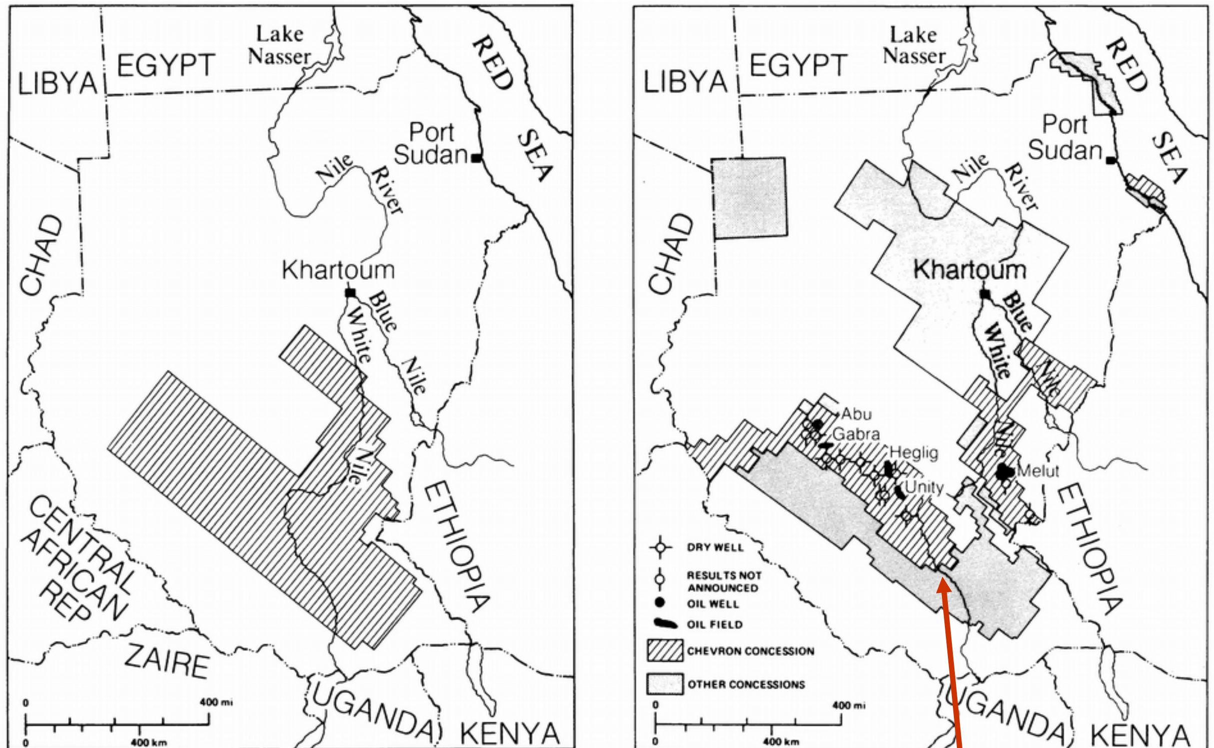
Wed. Apr. 18, 2018

- Sabins Chapter 10 Sudan and Central Arabian Arch (Oil)
- Reading:
  - Skim/Review Chapter 10 – Sabin's Older Petroleum case histories
    - I'll just briefly review the Sudan and Central Arabian Arch cases today
  - Skim/Review Chapter 11 Sabin's Mineral Exploration. We've actually covered most of this in labs

Typical Oil Exploration Program

- Sabins overview of typical oil exploration program:
- 1) Regional remote sensing reconnaissance
  - Use Landsat scale mosaics over ~10^5 km^2 to locate sedimentary basins
- 2) Reconnaissance geophysical surveys
  - Aerial magnetic surveys
    - Sedimentary basins have lower magnetic intensities than areas with igneous and metamorphic rocks
  - Surface gravity surveys
    - Sedimentary rocks are lower density, so lower gravity
  - Both of above may also show regional structural features
- 3) Detailed remote sensing interpretation
  - Map structures such as anticlines and faults
    - Can use Landsat images, or radar in areas with bad cloud cover
  - Field work to check interpretation and collect samples
- 4) Seismic surveys
  - To record subsurface geologic structure
  - Remote sensing can aid in planning of seismic work in uncharted regions
- 5) Drilling
  - Wildcat wells to test oil prospects. ~20% successful (at least at time of Sabins work)
  - Development wells to produce oil.

Sudan Overview Maps



A. Original Chevron exploration concession, 1974.

B. Status of exploration and concessions, 1982.

Figure 10-2 Maps showing the status of oil exploration in Sudan.

Sudd Swamp

- Chevron 1974 project to extend Landsat work done in Kenya.
  - Possible extension of sedimentary basin from NW Kenya into Sudan
- 1972-1982 roughly time of 10 year cease fire in N-S Sudan civil war

Landsat MSS Mosaic

Figure 10-1 Mosaic of Landsat MSS band 2 images of southern Sudan, showing the boundaries of the original Chevron exploration concession granted in 1974.

- Chevron's J.B. Miller recognizes sedimentary basin in Sudd Swamp
- He also notices straight river segments (i.e. lineaments) suggesting fault control
- Based on Landsat data Chevron obtains exploration concession from Sudanese government for outlined area
- Landsat data used to produce IR color images and base map used for rest of project.

Basins defined by geophysical surveys

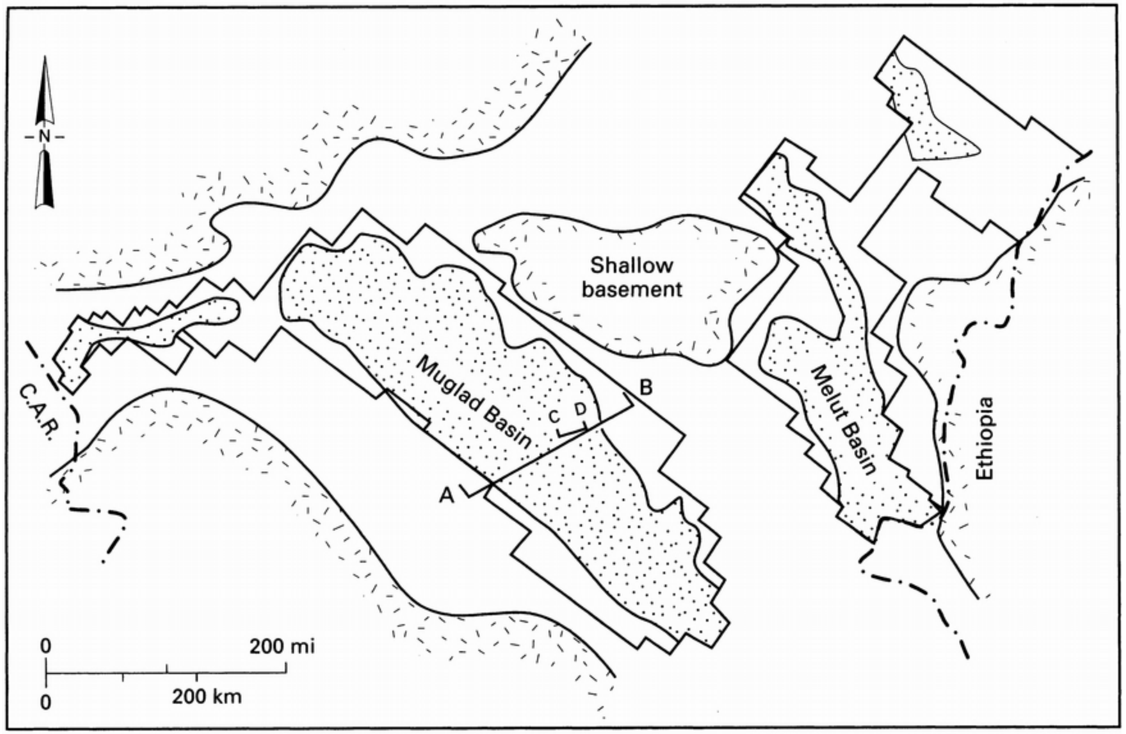


Figure 10-3 Sedimentary basins in southern Sudan defined by geophysical surveys and drilling.

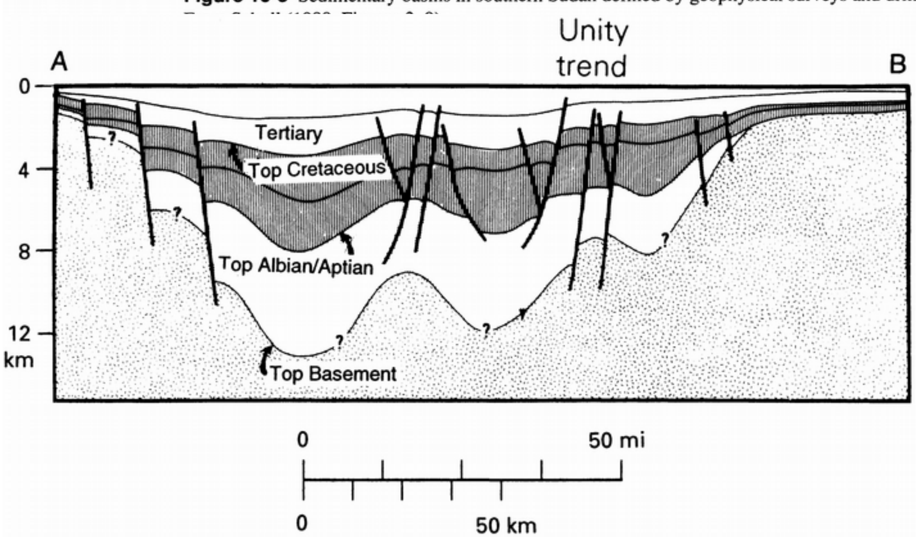
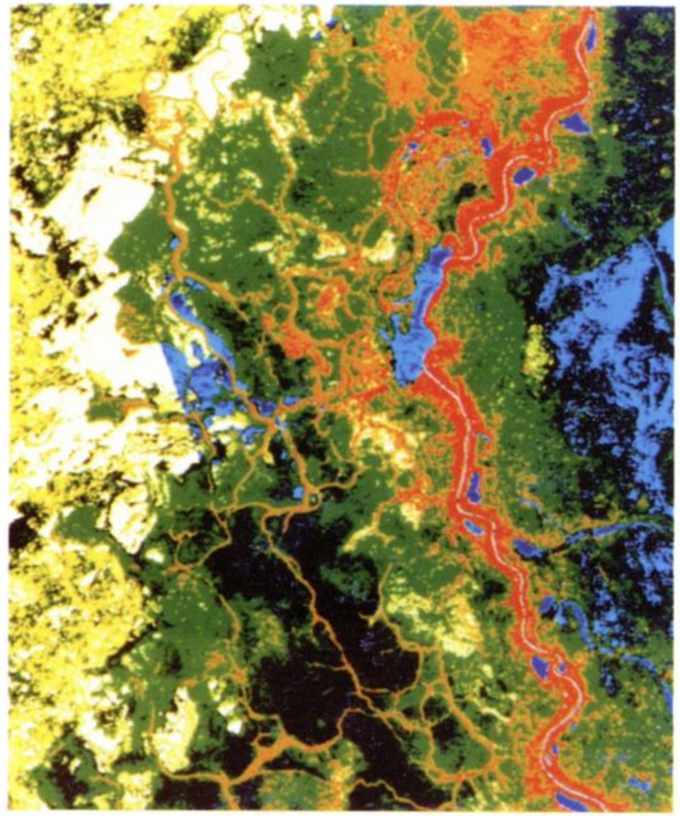


Figure 10-4 Regional cross section (A–B) across the Muglad Basin. From Schull (1988, Figure 11).

- Aerial magnetic and gravity surveys define extent and depth of basins.
- Seismic work defines detailed structures
- Surface expression of faults confirmed on Landsat images
- Transportation very difficult in Sudd Swamp. Land classification based on Landsat data very useful in guiding transport plans

Terrain classification

A. Landsat MSS image, Sudan.



B. Supervised classification of MSS image, Sudan.

Dark blue	Open Water
Light blue	Shallow water with vegetation
Red	Papyrus and water hyacinth
Orange	Wet grass with standing water
Green	Bullrushes
Black	Bullrushes with standing water
Dark yellow	Dry grass
Light yellow	Upland areas, driest areas

- Landsat MSS image obtained during dry season
- Supervised classification used to map categories at right
- When laying out seismic lines
  - swamp buggies used in marsh areas – avoiding papyrus areas which jam drives

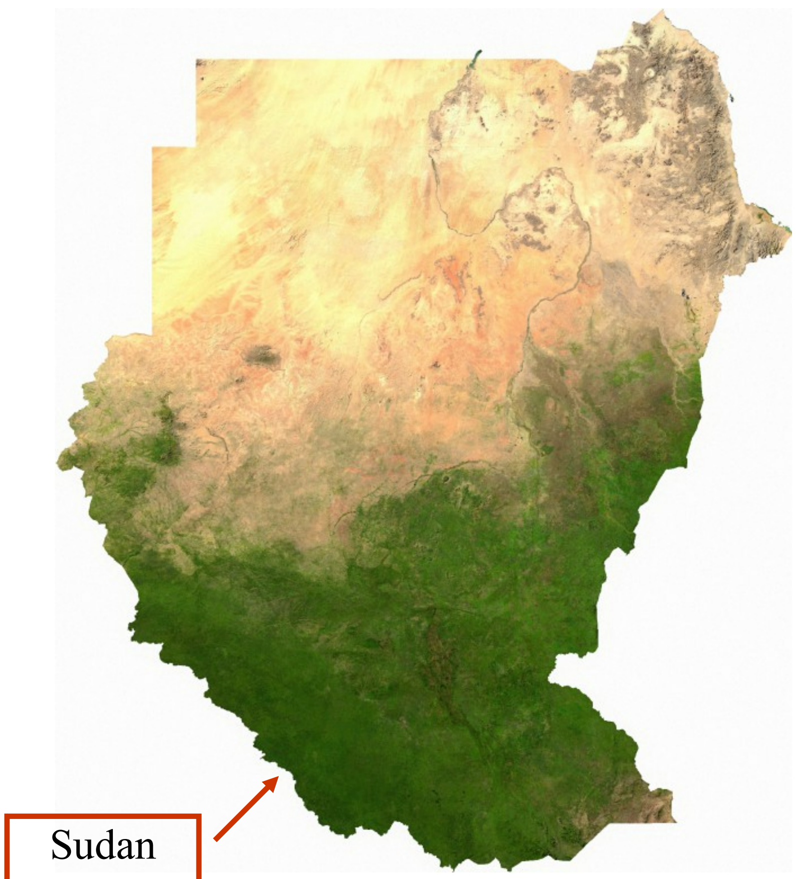
Oil Development

- Noncommercial quantities discovered at second well in May 1978
- Significant flow from 5th well in 1979
- Important discovery at Unity 2 well in 1980
- Subsequent discoveries at Heglig field
- Pipeline planned to Port Sudan on Red Sea.
- In early 1980's N-S civil war resumes, stopping further oil development
- Recent Events
  - N-S "peace" from 2005-2011 leading up to elections on separation
  - Jan. 2011 South Sudan votes overwhelmingly for independence, which takes effect July 2011
  - Since independence, intermittent civil war between different groups in South Sudan
  - Heavy involvement in oil development by Chinese and some other companies
  - Oil now Sudan's major export As of a few years ago it supplied ~10% of China's consumption. War in S. Sudan and disagreements over transport with North Sudan have slowed development

Overview – Sudan vs. Central Arabian Arch

- In Sudan areas of interest heavily vegetated
- Landsat work suggested sedimentary basins and provided terrain classification, however, it wasn't used in discerning detailed geology

- In Central Arabian Arch arid conditions ideal for remote sensing, and Landsat provided much more geological detail.
  - Before 1986 exploration was largely limited to the "Retained Areas"
  - Large "unknown" areas needed to be surveyed



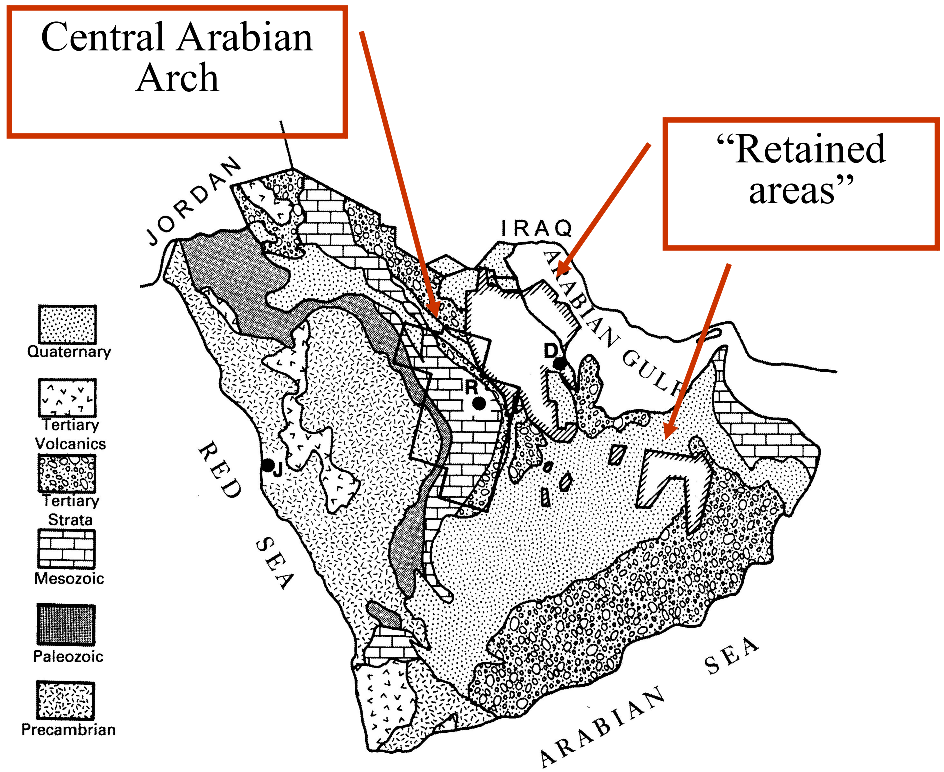


Figure 10-13 Location map of the Arabian Peninsula showing the location of the Central Arabian Arch project. Retained Areas are indicated by hachured borders. D = Dhahran, J = Jiddah, R = Riyadh.

Regional Geological Map from Landsat TM images

Sabins Plate 4
after pg. 242

Plate 4 Analog mosaic of the Central Arabian Arch compiled from Landsat TM 2-4-7 prints.

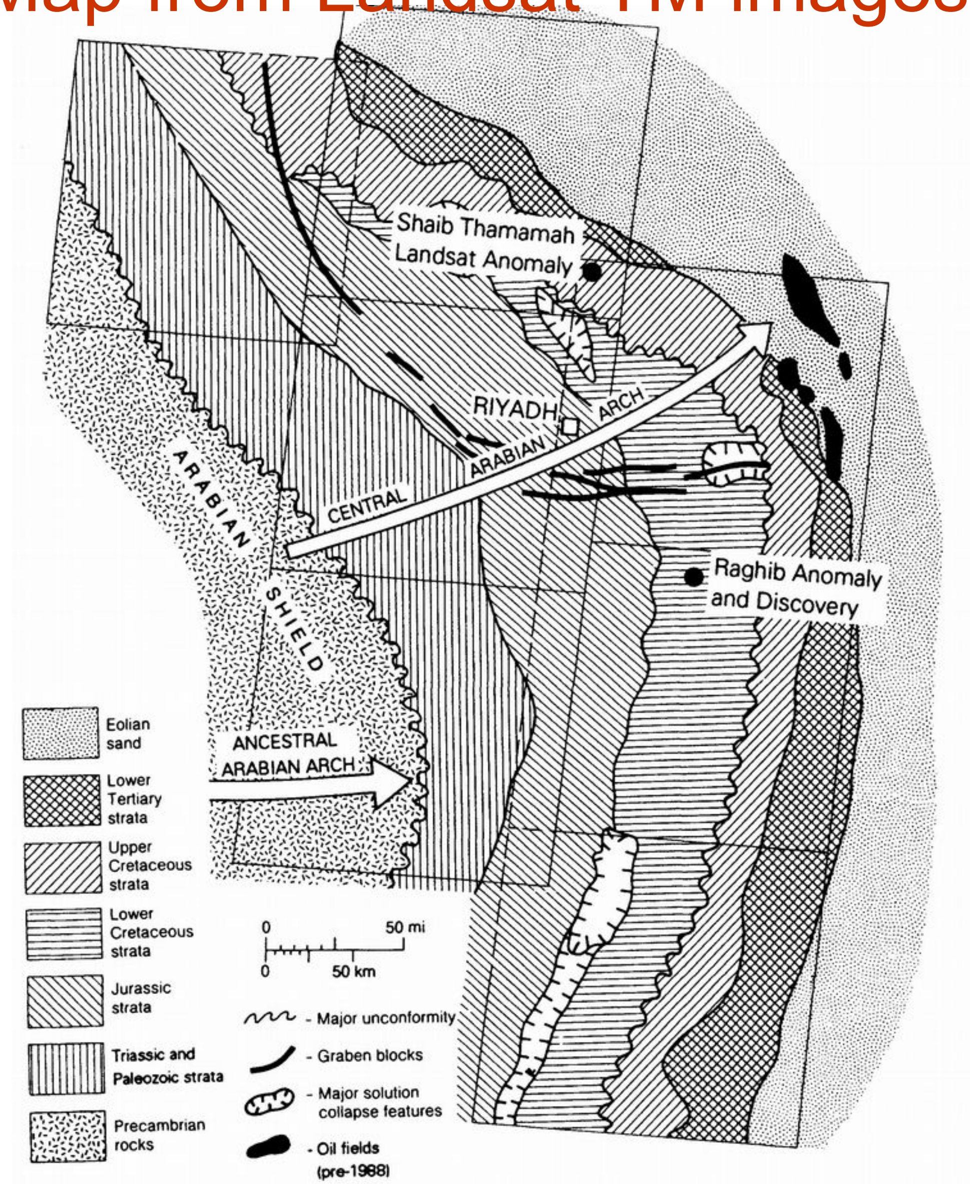


Figure 10-14 Geologic map of the Central Arabian Arch interpreted from TM images. Images boundaries are shown. From Wender and Sabins (1991, Figure 2).

Regional Geology

- Project on east flank of Arabian Shield
  - Shield is regionally uplifted Precambrian basement
  - To east it provides slowly subsiding base for 5500m of Paleozoic to Tertiary sediments
- Structure in sediments dominated by regional dip of 1^{o} to east, away from Shield
  - Dip changes direction along the Central Arabian Arch
- With gentle structure, dipslopes extend
  - hundred's of km along strike
  - 10's of km in dip direction
- 2nd phase of project (once regional geology defined) is to search for structural anomalies which could produce petroleum traps

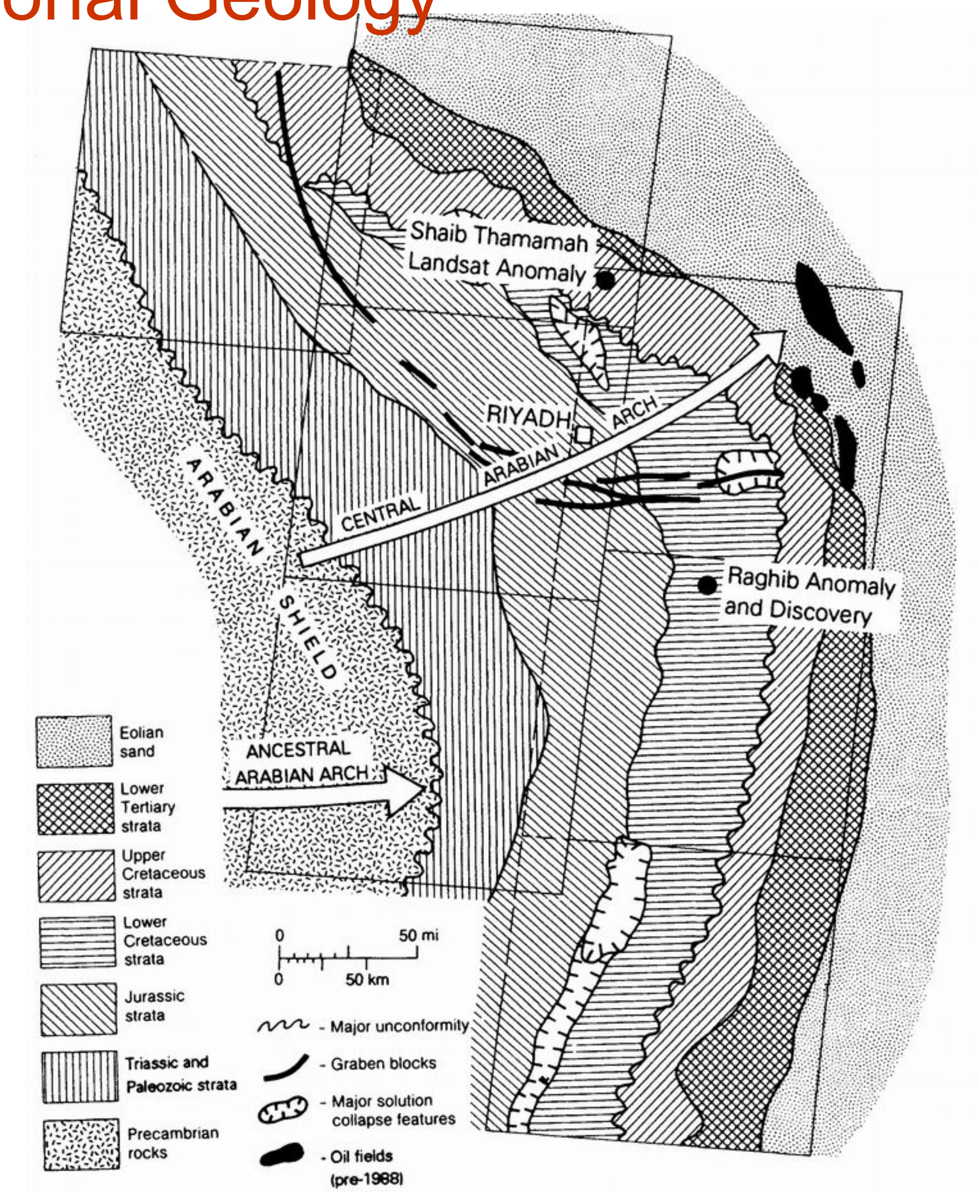
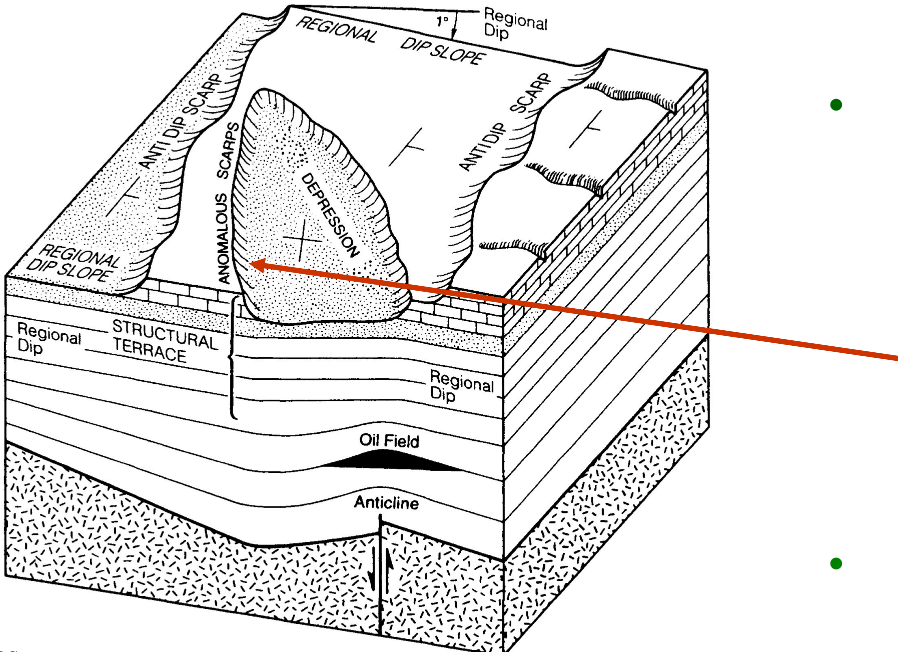


Figure 10-14 Geologic map of the Central Arabian Arch interpreted from TM images. Images boundaries are shown. From Wender and Sabins (1991, Figure 2).

Sabins Plate 4
after pg. 242

Assume similar subsurface structure as in Retained Areas

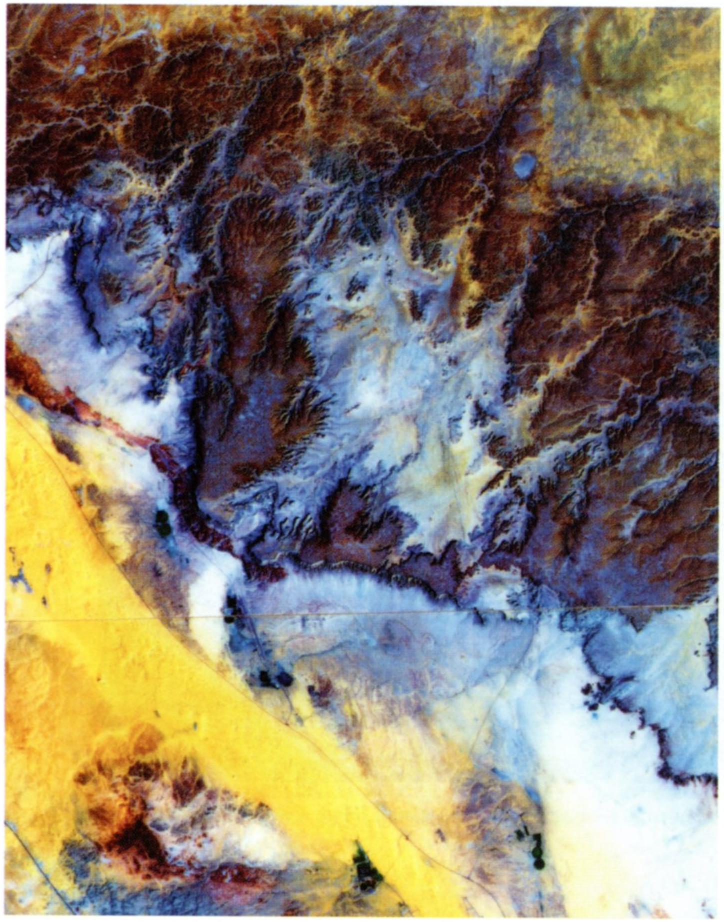


Sabins

Figure 10-15 Geologic model for oil exploration in terrain with subhorizontal strata. The topographic and geologic anomaly at the surface is caused by the same subsurface structure that forms the oil field.

- Within Retained Areas, oil fields are simple drape anticlines in Mesozoic strata, formed over high angle faults in deeper layers.
- Along arch, expect anticlines to show as structural terraces where regional dips reverse or at least flatten out
  - Anomalous scarps will face in opposite direction to regional ones
  - “Closed” depressions may exist on structural terraces
- Two such anomalies found in Landsat data and discussed by Sabins
  - Shaib Thamamah in north
  - Raghib Anomaly in south

Shaib Thamamah Anomaly



C. TM 2-4-7 image, Shaib Thamamah anomaly, Saudi Arabia.

Sabins, 1997

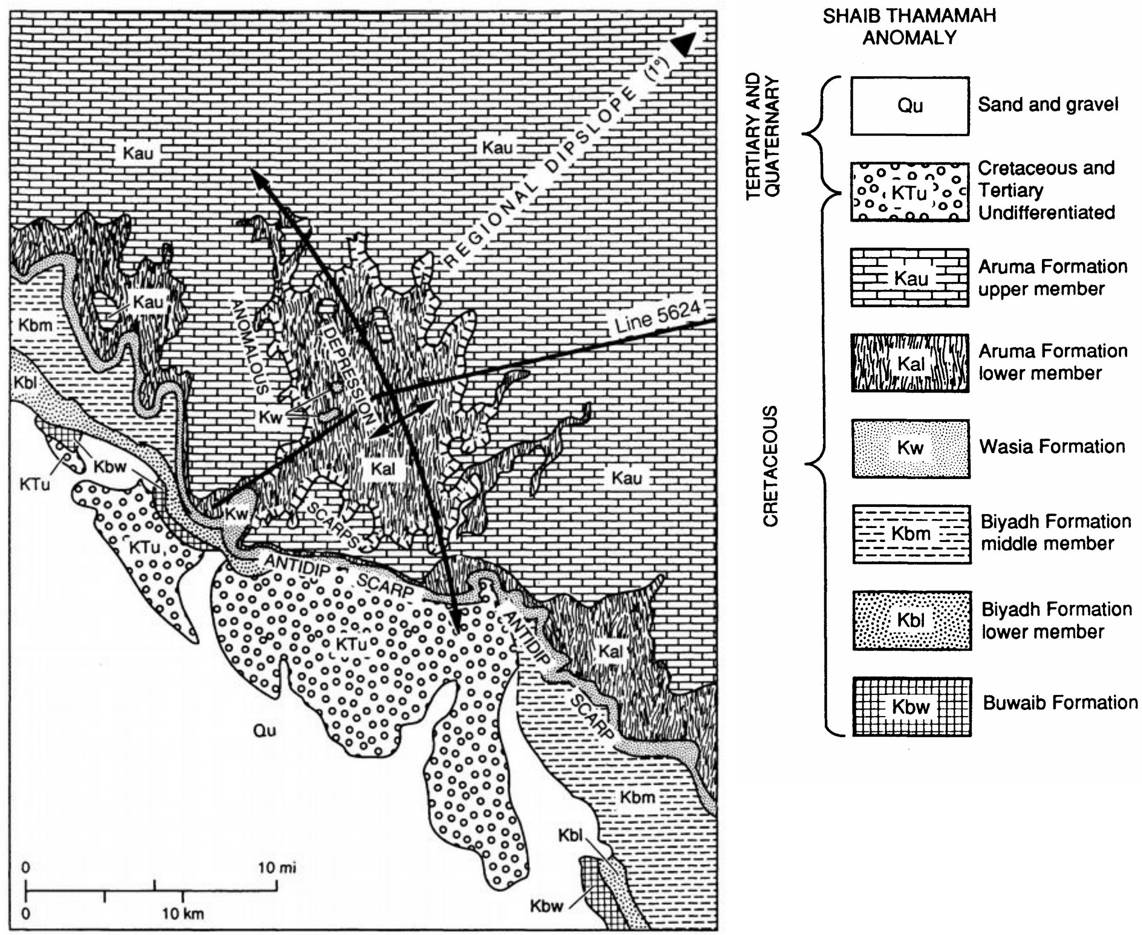


Figure 10-16 Geologic interpretation map of the Shaib Thamamah Landsat anomaly (Plate 20C). The location of the anomaly is shown in Figure 10-14. Symbols are explained in Figure 10-17. From Wender and Sabins (1991, Figure 4).

Closed depression erodes Arum Formation upper member (Kau), exposing lower member (Kal).

In two small areas next lower layer Wasia sandstone (Kw) is exposed.

<u>This is an anticline</u> – just so gentle you can’t easily see dips in the field

Shaib Thamamah Anomaly Seismic profile

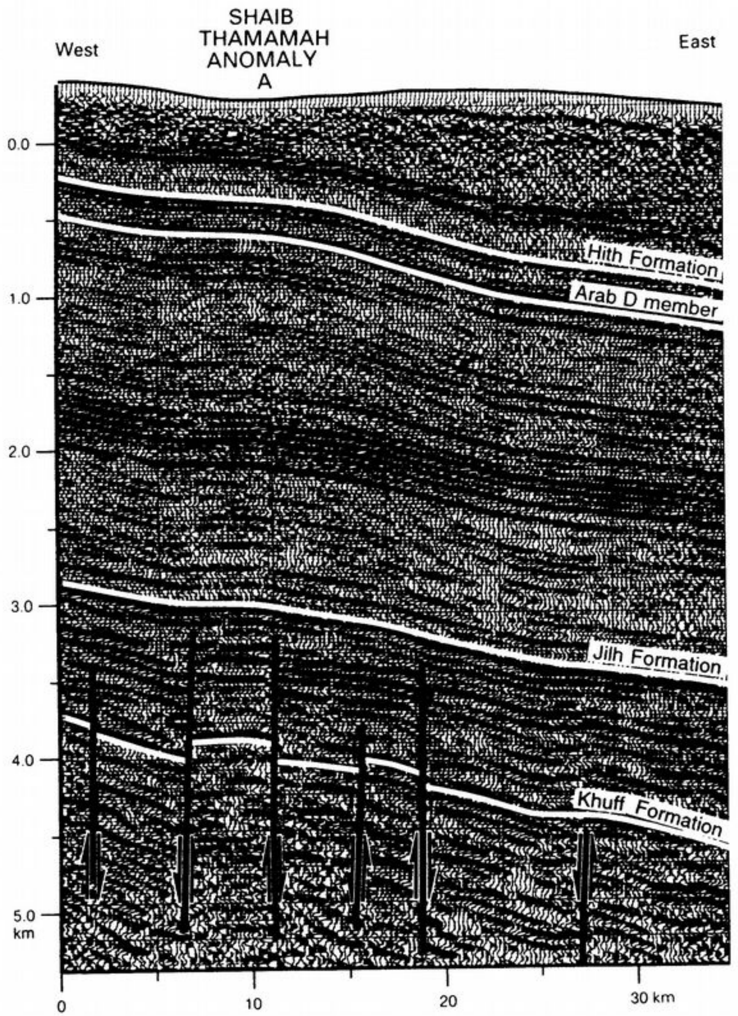


Figure 10-19 Seismic section 5624 across the Shaib Thamamah anomaly (Plate 20D). The location of the section is shown in Figure 10-16.

Sabins, 1997

Seismic profile shows vertical faults at ~4km depth in Permian Khuff Formation, which control dip of overlying draped formations

Raghib Anomaly

D. TM 2-4-7 image, Raghib oil discovery, Saudi Arabia.

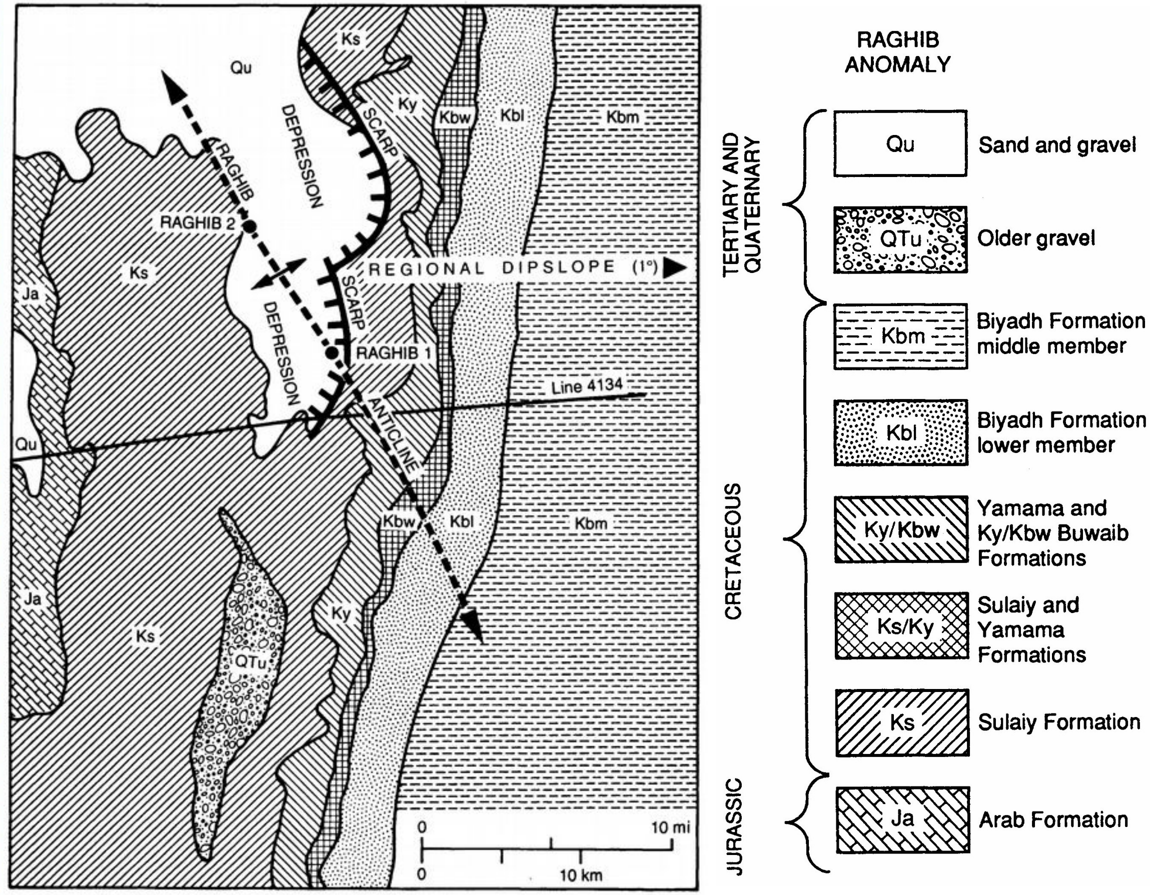


Figure 10-20 Geologic interpretation map of the Raghib Landsat anomaly (Plate 20D). Raghib 1 and 2 are the discovery well and confirmation well for the Raghib oil field. Symbols are explained in Figure 10-17. Location of Raghib anomaly is shown in Figure 10-14. From Wender and Sabins (1991, Figure 7).

Sabins, 1995

Geology at Raghib more complicated because of irregular solution and collapse of limestone units, and cover by windblown sand.

Nevertheless – do see broad pattern of “enclosed” depression in Sulaiy Formation (Ks)

Raghib Anomaly: Seismic structure map

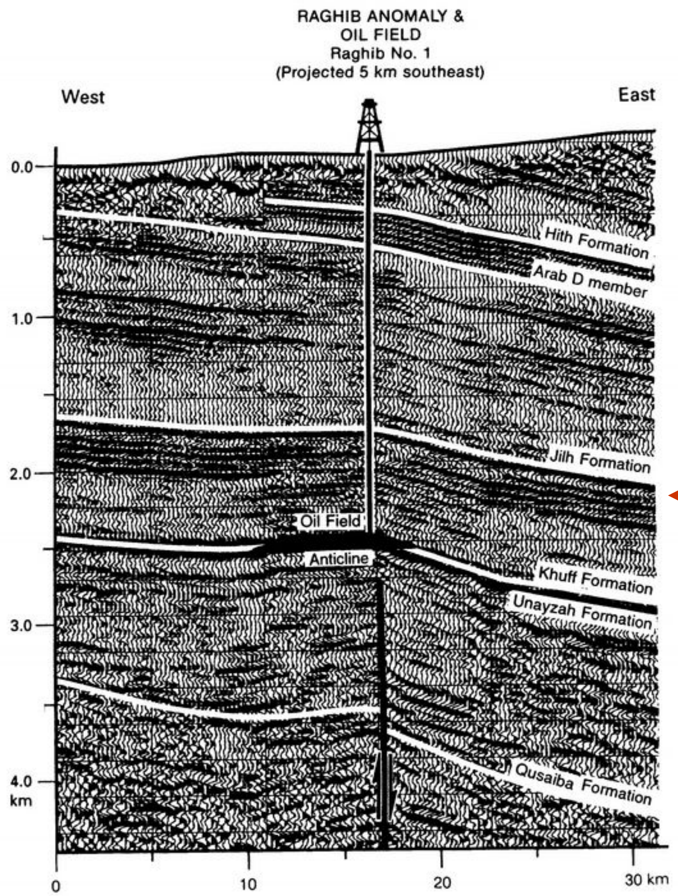


Figure 10-22 Seismic section 4134 across the Raghib oil field. The location of the line is shown in Figures 10-20 and 10-21. Sandstone of the Unayzah Formation (Pennsylvanian and Permian) is the reservoir for the field. Organic-rich shale of the Qusaiba Formation (Silurian) is the source of the oil.

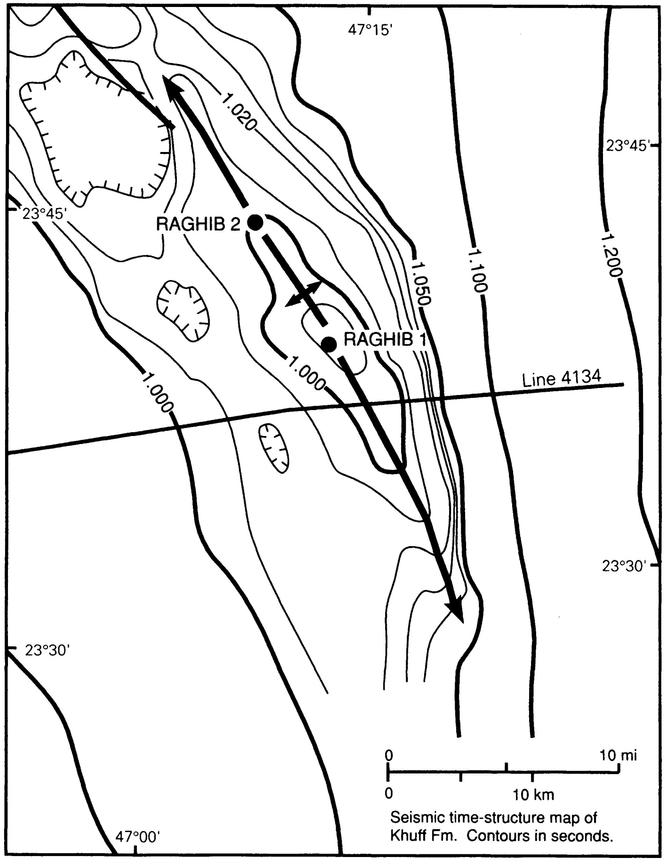


Figure 10-21 Seismic structure map of the Raghib oil field. The area coincides with the Landsat image (Plate 20D) and the geologic map (Figure 10-20). Contours are drawn on top of Khuff Limestone (Permian). From Wender and Sabins (1991, Figure 8)

Sabins, 1995

Seismic structure map – contours at top of Khuff Formation, do clearly show anticline

Oil now produced from this area:

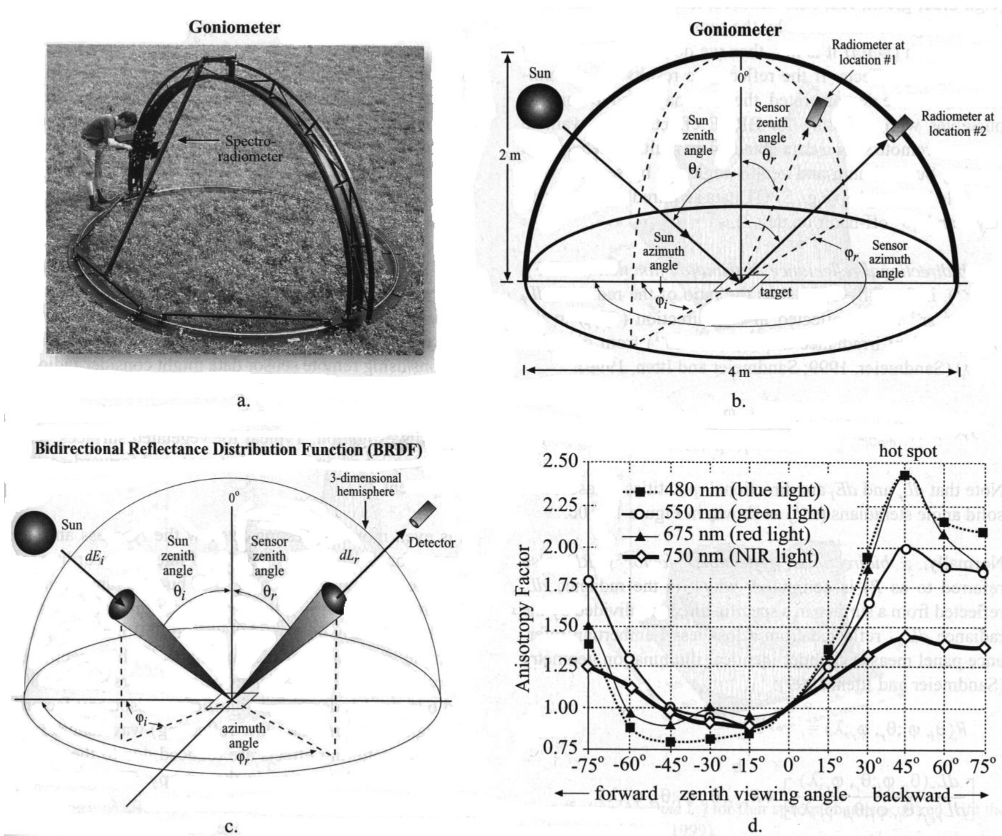
Unayzah Formation sandstone is reservoir, organic shale of the Qusaiba Formation is the source

Summary

- Landsat and similar remote sensing observations useful for
  - Locating sedimentary basins in unmapped regions
  - Detecting structural anomalies indicative of anticlines
  - Providing terrain classification maps useful for planning logistics

- Direct detection:
  - Oil and gas seeps can alter (reduce) surface rocks in detectable ways
    - At Cement and Velma oil fields in southern Oklahoma red sandstone outcrops are changed to gray by reduction of oxidized Fe
    - Carbon in hydrocarbons can be oxidized and incorporated into secondary carbonate minerals.
  - Hydrocarbons can affect surface vegetation in detectable ways

Angular Effects – Both for vegetation and geology



Field Goniometer

Solar zenith angle = 35°

Jenson Figure 11-10

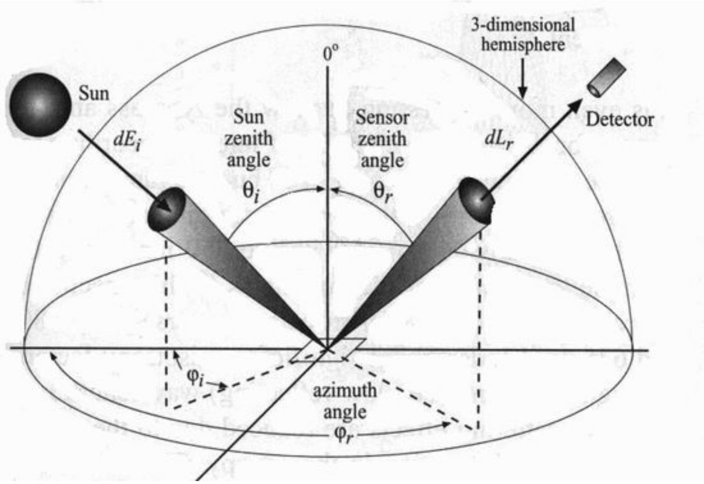
- Reflectance can change with angle of incoming and outgoing light
- Bidirectional Reflectance Distribution Function (BRDF)
- Tends to have peaks for backscatter and specular reflection

3 Essential Angles Involved:

- Incidence angle θ_i below
- Emission angle θ_r below
- Phase angle α Angle measured directly between incoming and outgoing beam

$\alpha = 0$ Backscatter: Sun is "behind" viewer

$\alpha = 180$ Forward scatter: Sun is almost in your eyes



Univ. of Bern PHIRE Goniometer

Angular Effects – Wavelength dependent

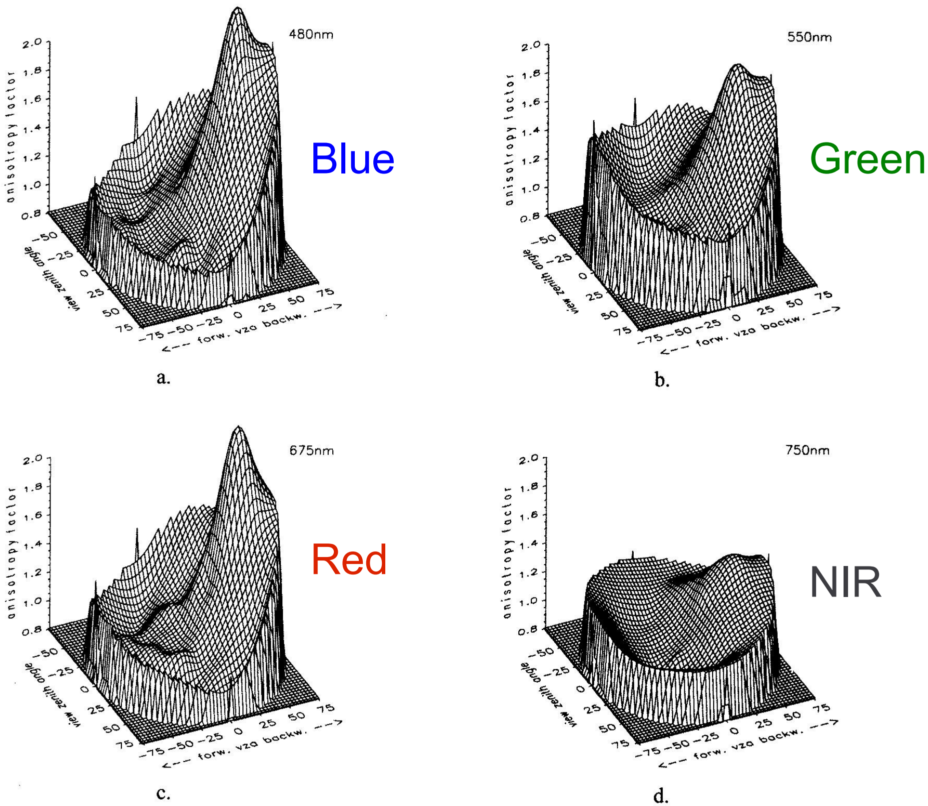


Figure 11-11 Anisotropy factors (nadir-normalized BRDF data) of ryegrass (*Lolium perenne L.*) for four spectral bands acquired with the FIGOS instrument with a Sun zenith angle of 35° (after Sandmeier and Itten, 1999).

Measured BRDF

Ryegrass

Solar zenith angle = 35°

Jenson Figure 11-11

- At wavelengths where leaves are dark:
  - mostly get reflectance from first surface – highly directional
- At wavelengths where leaves are reflective and transmitting
  - get multiple scattering and almost uniform ("Lambertian") reflectance
- <u>Spectrum will be different for different viewing geometries</u>

Hapke Scattering Theory (1)

- Previous mixing models were "linear"
  - $R_{avg} = f_1 \times R_1 + f_2 \times R_2$ where
    fraction f_1 of surface has reflectance R_1
    fraction f_2 of surface has reflectance R_2
    and $f_1 + f_2 = 1$
  - Get linear mixing with "areal" or "checkerboard" or "macroscopic" mixing
    - Regions of type 1 and type 2 material are large enough photons only see one or the other – can't bounce between both.
- Microscopic or "intimate" mixing in "non-linear"
  - Darker material dominates at each wavelength
- <u>Need much more detailed knowledge of mix to model this</u>

Hapke Scattering Theory (2)

- Need much more detailed knowledge of mix to model this
  - Size of individual grains
  - Albedo of individual grains
  - Way they scatter light (forward, backward, isotropic?)

- To have enough information to model microscopic mixing, need either:
  - "Laboratory" data about grains (sizes, shapes, individual spectra) or
  - Observations at many incidence and emission angles

- Hapke theory approximates how photons scatter between different grains.
  - Lets you model intimate mixtures and predict "bidirectional reflectance" spectra
  - Besides getting composition of grains, can get sizes, shapes, how densely packed they are

Hapke Scattering Theory (3)

- Break scattered light up into two parts:
  - Singly Scattered light
    - Angular Scattering function from individual grains controls "non-isotropic" scattering from surface
  - Multiply scattered light
    - Simplified by assuming that light scattered more than once loses memory of which direction it comes from, so can treat individual scatterings as isotropic.
    - Can still get overall angular dependence from: Shadow Hiding and Coherent Backscatter
  - Overall Bidirectional Reflectance Distribution Function controlled primarily by
    - Single particle scattering function
    - Albedo(s) for single scattering
    - Weighted particle abundances
    - Packing density
    - Surface Roughness