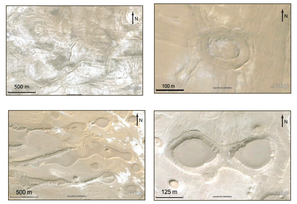
Polygonal Patterns and Desert Eyes: Reconnaissance Study of Fold and Fault Structures in Late Cretaceous and Early Tertiary Limestones of the Western Desert, Egypt

Barbara Tewksbury[1], Simon Kattenhorn[2], Elhamy Tarabees[3], John Hogan[4], Carolyn Tewksbury-Christle[5] & David Saint-Jacques[6]

[1]Hamilton College, [2]University of Idaho, [3]Damanhour University, [4]Missouri University of Science and Technology, [5]United States Air Force, & [6]Canadian Space Agency

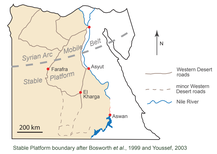
The problem

High resolution satellite images of the Western Desert of Egypt reveal a wide variety of previously unstudied polygonal, linear, and circular features.



They are bedrock structures, not surficial features (Tewksbury *et al.*, 2009, 2011, and in press), and are exposed over literally tens of thousands of square kilometers in Late Cretaceous and Early Tertiary carbonate bedrock.

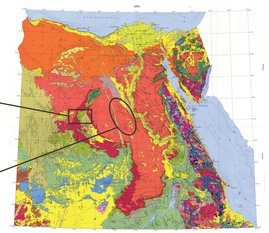
- These structures occur in rocks of the Stable Platform of Egypt, the stratigraphy of which has been well-studied (*e.g.,* Said, 1990; Hermina, 1990; Issawi, 1999).
- By contrast, structures in the Stable Platform have received less attention, and the published literature in the central Western Desert focuses on regional structure (*e.g.*, Barakat and Hamid, 1974; El Eraqi et al., 1999; , Youssef, 2003).
- As far as we have been able to determine, the small-scale structures that are the subject of our research have been previously unrecognized and unstudied.



Stable Platform boundary after Bosworth et al., 1999 and Youssef, 2003

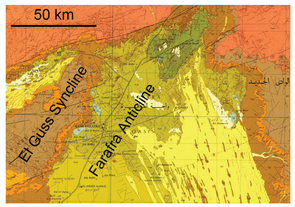
This poster presents on-going work on the nature, origin, and timing of development of structures in two areas:

- Polygonal ridge networks and eyes in the latest Cretaceous Khoman Chalk exposed in the core of the broad regional Farafra anticline (box at right and map below right).
- "Bubble wrap" structures in Paleocene carbonates of the Thebes Group, Minia Formation, and Mokattam Group exposed in the flat desert plains mostly west of the Nile (oval at right).

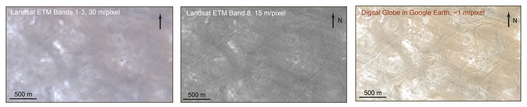


A portion of the Geological Map of Egypt (Egyptian Geological Survey and Mining Authority, 1981)

- The map at right shows the outcrop area of the Khoman Chalk in medium olive green.
- Younger units are shown in browns, orange, and pale red.
- Units lying beneath the Khoman are shown in dark green.
- The regional Farafra anticline is broad and gentle with limb dips of only a few degrees.

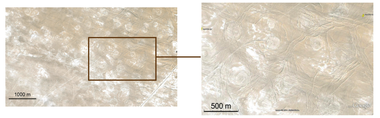


Why previously unrecognized

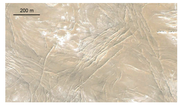


- One reason that these structures have remained essentially invisible until now is that they are too small to have been identified and studied in the satellite imagery that was freely available until very recently (above).
- The low relief of the terrain where these structures are exposed over huge areas (foreground and middle distance in the panorama below) also conspires against seeing them, because the structures are big enough (500-1000 m across) to make it difficult to see them from ground level.

Polygonal ridge networks

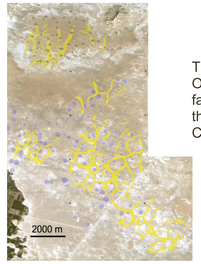


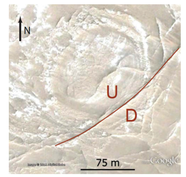
- High resolution satellite images of the Khoman Chalk near Farafra Oasis show thousands of ridges that occur in clusters outlining polygonal areas that contain fewer ridges (above). Yellow at right shows network of bands with more than 5 ridges/100 m.
- Ridge clusters form a network of polygons each 500-1000 m across.



In the satellite images, the ridges appear to be significant features with substantial shadows (left & right). In reality, the ridges are very low (above) and are visible in the imagery only because prevailing NW winds have concentrated dark lag on the upwind (NW) sides and light-colored sand and chalk on the down wind (SE) sides.

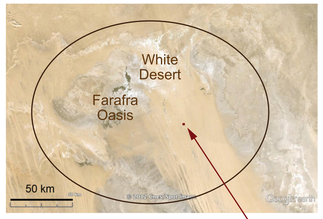
- The ridges mark the locations of faults. Calcite veins and iron sulfide veins (probably originally marcasite but now largely iron oxides) along the faults are more resistant than the surrounding chalk.
- Chalk and calcite veins are strongly grooved (rakes 75-90°); calcite veins appear to be multiphase.



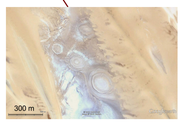


- Fault dip directions + rakes of slip indicators + offsets of dipping layers indicate normal slip.
- Dips of offset layers are shallow.
- Normal fault throw is small.

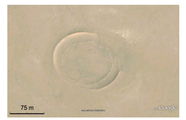
The White Desert of the Farafra Oasis region is best known for fantastic erosional landforms in the white chalks of the Late Cretaceous Khoman Formation.

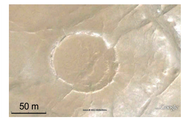


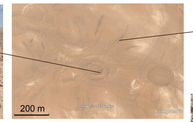
Google Earth has made this work possible. I combed an area ~150 x 250 km (nearly 40,000 km^2) to find features such as those at right (note scale!). High resolution commercial imagery for the area at $25/ km^2 would have cost about $1 million.

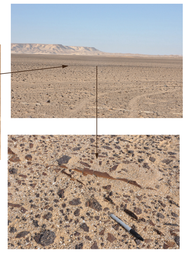


Low relief eyes and eye-shaped mesas

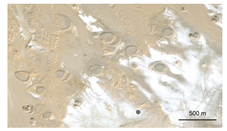


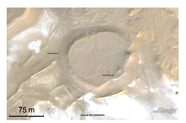




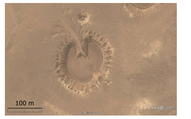


- The upper layers of the Khoman Chalk display hundreds of very low-relief, nearly circular structures ranging from 100-200 m in diameter.
- Dips in the eyes are shallow and inward (*i.e.*, they are quasi-circular basins) but there is no evidence for companion domes.
- Some are faulted, and some have rays (above).
- Eyes & rays are almost impossible to see from the ground (above left and top right).
- The rays are dark weathered lag from tiny iron veins.

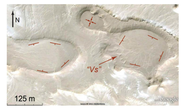




- The uppermost layers of the Khoman Chalk and the lowermost layers of the overlying Dakhla are dotted with many hundreds of eye-shaped mesas ~10 m high and 100-200 m diam.
- The underlying country rock contains scattered faults with multi-phase calcite veins; some faults extend upwards into mesa units.

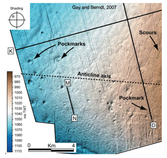


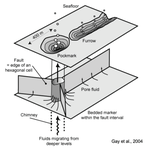
- The mesas are capped by inward-dipping layers (right), making them basin structures; there are no companion domes.
- Some of the mesas have "necklaces" (above).

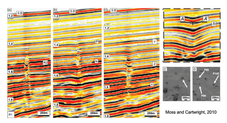


Shallow inward dip of the layering in the mesas.

Working hypothesis: eyes are fluid escape structures overlying polygonal faults

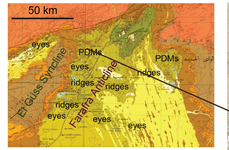


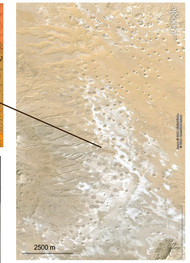




- Polygonal fault systems in the modern world are commonly overlain by "pockmarks" on the seafloor (left above), depressions typically a few 100 m across.
- Seismic lines show concave up reflectors in a sequence of otherwise flat reflectors with a negative relief of 10s of meters. These have been interpreted as fluid escape pipes and the subsurface expression of pockmarks.
- Pockmarks and furrows created by fluid escape are later draped with sediment, creating inward dipping layers.

- In the Farafra region, the eye-shaped mesas (PDMs at right) and low-relief eyes lie stratigraphically above the polygonal ridge terrain (map at right).
- Ridges occur associated with the eye-shaped mesas, and the layers in the narrow ridges (far right) also dip inward.

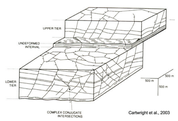




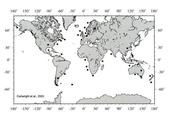
Are the eyes and eye-shaped mesas fluid escape features in the upper Khoman and lower Dakhla overlying a set of polygonal faults in the lower and middle Khoman?

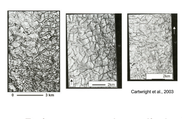
- Do the "rays" represent hydrofracs around a pipe?
- Were methane-rich fluids involved?
  - Spectacular "morning star" mineral forms occur in the chalks; originally marcasite, now goethite.
  - Were these originally methane-related glendonites??

Working hypothesis: the ridge network in the Khoman Chalk is a polygonal fault system



Cartwright et al., 2003





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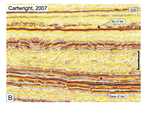

- Polygonal faults are an array of extensional faults with diverse strikes, partially or fully intersecting in a polygonal pattern.
- Polygonal faults are layer-bound.
- They occur exclusively in fine-grained seds (muds, chalk) and form early during consolidation.
- They are genetically related to sediment contraction and associated with multiple fluid expulsion events.

- They occur in >31 sedimentary basins worldwide; virtually all are submarine.
- Virtually all data about them are oil industry 2D & 3D seismic data.

- Polygons are broadly in the 1 km range.
- Throws are typically a few meters to a few 10s of meters.
- Calculated strain in North Sea polygonal faults is ~10% and uniform radially.
- There is no net layer extension; heave is compensated for by horizontal bed contraction.

Not only do the fault systems in the Khoman Chalk have the features of typical polygonal faults but seismic data courtesy of Khalda Petroleum (right) clearly show polygonal faults in the subsurface in much younger (Eocene) rocks of the Unstable Platform in Egypt about 300 km north of Farafra.

Summary of observations to date

- The polygonal ridge network in the Khoman Chalk consists of clusters of normal faults.
- Preliminary geophysical and image data suggest that faults are confined to the Khoman Chalk.
- The polygons are not formed by intersection of multiple regional sets of faults of different ages; rather, multiple fault orientations were active simultaneously and mechanically interacting.
- The horizontal strain field appears to have been essentially isotropic.
- Multiple (high P_f?) fluid events resulted in calcite veins along faults.

The bubble wrap terrain

Previous work on polygonal faults, pockmarks, and fluid escape structures in the modern marine basins of the world described at left and above left come from a number of sources, including Cartwright et al., 2003; Cartwright, 2007; Davies, 2005; Davies and Ireland, 2011; Gay and Berndt, 2007; Gay et al., 2004; Hansen et al., 2004; Hibsch, 2003; Hustoft et al., 2010; and Moss and Cartwright, 2010.

- In the North Sea, broad hummocks a few 100 m to a km across overlie a polygonal fault system.
- The hummocks are domes in the layers; the troughs are a network of synclines.
- The troughs/synclines directly overlie faults of the polygonal network.
- Davies (2005): silica diagenesis and volume decrease over polygonal faults created the network of synclines – rise of warm fluids on faults?

- West of the Nile (oval at right), Eocene carbonates have previously unrecognized broad, low-amplitude domes a few 100 m to a km across with networks of narrow synclines between (above left). This "bubble wrap" geometry is similar to North Sea hummocks, and the scale is similar as well. Are there polygonal faults beneath the bubble wrap?
- Furthermore, the polygonal faults at Farafra are same scale as the bubble wrap (above right).

One of the main reasons for the extraordinary exposure of the features at Farafra is that the topographic surface is essentially a bedding plane surface in the Khoman Chalk. Very low limb dips on the regional Farafra Anticline, coupled with essentially no topographic relief, also means that slightly younger rocks than those hosting the polygonal faults are exposed over great distances on both flanks of the Anticline.

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