will be greater than 45°. Conversely, if conductivity decreases with depth, then the phases will be less than 45°. The phases are preferred as qualitative indicators, as they are unaffected by galvanic static shifts (12) that often distort apparent resistivity curves. At most sites, the apparent resistivity curves of the two modes (TE and TM) (9) coalesced at high frequencies (>30 Hz).
11. C. deGroot-Hedlin and S. C. Constable, *Geophysics* **55**, 1613 (1990). J. T. Smith and J. R. Booker, *J. Geophys. Res.* **96**, 3905 (1991).
12. Static shifts of MT data are so-called because local, small-scale scatterers will distort the amplitudes of the electric field but not affect the phase nor the magnetic field. This condition leads to a period-independent multiplicative shift of the apparent resistivity curve, causing model depths to be in error. See A.G. Jones, *Geophysics* **53**, 967 (1988). These data were surprisingly little affected by severe static shift problems.
13. L. D. Brown *et al.*, *Science* **274**, 1688 (1996).
14. A. G. Jones, in *Continental Lower Crust*, D. M. Fountain, R. J. Arculus, R. W. Kay, Eds. (Elsevier, Amsterdam, 1992), pp. 81–143.
15. J. Francheteau, C. Jaupart, Shen Xian Jie, Kang Wen-Hua, Lee De-Lu, Bai Jia-Chi *et al.*, *Nature* **307**, 32 (1984).
16. P. E. Wannamaker *et al.*, *J. Geophys. Res.* **94**, 14127 (1989).
17. Financial support was provided by NSF grant EAR-9418822 and by a grant from the Chinese Ministry of Geology and Mineral Resources. Phoenix Geophysics (Canada) Ltd. provided V5 time series recording capability and laptop computers. We thank I. Billings and B. Narod for serving as field technicians for the LIMS data acquisition and the staff of the Tibetan Ministry of Geology for support. Geological Survey of Canada contribution number 1996194.

2 August 1996; accepted 5 November 1996

The Origin of the Great Bend of the Nile from SIR-C/X-SAR Imagery

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The course of the Nile in northern Sudan follows a contorted path through Precambrian bedrock. Radar imagery shows that basement structures control the river's course in this region. Northward-flowing segments follow Precambrian fabrics, whereas east-west segments follow faults of much younger age. These faults may reflect recent uplift of the Nubian Swell and deflection of the river to the southwest to form the great bend of the Nile.

The Nile (6825 km long) (*1*) transports water from high-rainfall regions in Ethiopia and equatorial Africa across the Sahara Desert to Egypt. In northern Sudan, the Nile forms a great bend, first flowing north from Khartoum, then southwest for over 300 km before it resumes its northward course (Fig. 1). Bedrock fabrics are an important control on the course of the Nile in this region (*2, 3*), although relations between crustal movements and the river's course are poorly understood. Here we present remote sensing data on this part of the Nile, acquired with the SIR-C/X-SAR imaging radar system (*4*) during two flights of the NASA space shuttle Endeavor in 1994. These data reveal how bedrock structures of different age control much of the Nile's course. Many of these structures could be mapped on the ground, but such studies have been inhibited by the size and harsh climate of the study area. Other structures are revealed for the first time by the radar images (*5*).

The evolution of the Nile can be traced from the Late Miocene desiccation of the Mediterranean Sea (*6*). Lowering of the hydrologic base level led to the carving of a deep canyon [2.5 km deep beneath Cairo (*1*)] and vigorous stream piracy upstream from Aswan. Reflooding of the Mediterranean basin at the end of the Miocene drowned this canyon, and sedimentary filling of the estuary produced the broad and fertile Nile floodplains north of Aswan [the "Egyptian region" of (*7*)]. The Cataract region of the Nile extends 1850 km south from the first cataract at Aswan to the sixth cataract just north of Khartoum. Although parts of this region are occupied by broad floodplains, the Nile is mostly incising its channel into Precambrian basement (*8*) (Fig. 1).

We focused on the third, fourth, and fifth cataract stretches. The third cataract stretch extends north over basement exposures from about 19°45′N to Lake Nasser, as the river traverses the Nubian Swell (Fig. 1 and Fig. 2A) (*9*). The fourth cataract stretch extends SW from the bend at Abu Hamed, where the Nile flows over basement rocks for about 200 km before Cretaceous sandstones are encountered (Fig. 1). The fifth cataract stretch extends NNW from Atbara for over 200 km to Abu Hamed (Fig. 2B) and is entirely over Precambrian basement rocks.

Cataract-region Precambrian granitic and metamorphic rocks (Fig. 1) (*10–12*) were covered by Cretaceous sandstones (*13*) affected by 47- to 81-million-year-old igneous intrusions and lava flows (*14*). Volcanic fields younger than 15 million years ago (Ma) are scattered across the Bayuda Desert (*15*). Pleistocene and younger alluvial cover occurs discontinuously along the river's course. Cataract-region rocks preserve three sets of planar fabrics. The early structures formed at about 700 Ma (*10, 12*), have NE-SW to E-W orientations and are exemplified by the Abu Hamed and Dam et Tor fold-and-thrust belts (Fig. 2B). These structures rarely control the course of the Nile, probably because they generally do not dip steeply. They are overprinted by the younger NNW-trending sinistral Abu Hamed and Abu Dis shear zones in the east (Fig. 2B) (*12*) and the N-S trending Akasha and Kosha shear zones to the west (Fig. 2A). These formed about 600 Ma (*16*) and strongly control the Nile along the third and fifth cataract stretches. There is no evidence for NW-SE Mesozoic rift structures that control much of the course of the Nile in the central Sudan (*17*). E-W steep, normal, or strike-slip faults of late Cretaceous or younger age are common along the third cataract stretch. Faults with this orientation are rarely reported from the Sudan (*18*) but are common in southern Egypt (*19*). Because they affect Cretaceous sedimentary rocks, these faults must be Cretaceous and younger in age. An intrusion is truncated by an E-W fault (Fig. 2A), giving an apparent displacement up to the south. A similar intrusion at Jebel Sheikh (Fig. 2A) yields a K-Ar isochron age of 90 ± 2 Ma (*20*).

At the start of the fourth cataract stretch downstream from Abu Hamed, the river follows the northern margin of the Abu Hamed fold-and-thrust belt. Southwest of this, the river follows multiple channels controlled by NNE and E-W fractures (Fig. 3). The E-W portion of the Nile south of Us Island is controlled by a zone of "highly crushed granite," whereas the NNE-SSW portion of the Nile west of Us Island (Fig. 3) follows easily eroded dikes and "splintered granite" (*21*). A recent change in the river's course is demonstrated by a previously unknown paleochannel 25 km long (Fig. 3), lying as much as 10 km north of the Nile. A shuttle photograph of the region SW of that shown in Fig. 3 shows a north-flowing stream course, now crossed by the Nile. These observations indicate that the course of the Nile along the fourth cataract stretch has recently shifted to the south, due to relative uplift of adjacent regions of the Nubian swell. NNE and E-W structural controls cannot be inferred from the course of the paleochannel, and we infer that fracturing accompanied or followed tectonic uplift. The Nile in Egypt has had dramatic changes in flow regime during Quaternary time (*1, 22*). These are generally ascribed to climatic changes in Ethiopia and equatorial

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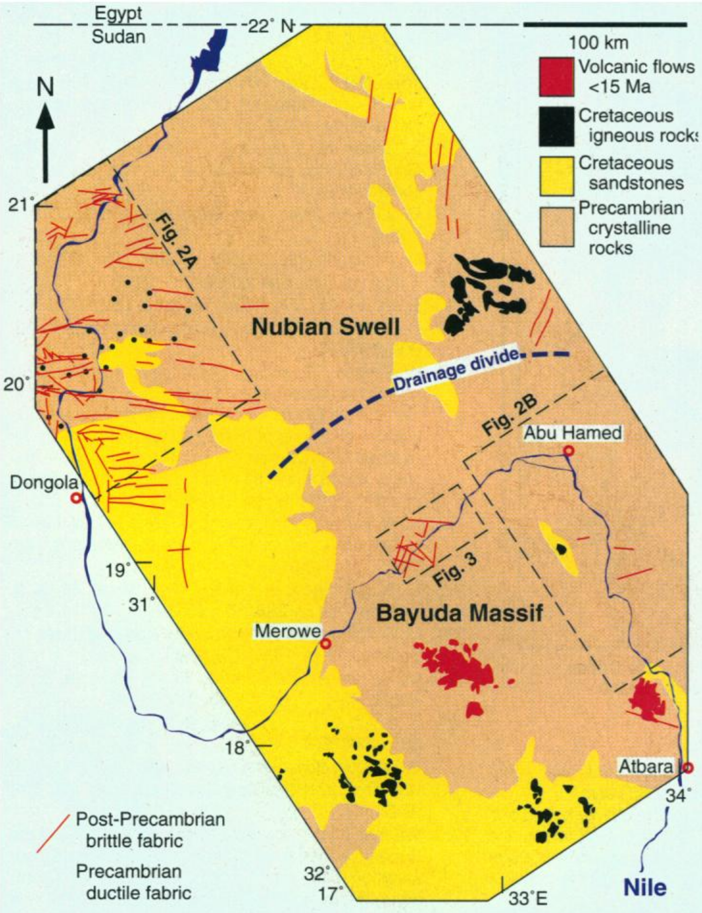

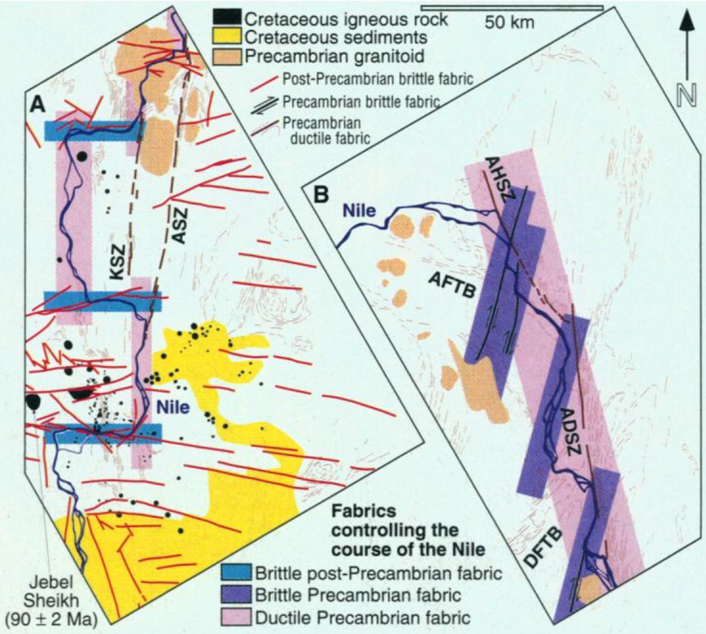

Fig. 1 (left). Geological map of the Cataract region of the Nile. Lithological divisions are simplified after maps published in 1988 by the Geological Research Authority of the Sudan and Robertson Research. Structural trends are based on interpretation of an SIR-C/X-SAR mosaic that comprises data takes SRL-1 50.4, 66.5, 82.42, 130.4, and 146.4, and SRL-2 82.42. Locations of Fig. 2, A and B, and Fig. 3 are outlined with dashes. **Fig. 2 (right).** Structural features of the third (**A**) and fifth (**B**) cataract stretches of the Nile, based on interpretation of an SIR-C/X-SAR survey product mosaic and of L_{tp} (total power) images. Colored portions of the Nile indicate regions controlled by different structures. Interpretation of the third cataract stretch is based on data takes SRL-1 130.4 and 146.4. KSZ, Kosha shear zone; ASZ, Akasha shear zone. Interpretation of the fifth cataract stretch is based on data takes SRL-1 50.4 and 82.42 and SRL-2 82.42. AFTB, Abu Hamed fold-thrust belt; AHSZ, Abu Hamed shear zone; ADSZ, Abu Dis shear zone; DFTB, Dam et Tor fold-thrust belt.

Africa (*23*). Our data suggest that tectonic activity in the cataract region may also have affected the hydrologic regime of the Nile during the Quaternary.

The fifth cataract stretch (*12*) of the Nile follows structures associated with the boundary between the Nile craton and the Arabian-Nubian Shield (Fig. 4A). These structures continue north of Abu Hamed (*24*), yet the Nile turns away to form the great bend. The course of the Nile in Egypt also approximates the Late Precambrian continental margin (*25*), and this structure might be expected to control the Nile north from Atbara all the way to the Mediterranean.

The great bend must be due to relative uplift of the Bayuda Massif or Nubian Swell or both, and it is generally thought that uplift of the Bayuda is responsible (*3*, *26*). If so, the Nile should have been diverted away from the Bayuda to the east or north. Instead, the Nile follows a well-established course through the fifth cataract region to the east, and the diversion in the fourth cataract area is to the south. The Nubian Swell is interpreted as a late Paleozoic uplift (*27*), although the E-W faults reported here require a much younger age for some tectonic activity. Furthermore, the presence of marine sediments of Lower Tertiary age in northern Sudan south of the Nubian Swell indicates that this was not a positive tectonic element at that time (*28*). We thus suggest that recent uplift of the Nubian Swell diverted the Nile to form the great bend. In this case, E-W faults in northern Sudan and southern Egypt may be of late Cenozoic age and reflect Nubian Swell uplift. This hypothesis also explains the prox-

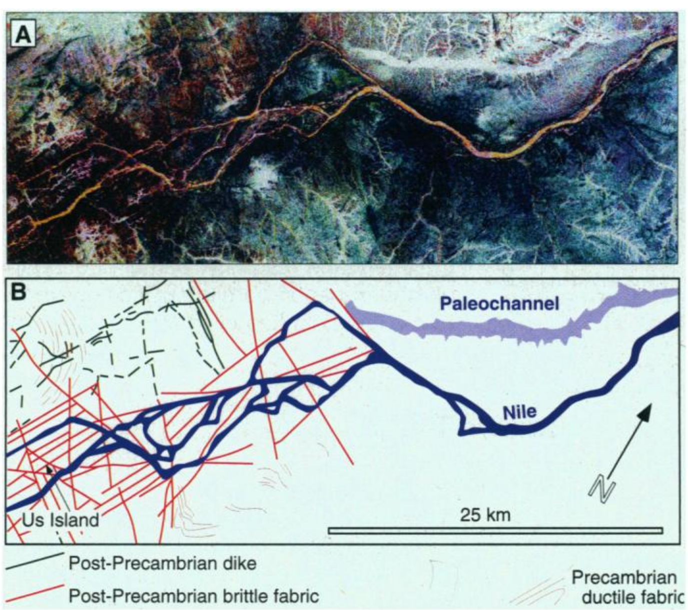

Fig. 3. Fourth cataract stretch of the Nile. (**A**) Color composite of data take SRL-1 66.5: $1/C_{hv}$ (red), $1/L_{hv}$ (green), and $1/L_{hh}$ (blue). The wavelength of the C band is 6 cm, whereas that of the L band is 24 cm. The abbreviation hv describes polarized radar waves that are horizontally transmitted and vertically received, and hh refers to radar waves horizontally transmitted and horizontally received. (**B**) Interpretation of the SIR-C/X-SAR image in (A).

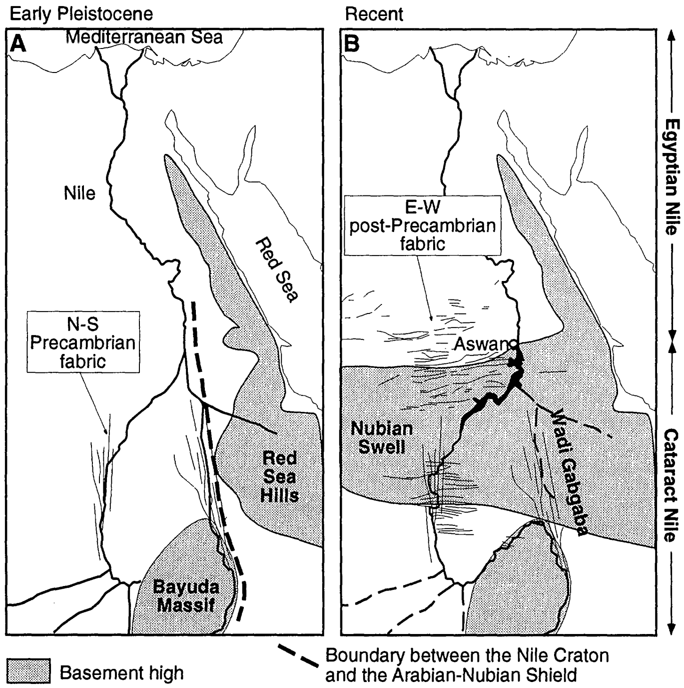

Fig. 4. A model explaining the Quaternary evolution of the Nile and the formation of the great bend. (**A**) The Nile in Nubia comprises two north-flowing branches that follow Precambrian fabrics. The main, eastern branch flows along the Late Precambrian suture between the older Nile craton to the west and the juvenile crust of the Arabian-Nubian Shield to the east. The western branch follows a fabric of similar age and orientation. (**B**) Uplift along an E-W axis to form the Nubian Swell diverts the eastern branch of the Nile to flow SW to connect with the western branch of the Nile. Wadi Gabgaba represents the abandoned course of the eastern branch.

imity of the Gabgaba-Nile drainage divide to the Nile (Fig. 1): We suggest that before Nubian Swell uplift, the drainage now flowing along the fifth cataract stretch continued north through what is now Wadi Gabgaba (Fig. 4A). Quaternary uplift diverted the Nile to the west, through the fourth cataract region, perhaps to join a tributary to the west (Fig. 4B), an interpretation that is consistent with the inference that the fourth cataract stretch of the Nile has only been established since the early Pleistocene (*2*). Uplift of the Nubian Swell continued to deflect the Nile to the south along the fourth cataract stretch.

REFERENCES AND NOTES

1. R. Said, *The Geological Evolution of the River Nile* (Springer-Verlag, New York, 1981).
2. L. Berry and A. J. Whiteman, *Geogr. J.* **134**, 1 (1968).
3. D. Adamson and F. Williams, in *The Sahara and the Nile*, M. A. J. Williams and H. Faure, Eds. (Balkema, Rotterdam, Netherlands, 1980), pp. 225–252.
4. R. L. Jordan, B. L. Huneycutt, M. Werner, *IEEE Trans. Geosci. Remote Sensing* **33**, 829 (1995).
5. The SIR-C/X-SAR radar system has advantages over visible and near-infrared imagery in that radar is sensitive to surface roughness and orientation and has limited capabilities for imaging beneath sand. Hence, the SIR-C/X-SAR imagery is more sensitive to geologic structures and is especially useful in hyperarid and poorly known regions such as the Sahara.
6. K. J. Hsu, W. B. F. Ryan, M. B. Cita, *Nature* **242**, 240 (1973).
7. R. Said, in *The Nile: Sharing a Scarce Resource*, P. P. Howell and J. A. Allan, Eds. (Cambridge Univ. Press, Cambridge, 1994), pp. 17–26.
8. H. G. Lyons, *The Physiography of the River Nile and Its Basin* (Survey Department, Cairo, Egypt, 1906). Lyons relays a report by Ball that the position of flood marks of the XII Dynasty near Semna along the second cataract stretch (now flooded) indicates about 8 m of erosion over the past 4000 years.
9. The Nubian Swell is a region of shallowly buried and exposed basement that extends E-W along the Egypt-Sudan border as far as J. Uweinat, 600 km west of the Nile. Only the eastern part of it is shown in Fig. 1.
10. H. Schandelmeier *et al.*, *Geology* **22**, 563 (1994).
11. U. Harms, D. P. F. Darbyshire, T. Denkler, M. Hengst, H. Schandelmeier, *Geol. Rundsch.* **83**, 591 (1994).
12. M. G. Abdelsalam and R. J. Stern, *J. Geophys. Res.* **101**, 23063 (1996).
13. E. H. Klitzsch and C. H. Squyres, *Am. Assoc. Petrol. Geol. Bull.* **74**, 1203 (1990).
14. G. Franz, U. Harms, T. Denkler, P. Pasteels, in *Geoscientific Research in Northeast Africa*, U. Thorweihe and H. Schandelmeier, Eds. (Balkema, Rotterdam, Netherlands, 1993), pp. 227–230.
15. L. Cahen, N. J. Snelling, J. Delhal, J. R. Vail, *The Geochronology and Evolution of Africa* (Clarendon, Oxford, 1984).
16. R. J. Stern, *Annu. Rev. Earth Planet. Sci.* **22**, 319 (1994).
17. W. Bosworth, *Tectonophysics* **209**, 115 (1992).
18. F. Ahmed, *Adv. Space Res.* **3**, 71 (1983).
19. B. Issawi, *Ann. Geol. Surv. Egypt* **3**, 25 (1973).
20. D. Müller-Sohnius and P. Horn, *Geol. Rundsch.* **83**, 604 (1994).
21. W. F. Hume, *Geology of Egypt, part I, The Metamorphic Rocks* (Government Press, Cairo, Egypt, 1934). Hume's geological reconnaissance of several of the islands in the fourth cataract stretch, which he reached by swimming through the rapids on inflated skins, remains the basis for our geological understanding of this region.
22. K. W. Butzer and C. L. Hansen, *Desert and River in Nubia* (Univ. of Wisconsin Press, Madison, WI, 1968).
23. D. A. Adamson, F. Gasse, F. A. Street, M. A. J. Williams, *Nature* **288**, 50 (1980).
24. M. G. Abdelsalam, R. J. Stern, H. Schandelmeier, M. Sultan, *J. Geol.* **103**, 475 (1995).
25. M. Sultan, R. D. Tucker, Z. El Alfy, R. Attia, A. G. Ragab, *Geol. Rundsch.* **83**, 514 (1994).
26. D. C. Almond, F. Ahmed, B. E. Khalil, *Bull. Volcanol.* **33**, 549 (1969).
27. E. Klitzsch, *Berl. Geowiss. Abh.* **50**, 23 (1984).
28. N. Barazi and J. Kuss, *Geol. Rundsch.* **76**, 529 (1987).
29. We thank the Geological Research Authority of the Sudan for their help, D. Amesbury for bringing our attention to the shuttle photograph of the fourth cataract stretch, and K. Burke and W. Bosworth for their ideas on the problem. Supported by NASA through subcontracts from the Jet Propulsion Laboratory. This is University of Texas at Dallas Programs in Geosciences Contribution 846.

30 July 1996; accepted 18 September 1996

Interplane Tunneling Magnetoresistance in a Layered Manganite Crystal

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The current-perpendicular-to-plane magnetoresistance (CPP-MR) has been investigated for the layered manganite, $La_{2-2x}Sr_{1+2x}Mn_2O_7$ ($x = 0.3$), which is composed of the ferromagnetic-metallic MnO_2 bilayers separated by nonmagnetic insulating block layers. The CPP-MR is extremely large (10^4 percent at 50 kilo-oersted) at temperatures near above the three-dimensional ordering temperature ($T_c \approx 90$ kelvin) because of the field-induced coherent motion between planes of the spin-polarized electrons. Below T_c, the interplane magnetic domain boundary on the insulating block layer serves as the charge-transport barrier, but it can be removed by a low saturation field, which gives rise to the low-field tunneling MR as large as 240 percent.

The discovery of the giant magnetoresistance (GMR) in magnetic multilayers (*1*) has stimulated much interest in relating spin polarization–dependent transport phenomena from the viewpoints of both the underlying physics and their immediate application to magnetic storage and sensor technology. A variety of the GMR structures have so far been investigated, such as antiferromagnetically coupled multilayers (*2*), granular films (*3*), spin valve (*4*), and tunneling structures (*5*). In these structures, the effects of spin-dependent electron scattering have been assigned to the fundamen-