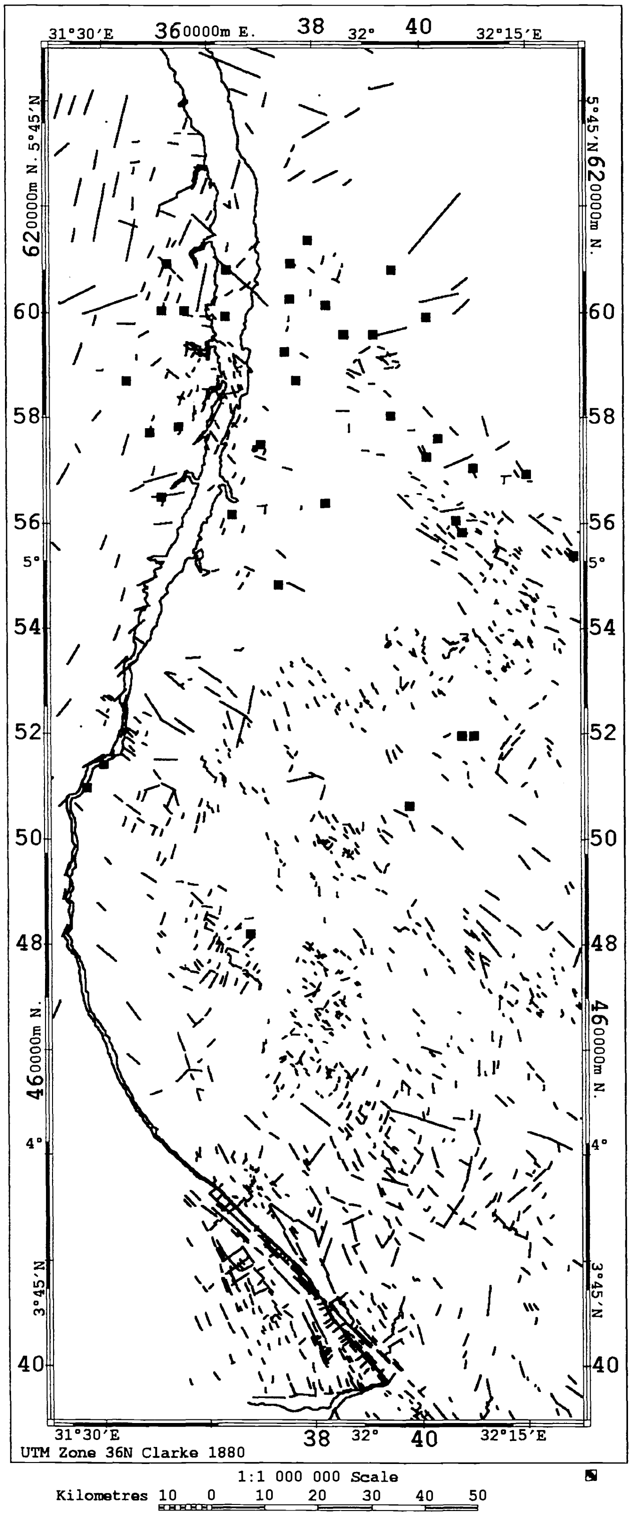


Figure 5: all major and minor features (black lines) digitized using interferometric products which characterize the adjacent areas northward of the Aswa lineament, the White river valley (black traces) and the recent seismic epicenters (black squares) are also drawn.

5. CONCLUSION

The main objective of the research was the construction of a high resolution SAR interferometric DTM for the Aswa lineament area and adjacent regions in order to analyse the geomorphology and the drainage patterns and to extract valuable tectonic information. This DTM was superimposed upon the spectral processing of 4 higher resolution Landsat-5 TM imagery and the result of the merging provides information about displacements, topographic steps, in the Aswa lineament itself and in the recent grounds in the alluvial plain of the White Nile and thus, contributes to a better understanding of the geological and tectonical phenomena of the studied area.

The major and minor lineaments oriented NW-SE and associated to recent seismic activity on the East side of the White Nile provide enough evidence to suggest that there are may be other unrecognized shear zones parallel to the Aswa shear zone but which are located approximately 100 km to 200 km north of itself.

The White Nile must be fault-controlled and the abrupt modification of the course trend from NE to NW probably coincides with one of the major shear located northward of the Aswa lineament.

The major lineament oriented NE-SW along the west side of the White Nile and in the river bed affecting alluvial deposits would be associated to accommodation processes resulted from the active extension zone southward of the unrecognized shear zones.

Finally, using our preliminary results, we conclude that the presence of tectonic features in recent deposits and the 1990-1991 seismic events prove the evidence of recent movement in the north of the Aswa lineament which was considered to be tectonically at rest until recently. Our hypothesis will be check in future works in processing the six other ERS1-ERS2 tandem pairs which cover the completely the studied area.

6. ACKNOWLEDGEMENT

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