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.
• 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
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

- 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

- 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.
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° 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

- 2\textsuperscript{nd} phase of project (once regional geology defined) is to search for structural anomalies which could produce petroleum traps

\textbf{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).
Assume similar subsurface structure as in Retained Areas

- 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

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**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.
Closed depression erodes Arum Formation upper member (Kau), exposing lower member (Kal). In two small areas next lower layer Wasia sandstone (Kw) is exposed. This is an anticline – just so gentle you can’t easily see dips in the field.
Seismic profile shows vertical faults at ~4km depth in Permian Khuff Formation, which control dip of overlying draped formations.

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

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 $\theta_i$ below
- Emission angle $\theta_r$ below
- Phase angle $\alpha$ 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
Angular Effects – Wavelength dependent

- 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
- Spectrum will be different for different viewing geometries

Measured BRDF
Ryegrass
Solar zenith angle = 35°

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 Ilten, 1999).
Hapke Scattering Theory (1)

• Previous mixing models were “linear”
  – \( R_{\text{avg}} = f_1 \times R_1 + f_2 \times R_2 \) 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
• Need much more detailed knowledge of mix to model this
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