Please note that this presentation was given during the United Nations Climate Change Conference (COP-15) in Copenhagen, December 7-18, 2009 for more information please visit http://www.cop15.state.gov/ .

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

Climate Change Impacts on Civilization
Insight From Space Observations

"The Thinker" ~5000 BCE

Figurine from Hamangia, Cernavodå

National History Museum of Romania, Bucharest

Photo: Marius Amarie

New York Times, November 30, 2009
"A Lost European Culture, Pulled From Obscurity" John Noble Wilford

Ronald G. Blom, Ph.D.
NASA Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena, CA 91109
ronald.blom@jpl.nasa.gov

NASA Jet Propulsion Laboratory: Forty-six Years of Exploration and Discovery

- The Jet Propulsion Laboratory is a NASA center managed by the California Institute of Technology for NASA
- JPL's charter is unmanned planetary exploration: Mars Rovers Spirit and Opportunity, Cassini Saturn Mission (w/ ESA/ASI), and the Orbiting Carbon Observatory
- To fulfill this role, state of the art instrumentation, spacecraft navigation, and operations are required
- JPL instruments, science and technology have many applications on Earth-climate observations, and even archaeology
- Across NASA we seek application of these technologies to provide insight into current, and past climate changes to address future challenges

Climate Stability is a Key Factor

In the Development of Agriculture and Complex Societies

Consider:

- Anatomically modern humans in Africa about *130,000 years ago*
- Humans migrate out of Africa during wet phases perhaps as early as ~120,000 years ago, but significant about *55,000 years ago*
- Stunning art and culture by about *30,000 years ago*
- BUT, no agriculture and no complex societies until *about 10,000 years ago*
- 120,000 years of human pre history with no agriculture or complex societies
- WHY?

ChauvetCave Art

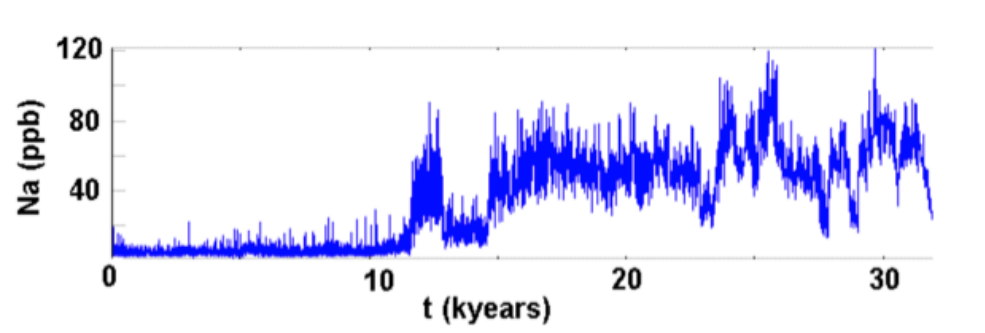
H. Valladas, J. Clottes, et al., Nature, 2001

Climate Stability is a Key Factor

In Development of Agriculture and Complex Societies

What happened?

- Various measures of climate stability show broad stabilization



- Plot of Na concentration in Greenland ice core
- Na proxy for wind and storms
- Climate becomes much more stable at end of Younger Dryas, 11,570 (+/- 200) years ago (Hughen, et al., Science 2000)

Climate Stability is a Key Factor

In Development of Agriculture and Complex Societies

- The stable climate at the end of the Younger Dryas ~11,570 ago was new to humans
- Long term stability allowed multiple independent agricultures and animal domestications to develop (Piperno& Pearsall, Academic, 1998; Feynman &Ruzmaikin, Climate Change, 2007)
- Agriculture and complex societies seem to take at least ~1000 years of stability to get organized

Place	Species	Starting (ybp)
Levant	wheat, legumes, sheep	10,500
China	rice, millet, pig, silkworm	9,500
Meso-america	maize, beans, squash, turkey	9,000
Andes & Amazonia	squash and gourds	10,000
Eastern US	sunflower, goosefoot	by 4,500

Climate Stability is a Key Factor

In Development of Agriculture and Complex Societies

Archaeology and paleo climate research aided by space observations can help document this transition, and the history of civilizations.

Example: Leaving the Sahara

The Sahara, now one of the driest places on Earth, was intermittently a grassland until recent drying out about 7,000 years ago

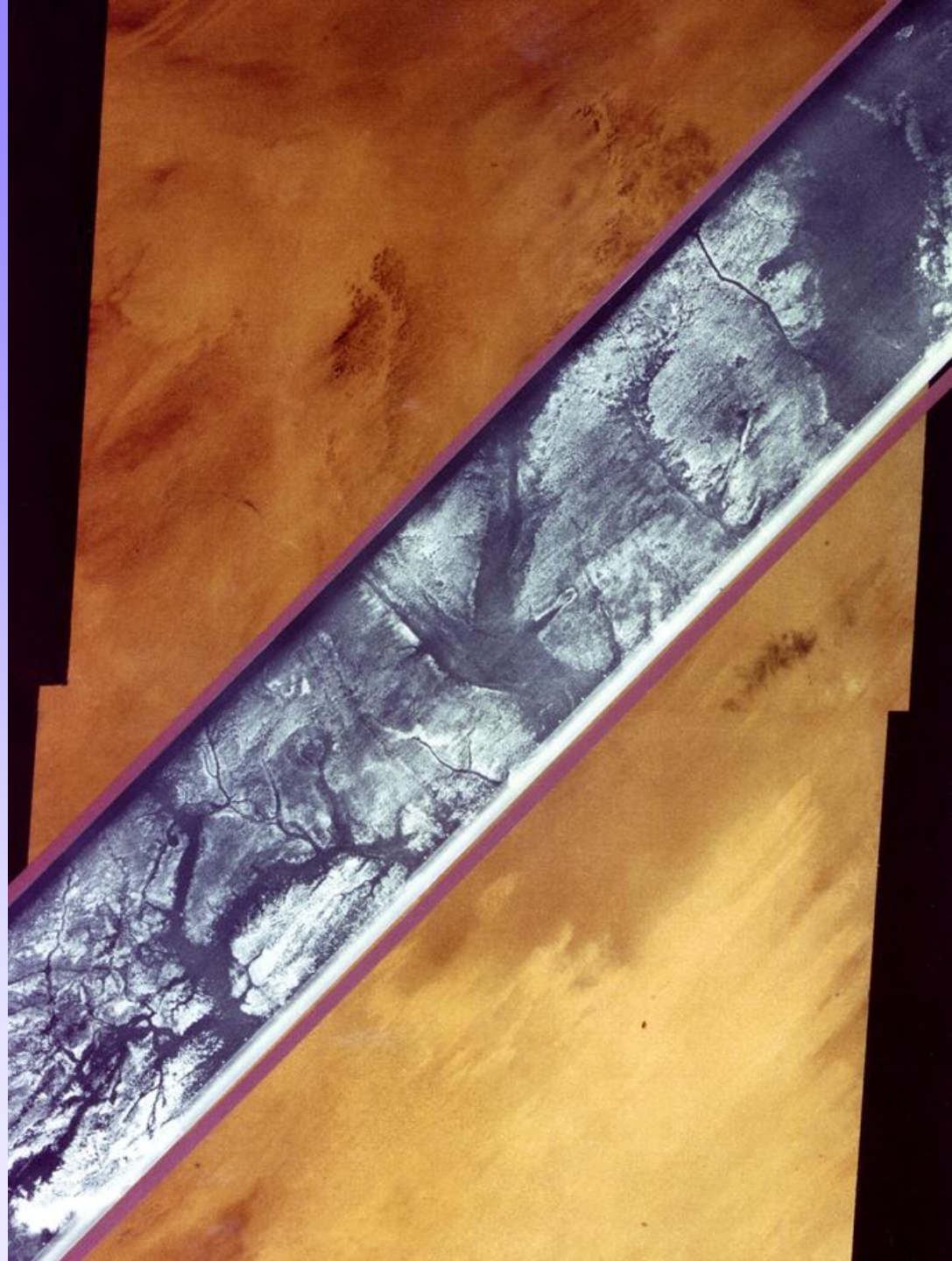
•Shuttle Imaging Radar-A flew on 2nd flight of Space Shuttle Columbia in 1981

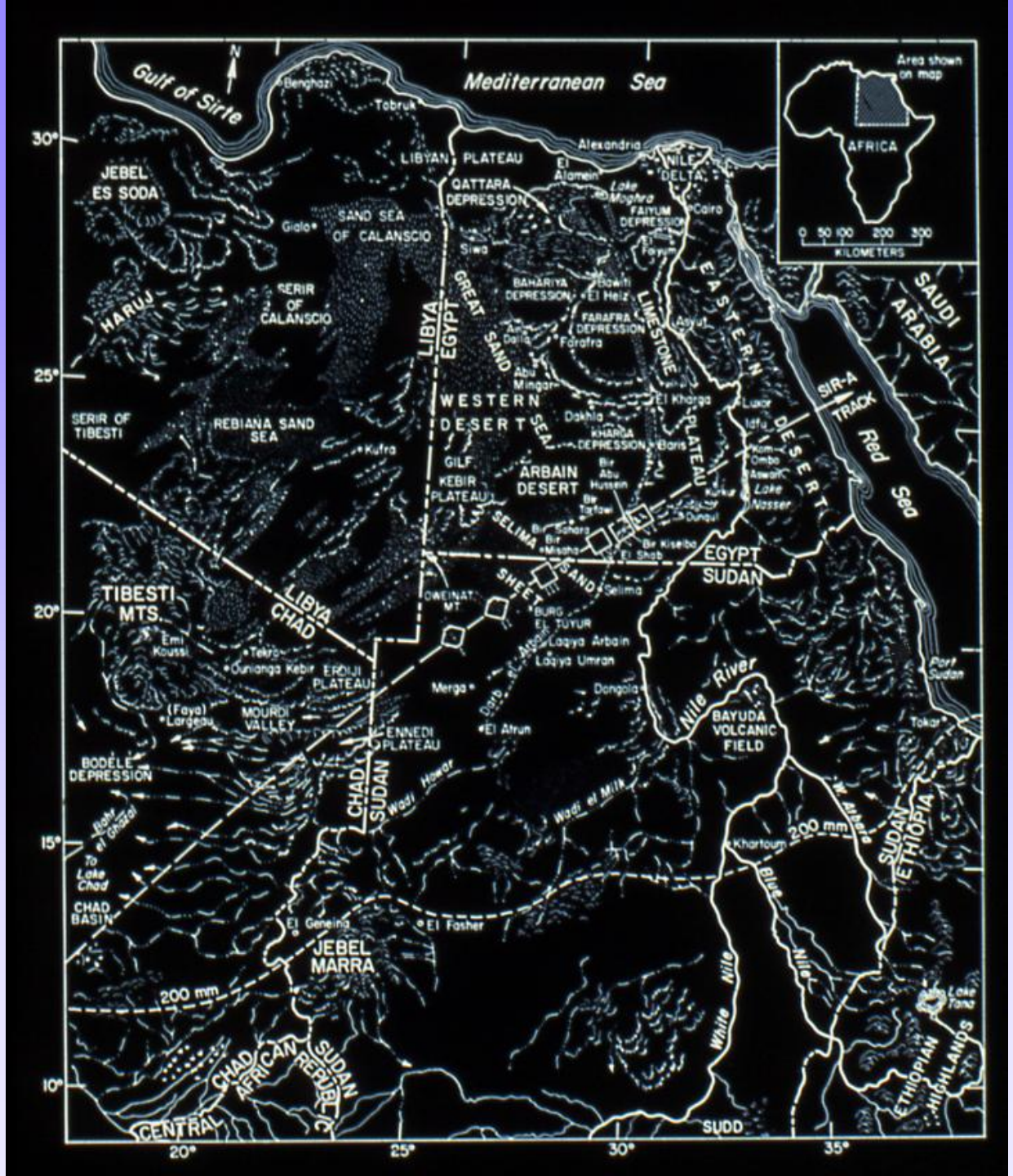
•Images show SIR-A radar over Landsat Multispectral Scanner-Southwestern Egypt

•L band (23 cm) radar image images thru 2+ meters of dry sand, shows integrated drainage systems

•Thin sand cover (0-few meters) obscures underlying, older fluvial landscape

•Neolithic artifacts abundant near “radar rivers”, evidence for significant human presence




Gulf of Sirte
Mediterranean Sea
Area shown on map
AFRICA
0 50 100 200 300
KILOMETERS
Benghazi
Tobruk
Alexandria
LIBYAN PLATEAU
El Alamein
NILE DELTA
Cairo
JEBEL ES SODA
QATTARA DEPRESSION
Lake Maghra
FAIYUM DEPRESSION
Gialo
SAND SEA OF CALANSCIO
Siwa
Fayum
SERIR OF CALANSCIO
HARUJ
BAHARIYA DEPRESSION
Bawiti
El Heiz
EASTERN LIMESTONE PLATEAU
Asyut
GREAT SAND SEA
FARAFRA DEPRESSION
Farafra
Dakhla
Abu Mingar
LIBYA
EGYPT
WESTERN DESERT
SAUDI ARABIA
SIR-A TRACK
Red Sea
SERIR OF TIBESTI
REBIANA SAND SEA
Kufra
El Kharga
Luxor
Idfu
KHARGA DEPRESSION
Baris
DESERT
GILF KEBIR PLATEAU
ARBAIN DESERT
Bir Abu Hussein
Bir Tarfawi
Kurkur
Dungul
Lake Nasser
SELIMA SAND SHEET
Bir Sahara
Bir Misaha
Bir Kiseiba
El Shab
EGYPT
SUDAN
TIBESTI MTS.
LIBYA
CHAD
OWEINAT MT.
Selima
BURG EL TUYUR
Laqiya Arbain
Laqiya Umran
Port Sudan
Emi Koussi
Tekro
Qunianga Kebir
EROUI PLATEAU
Merga
Darb el Arbain
Dongola
Nile River
(Faya) Largeau
MOURDI VALLEY
El Atrun
BAYUDA VOLCANIC FIELD
Tokar
ENNEDI PLATEAU
BODELE DEPRESSION
CHAD
SUDAN
Wadi Howar
Wadi el Milk
Khartoum
200 mm
SUDAN
ETHIOPIA
Blue Nile
To Lake Chad
CHAD BASIN
El Geneina
El Fasher
JEBEL MARRA
White Nile
Lake Tana
200 mm
CHAD
CENTRAL AFRICAN REPUBLIC
SUDAN
SUDD
ETHIOPIAN HIGHLANDS
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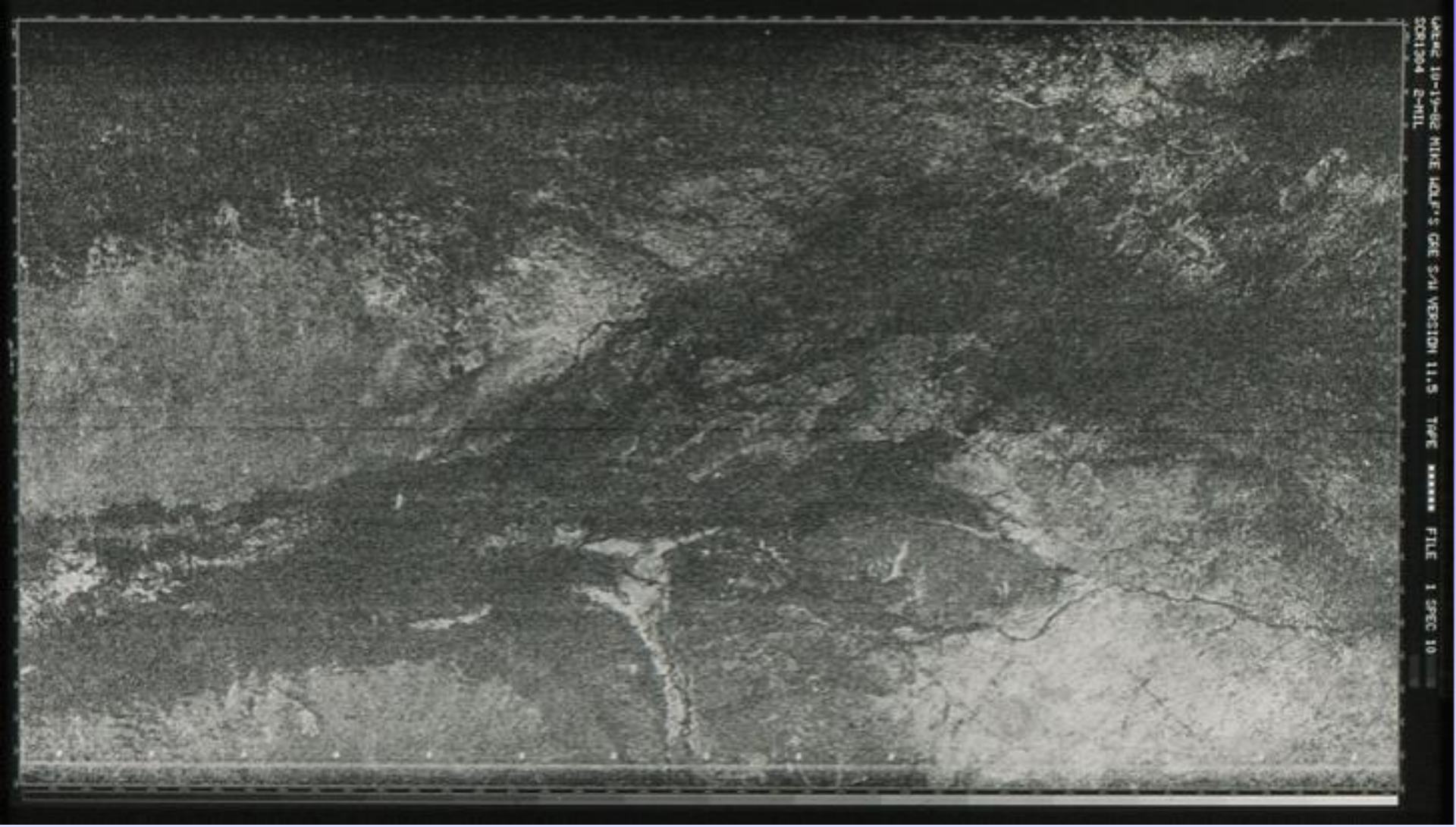
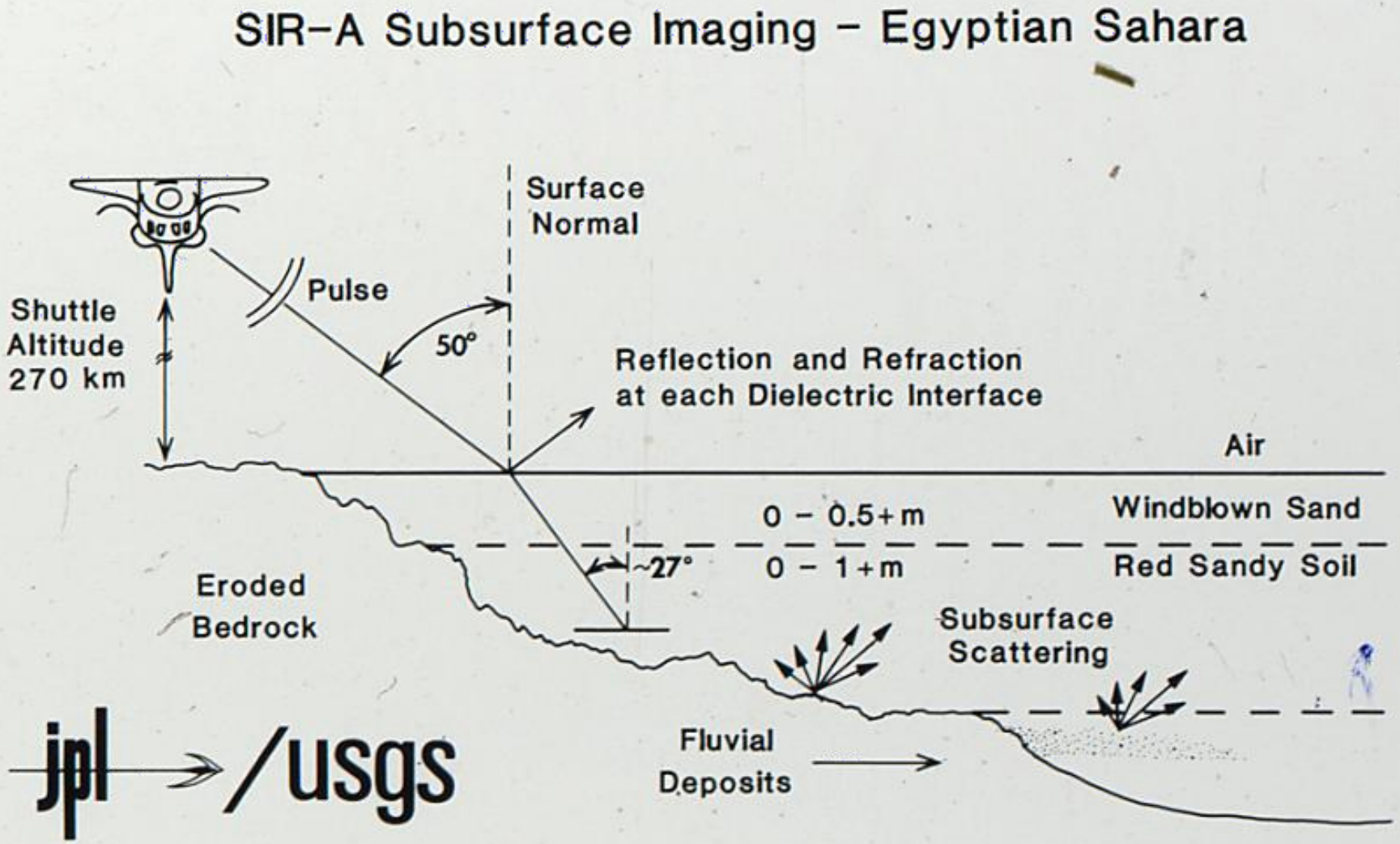
20°
15°
10°
20°
25°
30°
35°



- SIR-A radar image near Egypt Sudan border
- Image coverage is 50 km top to bottom
- Note large and small apparent river channels

A “radar river” field view and rounded pebbles



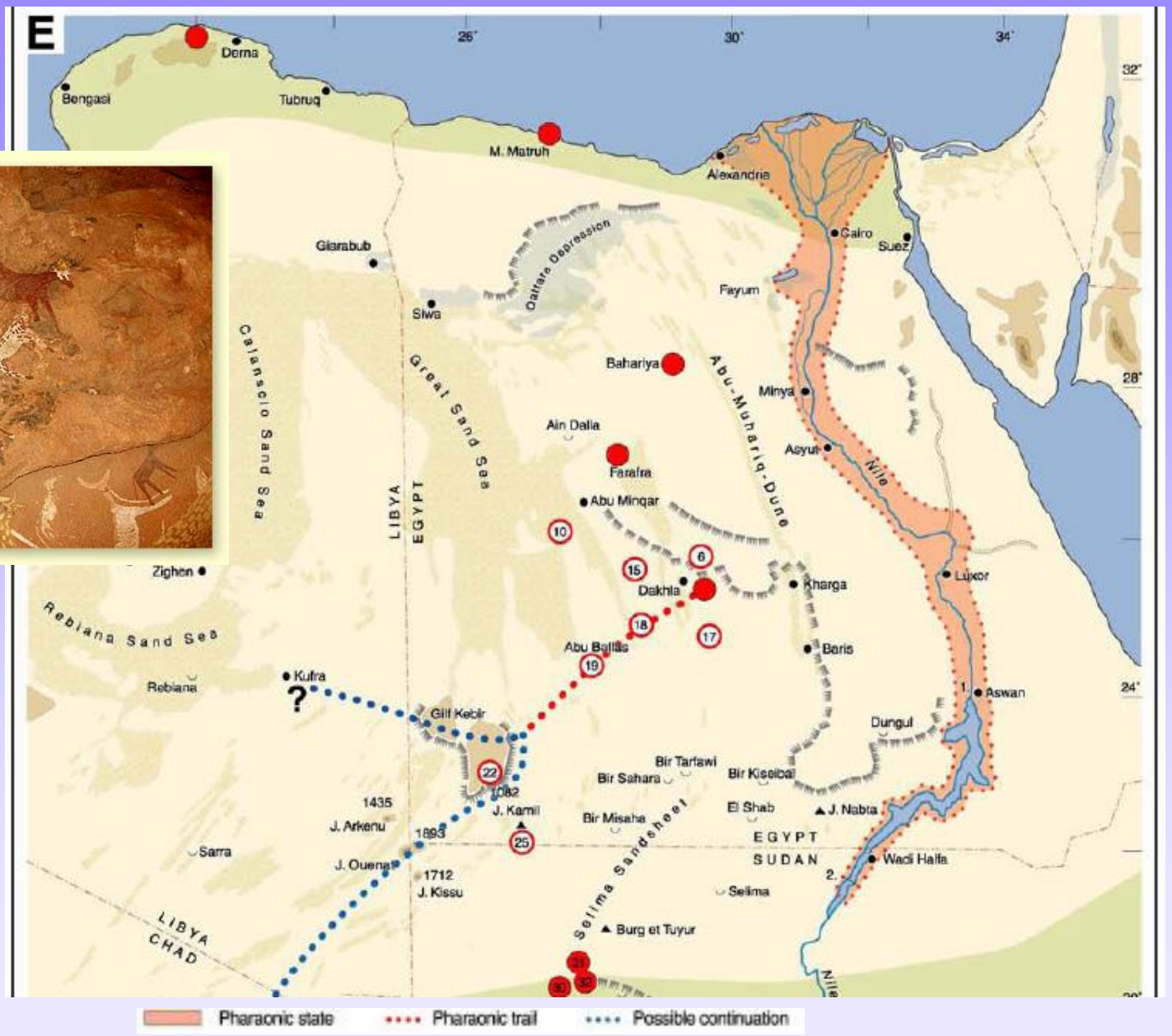
- Shuttle Imaging Radar-A flies on Space Shuttle Columbia, November 12-14, 1981
- L-band (23 cm) wavelength radar able to see subsurface in this extremely dry environment
- Radar is effectively a "time machine" showing a landscape from an earlier climatic regime

Human Occupation of the Sahara from Kuper&Kroepelin, Science, 2006.

Data from over 150 archaeological sites, maximum occupation of the Sahara at ~7.9K yrs

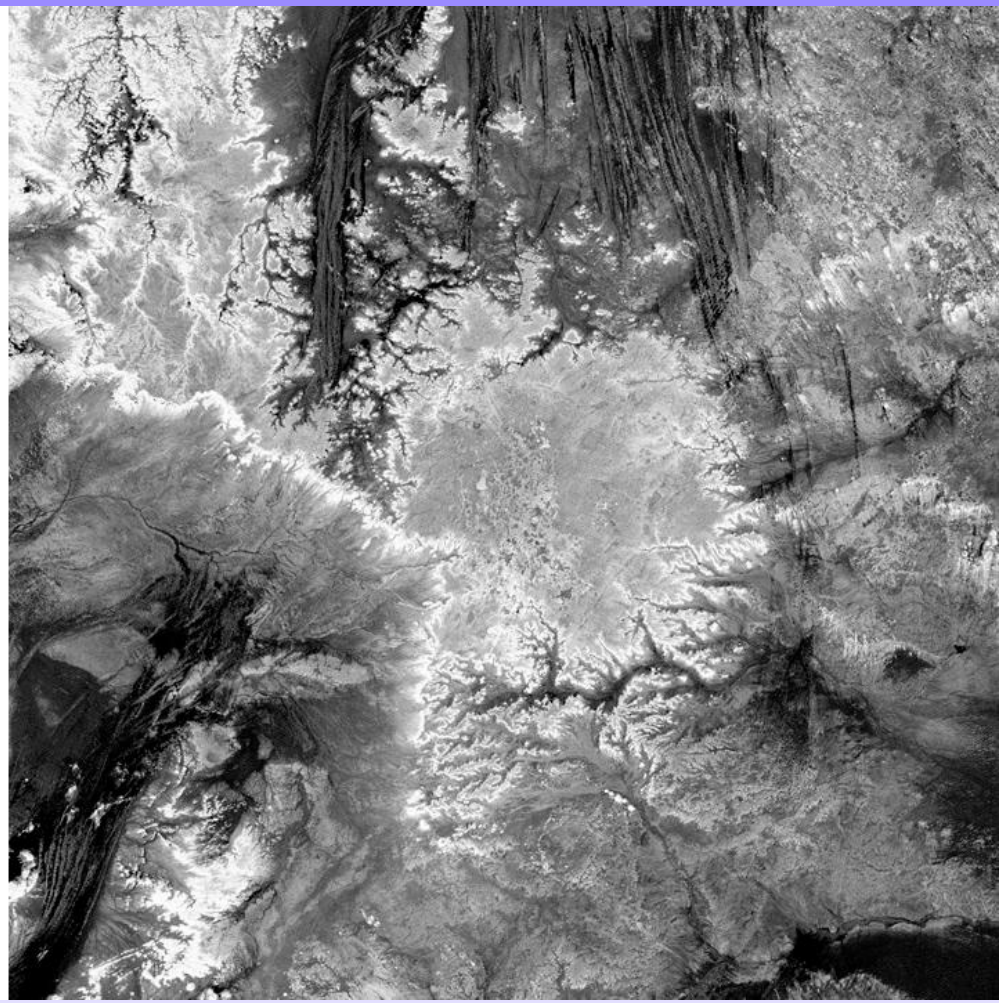
Where did people go when the Sahara dried out? They retreated south, and towards the Nile

Migration Routes Across the Sahara



Kuper and Kroepelin, 2006

The Gilf Kebir Plateau



Landsat (VNIR)

100 km

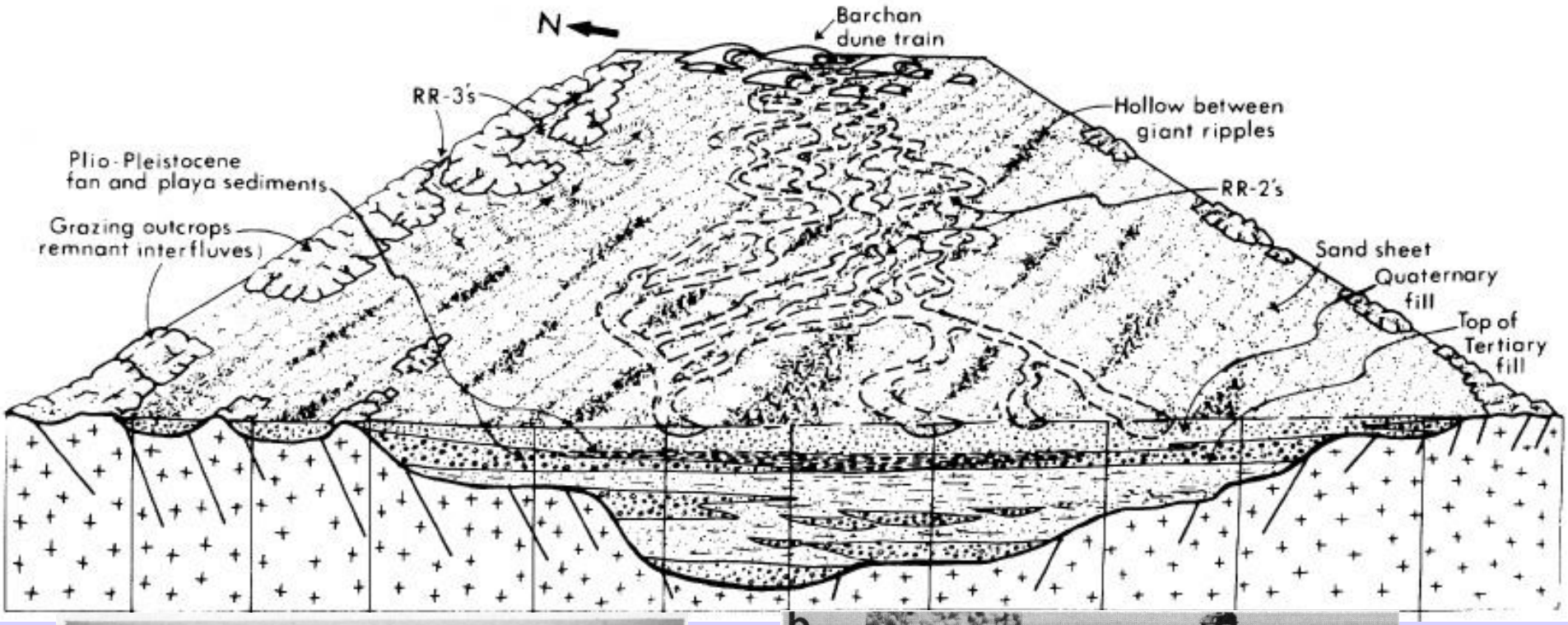
SRTM image (5.5 cm)

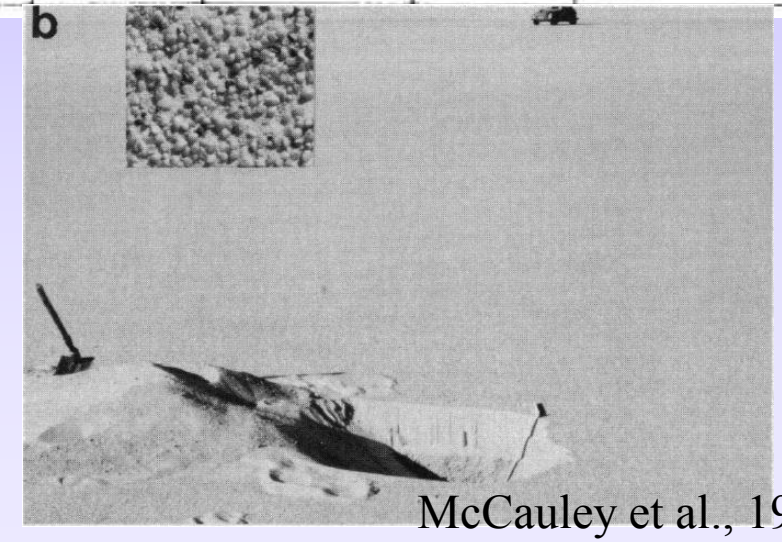
- The Gilf had continued occupation until ~4K yrs ago, and continued as a Saharan crossroads
- SRTM= Shuttle Radar Topography Mission, global topography and radar images, 2000

Farr, et al, 2008

Sand and a few Outcrops

Palimpsests: Multiple Generations of Rivers

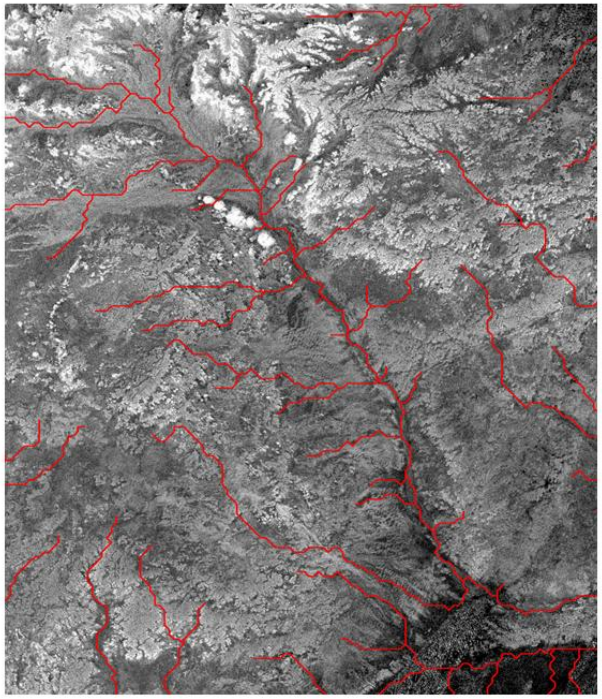


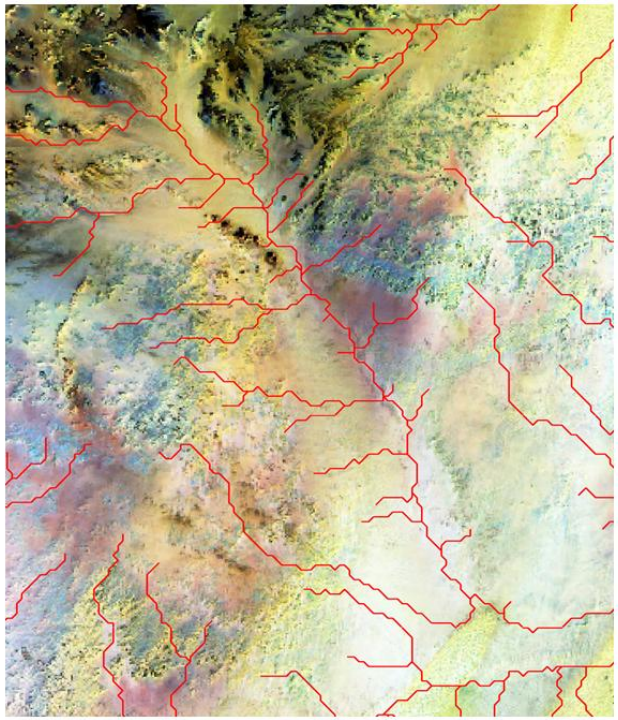


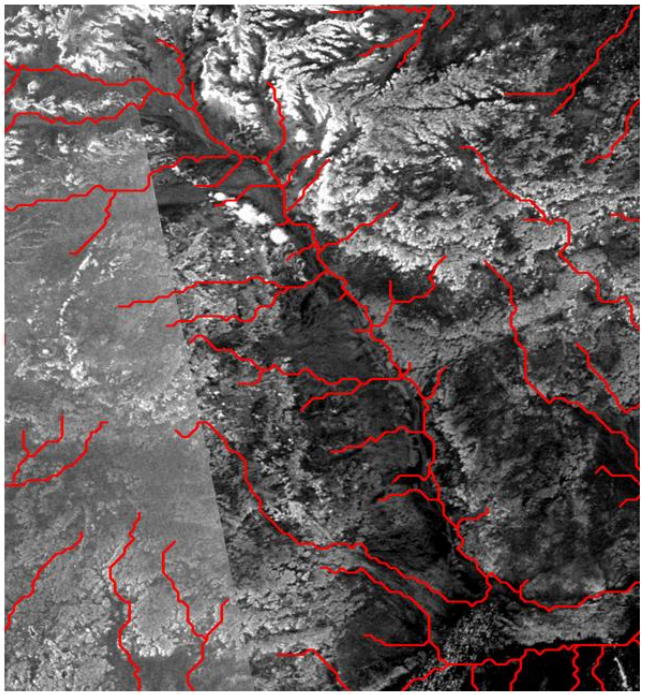
McCauley et al., 1982, 1986

Sahara Drainage Networks

Shallow Bedrock Channels







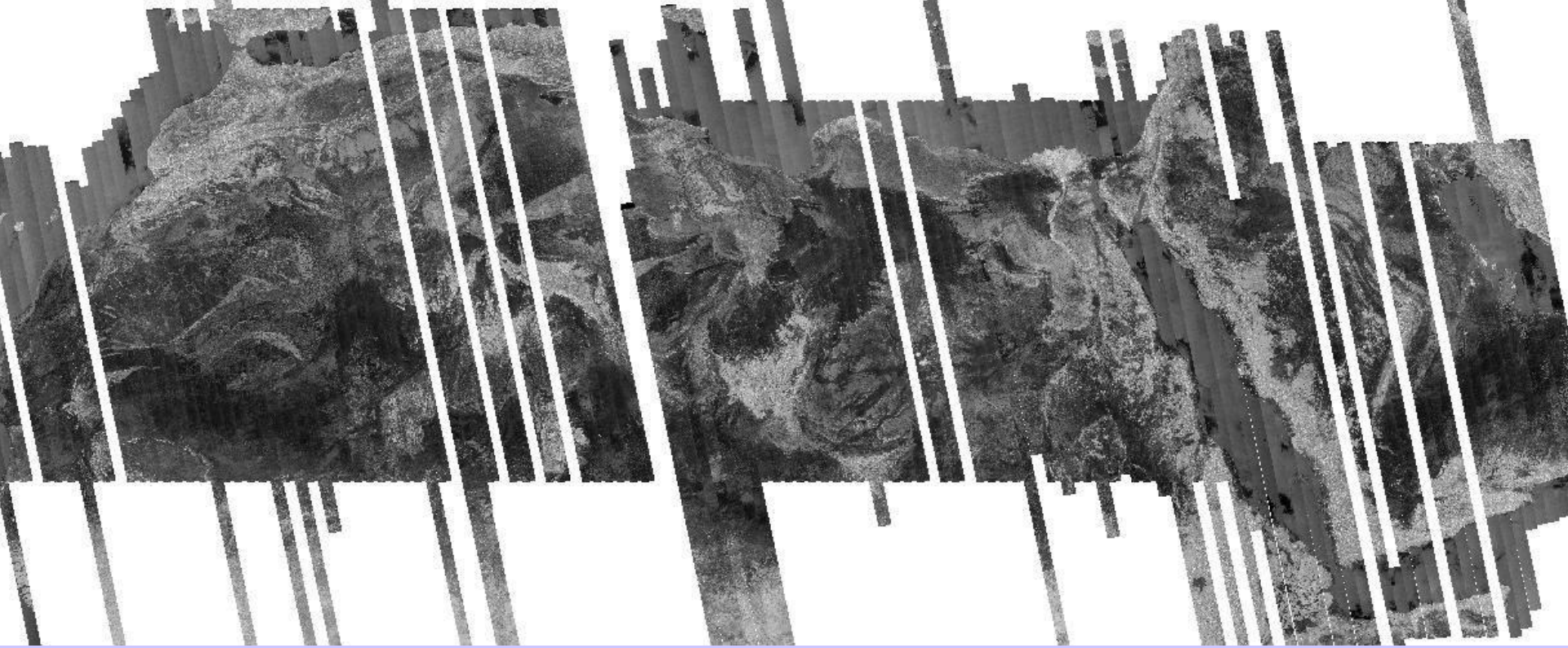
SRTM Image (5.5 cm)

TM (VNIR)

PALSAR (25 cm)

- Drainage networks derived from different sensors provide insight into paleo-hydrology
- Recent desert conditions are shown in the Landsat TM image, while the long wavelength PALSAR radar shows older drainages in great detail

Farr, et al, 2008



- Sahara SAR mosaic of PALSAR L- band radar images from the Japanese Advanced Land Observation Satellite
- When complete will be the first ever image showing integrated paleo-drainage features of north Africa
- Paleo-hydrologic history will be important data for understanding recent climate changes in North Africa
- Integration of this data with archaeological work should shed much light on human occupation of the area during climate changes

Paillou, et al, 2008

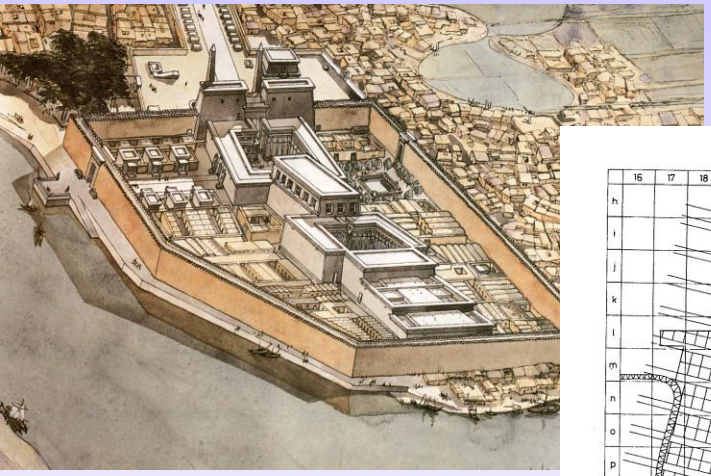
The End of Egypt's Pyramid Age from Space

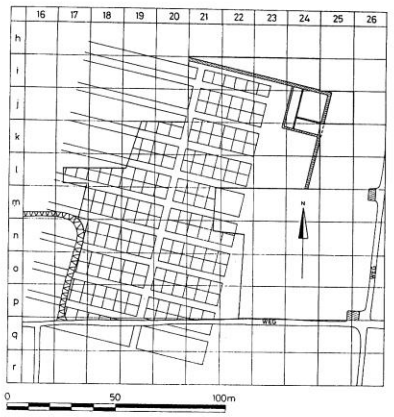
Prof Sarah Parcak, UAB

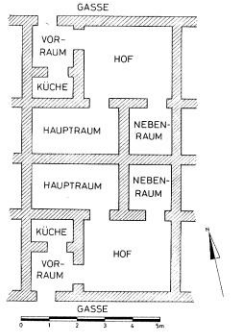
Settlement Pattern Studies in Egyptology

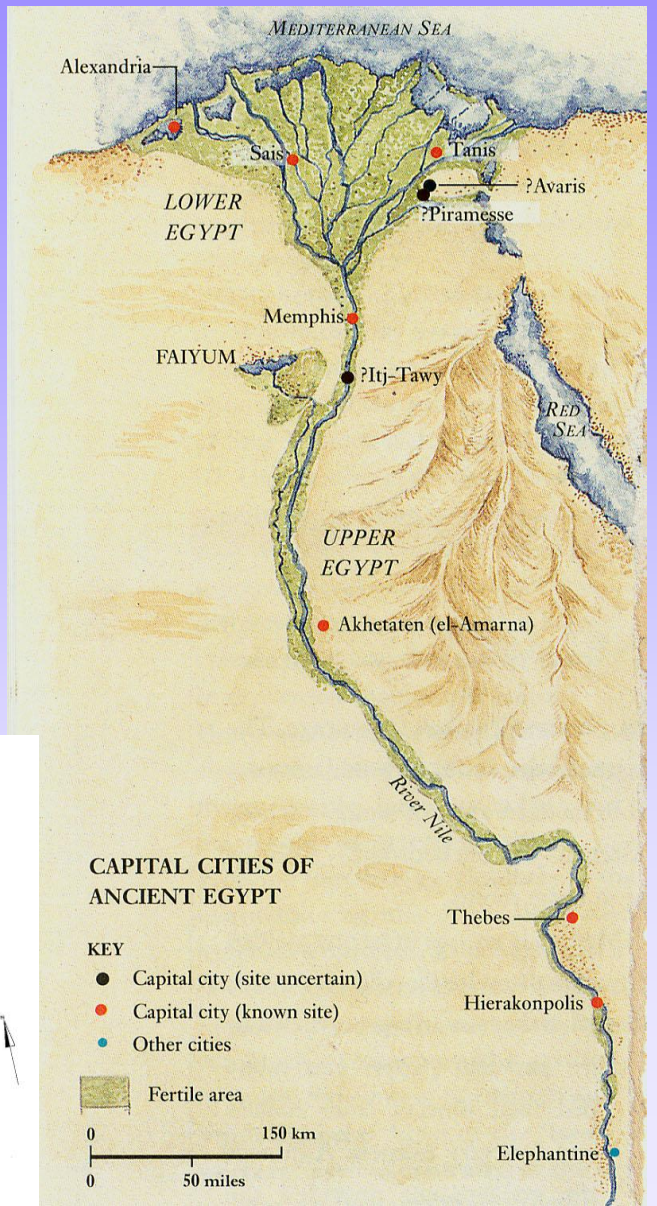
- Limited time, sites being over run by development
- Where are all the sites?
- How many towns/villages/cities? What time periods?
- Role of remote sensing-help find and document sites

provide regional context

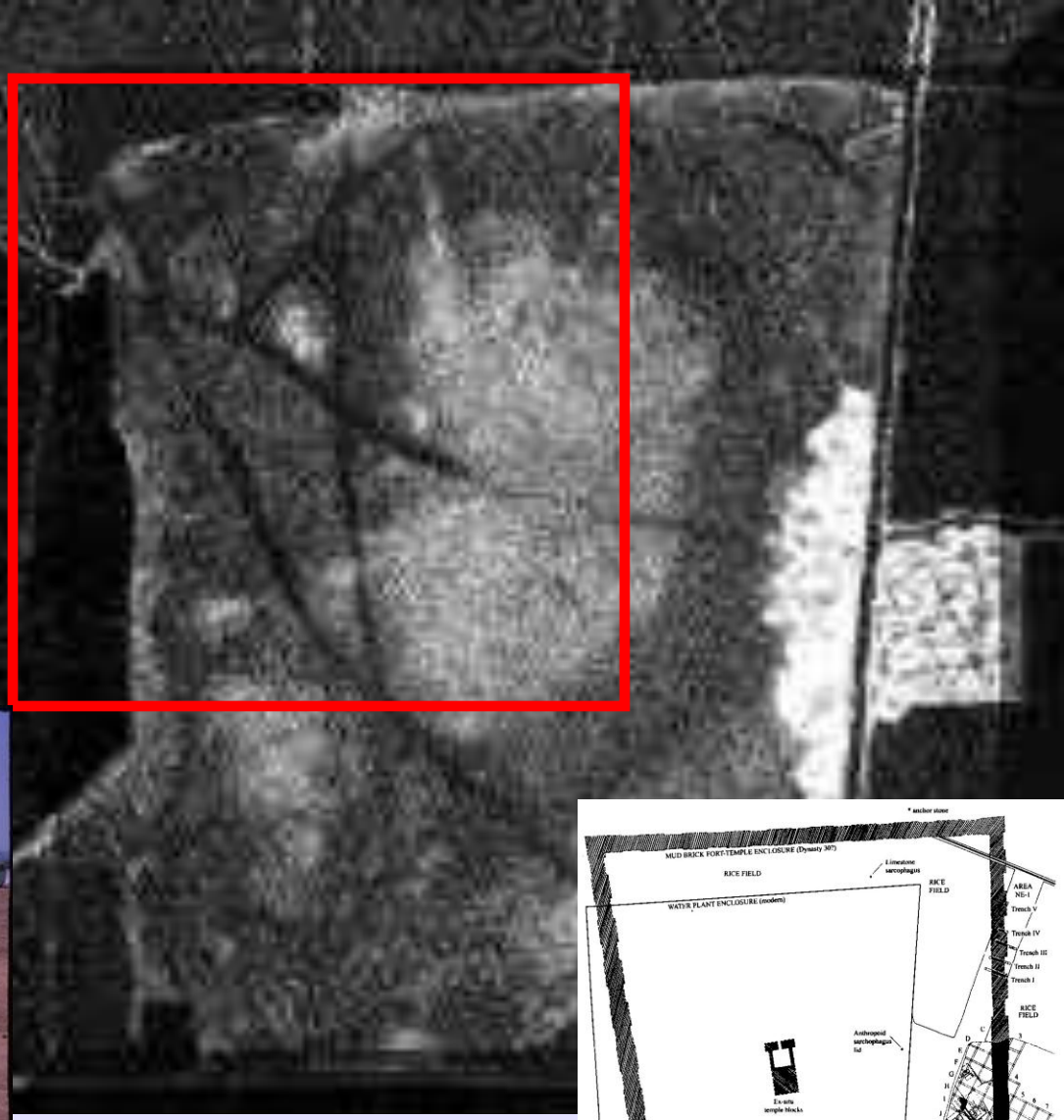








Landsat image of Tell Tebilla



•Corona spy satellite
•*PHOTOGRAPHIC* image of Tell Tebilla

•Enclosure wall at Tell Tebilla-remote sensing data tells archaeologists exactly where to dig

Why and how did the Old Kingdom collapse?

•Multiple factors with varying significance lie behind the Old Kingdom's collapse:

Late Old Kingdom, Dyn. 6+:
Last straw? vs. Cumulative?

2200 BC climatic & socio-cultural changes across globe

•Two great droughts
ended Neolithic Wet-Phase, causing 1 meter drop in average Nile height
→**reduced crop & income**.

• Drop in king's prestige
through failure to obtain higher flood levels from deities

i.e., The king is the guardian of the land

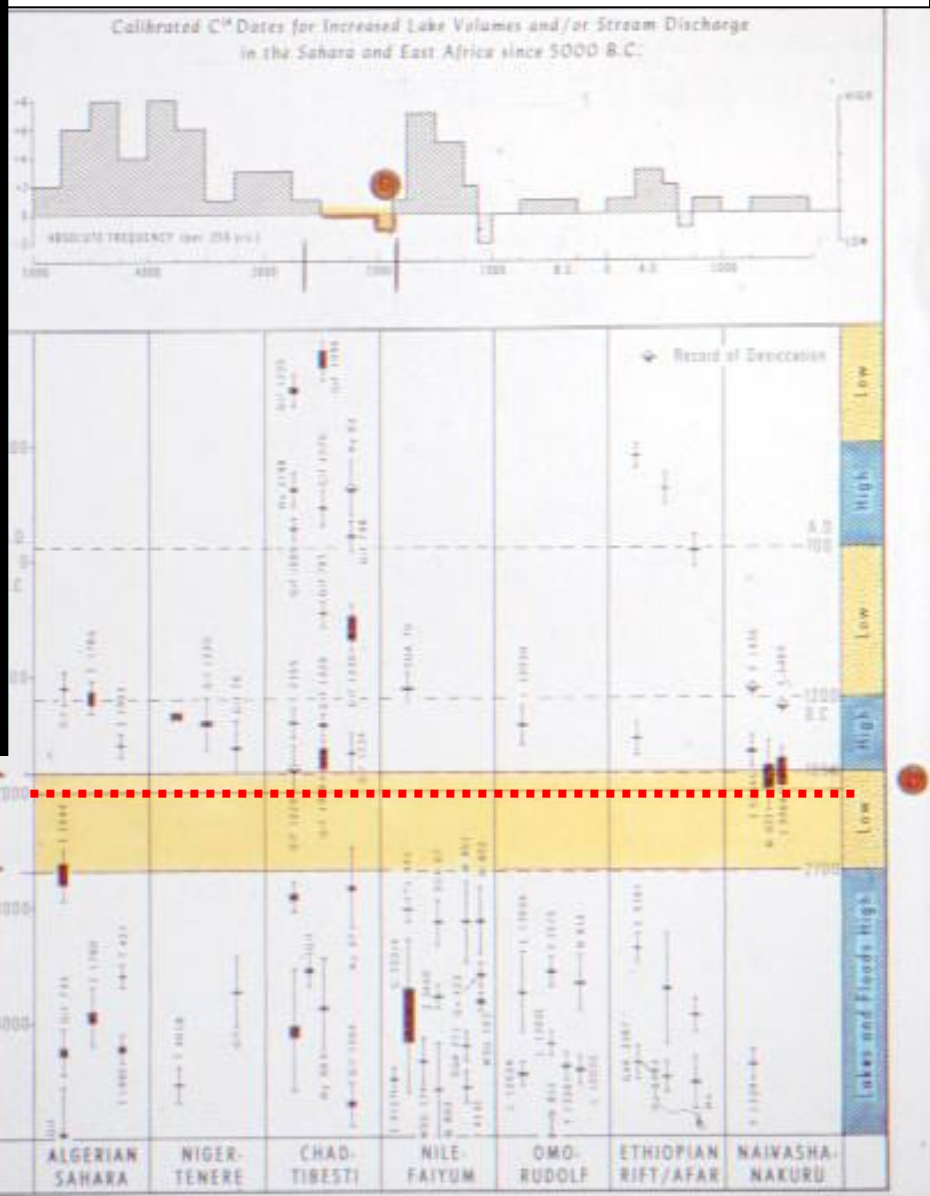
→ A major failure would reflect badly on him.

→ Public loss of face! & faith

1850 BC

2700 BC

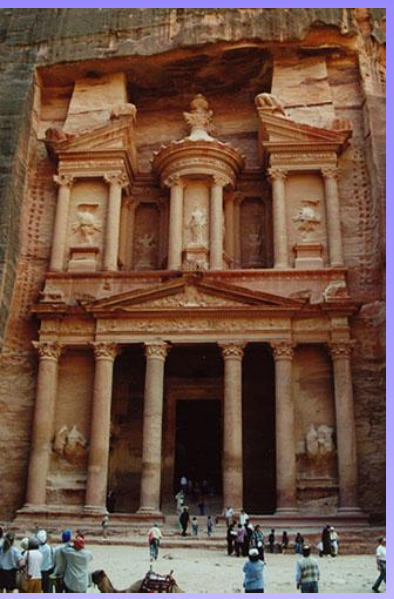
4.2 ka BP event = 2,200 BC



c.2200 BC global climatic event → var. effects

The 4.2K yr event-Possible change in circulation of Atlantic currents may have induced weak monsoons contributing to "decline"/"collapse" within Egypt, Syria-Palestine, Turkey, Mesopotamia, and the New World as well.

See: Weiss, Harvey and Raymond S. Bradley, 2001, What drives societal collapse? Science, 291: 609-610.

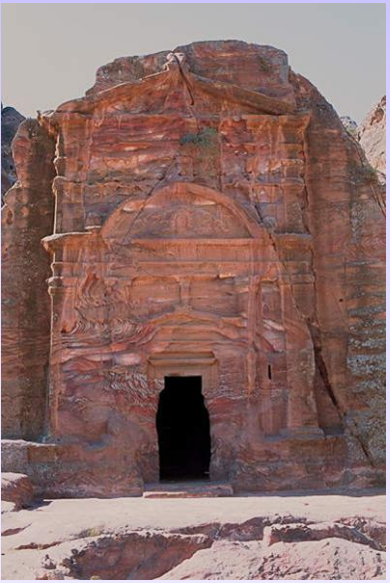


Petra World Heritage Site

Petra: interaction of people, environment and climate

•Petra was the center of the spice and incense trade in the Arabian Peninsula

• Under Roman influence in 1st and 2ndcenturies AD it became an agricultural production center for grapes, olives and grain



• Roman influence at Petra similar elsewhere such as North Africa- new cities, expanded agriculture

•Large population increase at Petra, >30,000

•Space archaeology reveals extensive field system

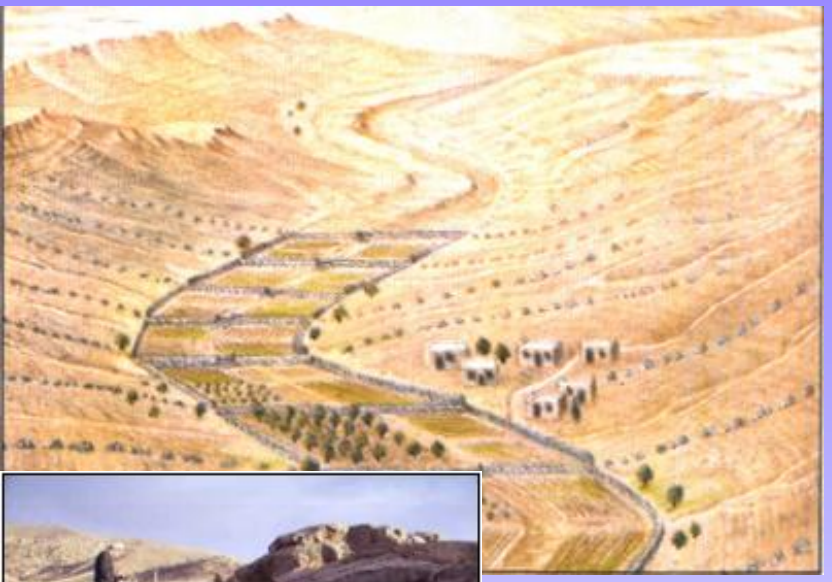
•Field surveys aided by space images find numerous olive and grape processing facilities

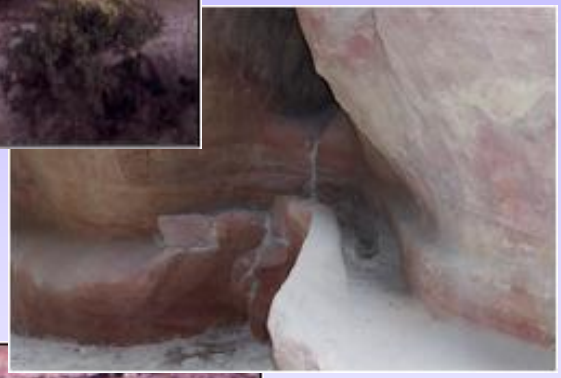
Courtesy: Douglas Comer CSRM

Petra-UNESCO World Heritage Site

- Originally a trading oasis on the edge of a sea of sand
- A desert today (vegetation in red in ASTER image draped over topography below)
- Archaeology indicates that this was not always so

NabataeanFields at Petra



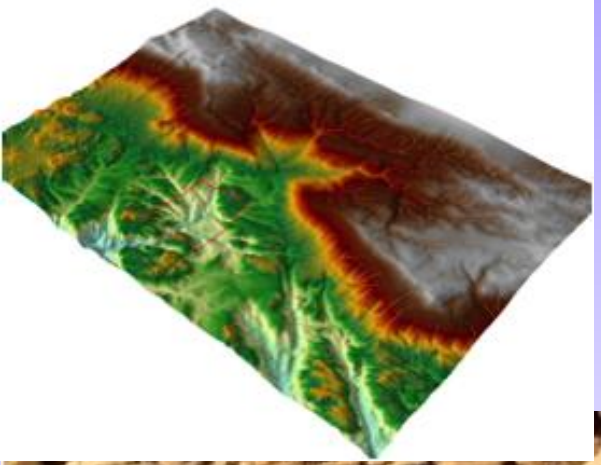


- Sophisticated water capture and management system allowed great productivity in this arid area
- Terraced to slow and distribute water, system directed water to fields, settling basins, cisterns and reservoirs
- Prosperity resulted in unprecedented population density, > 30,000 people, vs ~1,000 in 1900
- Earthquakes in 363 and 551 CE damaged the system
- Rome in decline does not rebuild, productivity plummets
- Large population reverts to goat herding>irreversible soil and vegetation degradation
- Lack of vegetation, decreased soil moisture, increased albedo decreases local rainfall, enhancing desertification that persists today (Lau, et al., 1999; Walker and Roundtree, 1976)
- Amplifies natural climate changes

Petra, Current Work

- Role of remote sensing: locate and document sites, provide regional context, monitor change
- Using ASTER, IKONOS, SRTM

SRTM DEM-Red=high



- Fields in IKONOS Image Draped Over Digital Elevation Model

Goats: Agents of desertification

CSRM
Cultural Site Research and Management

IKONOS satellite image courtesy Space Imaging

AIRSAR http://airsar.jpl.nasa.gov/

- AIRSAR-JPL's experimental Airborne Synthetic Aperture Radar System
- AIRSAR now decommissioned
- Flew on NASA's DC-8 flying laboratory based at Dryden, CA
- POLSAR-3 wavelengths and full Polarization diversity helps characterize targets
  - P, L, and C band at HH, HV, VH, VV polarizations
  - 3 modes 20, 40, and 80 MHz bandwidth.
    - Resolution increases with bandwidth while swath decreases
    - 80MHz L band resolution is 1.7m, 40 MHz is 3.3m, 20 MHz is 6.7m
    - Swath width is 5km@80MHz, 10Km@40MHz and 15Km@20MHz
    - Image calibration 3dB absolute, 0.2dB cross pol, 1.5dB between bands
- TOPSAR-Generates Hi Res DEMs at two wavelengths
  - Cross track interferometry
  - L and C band Digital Elevation Models (DEMs)
  - DEM postings at 5m (40 MHz), 1-3 m height accuracy

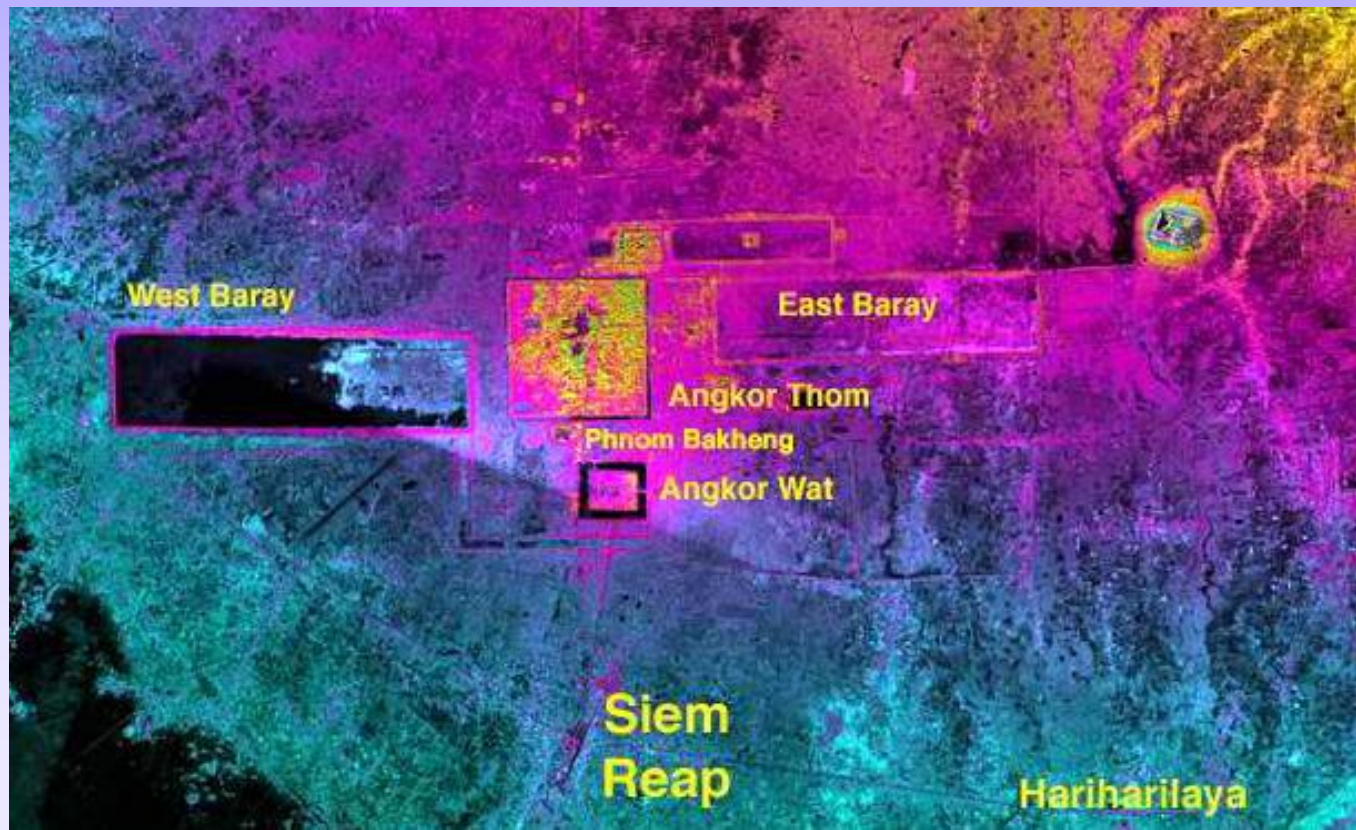
Current Antenna Configuration

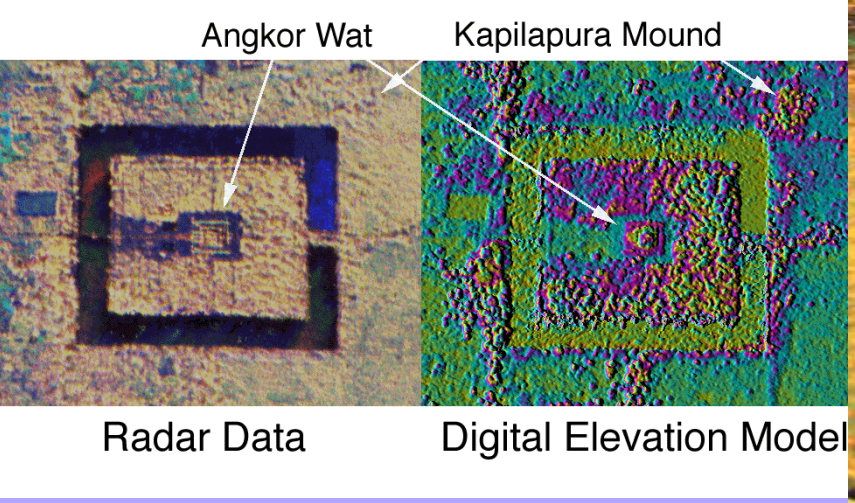
AIRSAR Instrument

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

- Angkor Wat-major religious/urban center and water system, ~9th-15th centuries
- Angkor region imaged by SIR-C and AIRSAR
- AIRSAR campaign also collected high resolution TOPSAR DEMs
- Collaborative research by archaeologists and remote sensing experts advances historical understanding

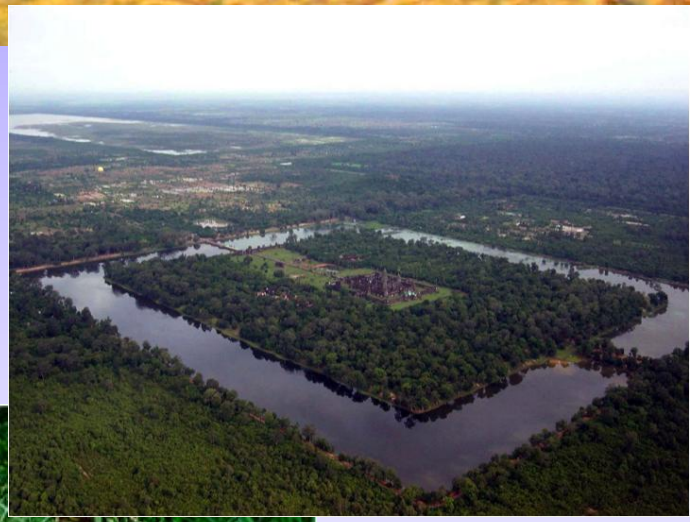
Angkor Wat Temple: Andrew Lih



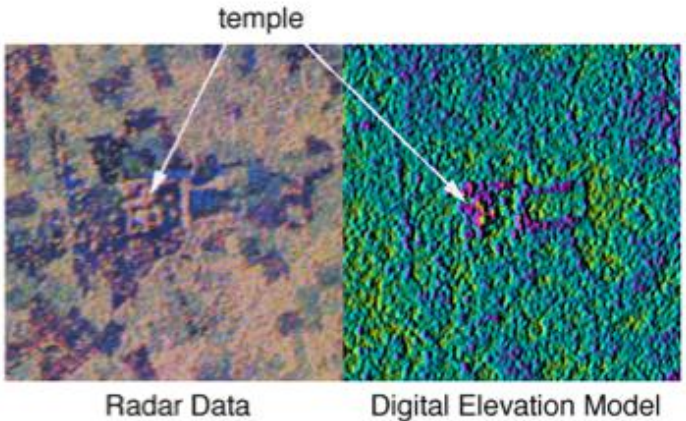


Angkor perspective view: AIRSAR on TOPSAR DEM

- Archaeological structures show both in radar images and DEM
- DEM provides water management insight



SmanTeng Temple



Archaeologists commute to work

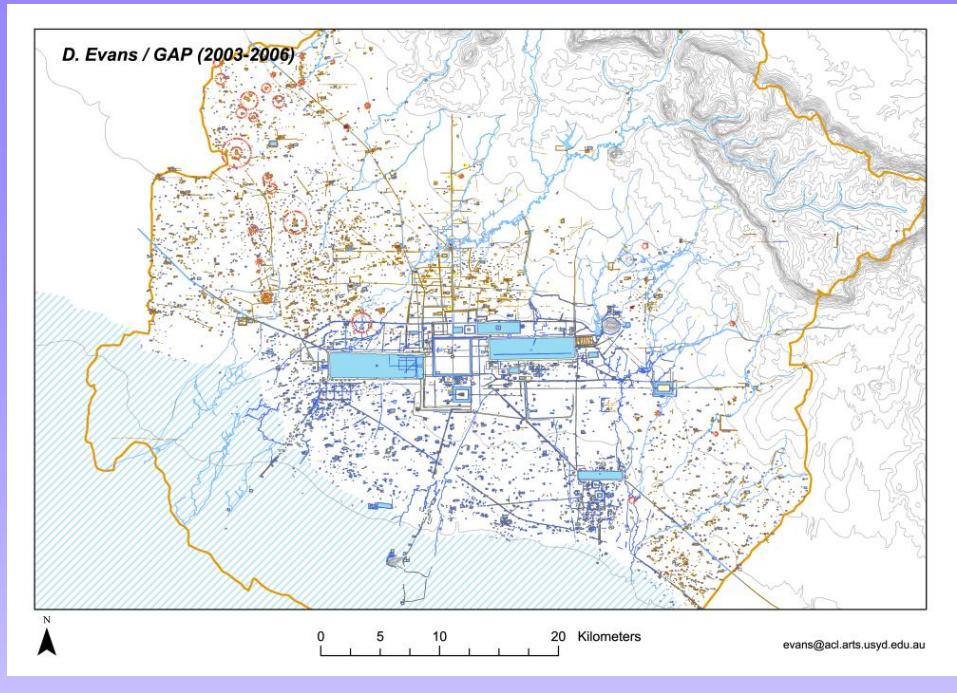
Angkor Wat

•Work by the Greater Angkor Project (GAP) and others, aided by AIRSAR and other remote sensing data have documented ~1000 additional temple sites, many thousands of occupation mounds, ponds, canals, etc stretching across more than 1500 km^2

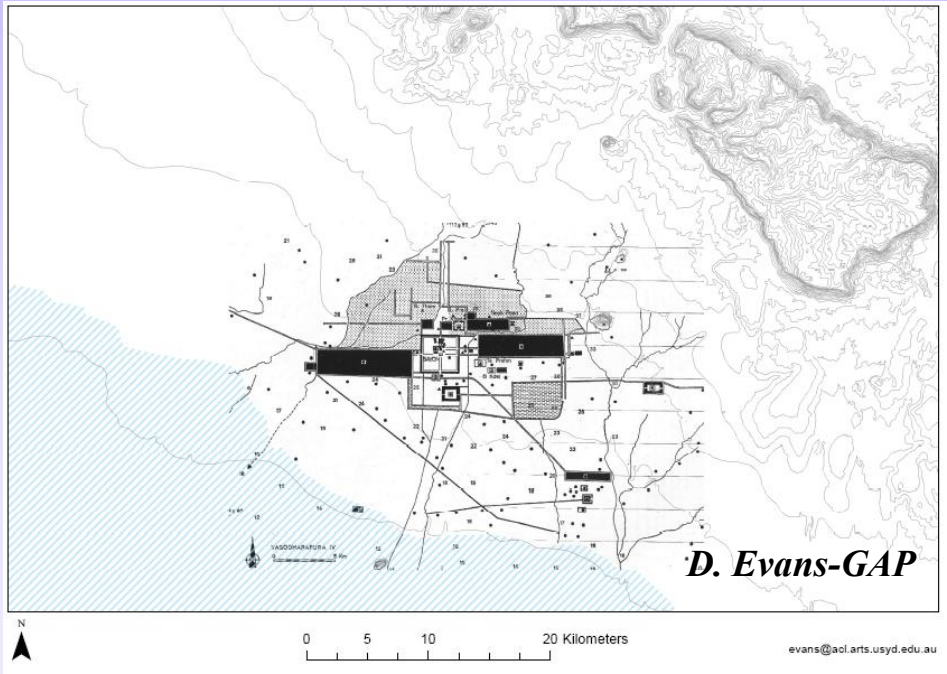
•Current insight shows Angkor to be an extensive urban complex with an increasingly elaborate water management system. Population 100's of 1000's at peak

•Angkor suffered many problems, current research focus by the GAP team indicates monsoons may have become erratic starting about 1300 (Little Ice Age); invasions and other disorder occur, barays silt up, rice yields drop

•Angkor declines after 1300's, infrastructure deterioration and environmental degradation contribute



Courtesy Evans, Fletcher, and GAP



Summary:

In this short overview we have seen space based data help document movement of people from the Neolithic hunter-gatherers to agriculture, and seen examples of past civilizations which failed to adapt to minor climate perturbations

Key Points:

- Anatomically modern humans emerge about 130K years ago
- Agriculture and complex societies only develop after climate stabilizes 11, 570 years ago
- Agriculture and complex societies take time to form
- Multiple applications of remote sensing data to archaeology and history
- Examples provided of transition out of Sahara, and history of Egypt, Petra, and Angkor
- Interestingly, each of the examples discussed relate to changes in WATER availability
- It is unlikely a coincidence that social changes occurred coincident with climate changes
- Indeed, deMenocal (Science, 2001) shows multidecadal to century scale drought are associated with population dislocations, urban abandonment, and even state collapse, and urges further study
- Also, Weiss, et al., (Science, 2001) analyze "What drives societal collapse?" and drought is a key issue
- ***Upcoming NASA missions include Soil Moisture (SMAP), Ice (ICESAT 2), ecosystems, cryosphere, and solid Earth (DESDynI) directly address climate change issues***

The DESDynI Mission

- NRC Decadal Survey released late summer 2007
- Among first tier missions recommended is DESDynI
- ***D***eformation, ***E***cosystems ***S***tructure, and ***Dyn***amics of ***I***ce
- InSAR and Lidar to provide observations for:
  - Solid Earth (surface deformation)
  - Ecosystems (terrestrial vegetation structure)
  - Crysosphere (ice dynamics for climate)
  - Ecosystems and cryosphere science directly address climate issues
- L-band synthetic aperture radar (SAR) system
  - Operated as a repeat-pass interferometer (InSAR)
  - Multiple polarization: single, dual, or fully polarimetric
  - Frequent (8-day) InSAR revisit
  - SweepSAR mode with a ~350 km swath
- Multiple-beam lidar
  - Operating in the infrared (1,064 nm)
  - 25-m spatial resolution
  - Canopy-height accuracy of 1 m