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

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DESERT EYES عيون الصحراء

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Abstract

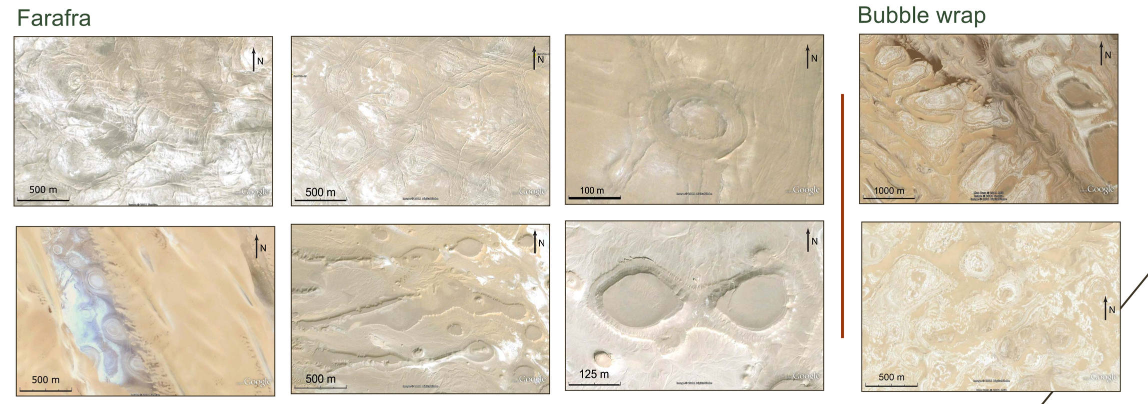
High resolution satellite imagery reveals previously unstudied structures in Cretaceous chalk of the Khoman Formation where it is exposed in the broad regional Farafra anticline. The oldest units of the Khoman chalk display a complex network of low, narrow (1-2 m) ridges that outline roughly polygonal areas 500-1000 m across. Offsets of bedding indicate that these are fault structures, and their positive relief suggests the presence of either deformation bands or mineralization. These polygonal networks occur in continuous surface exposure over an area of about 700 km^2 and extend over at least 2500 km^2 partly mantled by aeolian sand. Overlying this fault network across the entire Farafra region is a terrain of isolated, nearly circular basins. The basins range from ~50-200 m in diameter and have layering with very shallow inward dips and very little topographic relief. In the oldest rocks of this terrain, the polygonal ridge network cuts and locally offsets the basins, and basins are spatially associated with the ridge networks. Ridges are rare in the upper portions of this terrain. The top part of the Khoman Formation displays basins of similar size, but here the basins stand in relief, forming a polka-dot network of weakly aligned, eye-shaped mesas locally associated with narrow ridges aligned approximately EW. Curiously, the immediately overlying Paleocene Tarawan Formation has low amplitude dome structures of similar size.

About 120 km to the east, Eocene carbonates display thousands of low-amplitude domes up to 1000 m across separated from one another by a polygonal network of narrow interconnected synclines, forming structures with the geometry of bubble wrap. In the north and west parts of this terrain, structural trends are weak and faults are rare. In the south and east portions, a NNW-SSE structural alignment of narrow synclines dominates, and NNW-SSE faults are common.

The structures near Farafra Oasis bear a striking resemblance in both scale and geometry to polygonal fault systems and fluid escape structures reported from young marine sediment sequences in the North Sea, Lower Congo Basin, and offshore Namibia. Structures in the Eocene carbonates are strikingly similar in both scale and geometry to broad hummocks and narrow synclines in sediments above polygonal fault networks in the North Sea and elsewhere.

Farafra

Bubble wrap

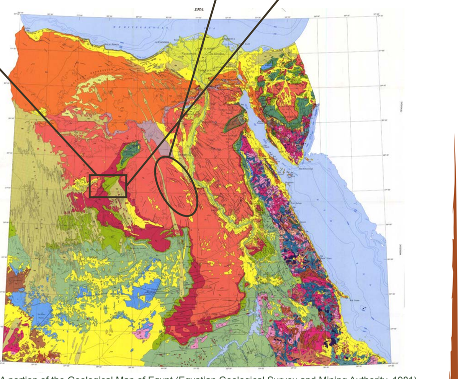


Introduction

High resolution satellite images (examples above) of the Western Desert of Egypt reveal a wide variety of previously unstudied polygonal, linear, and circular features. These features are bedrock structures not surficial features (Tewksbury *et al.*, 2009 and Tewksbury *et al.*, in press). These structures range in scale from about 100 m to 1000 m and are exposed over literally tens of thousands of square kilometers in Late Cretaceous and Early Tertiary carbonate bedrock.

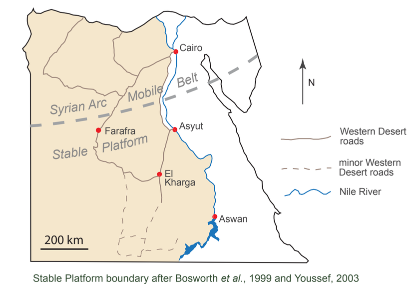
This poster presents reconnaissance results of work on structures in two areas:

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



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

This study



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

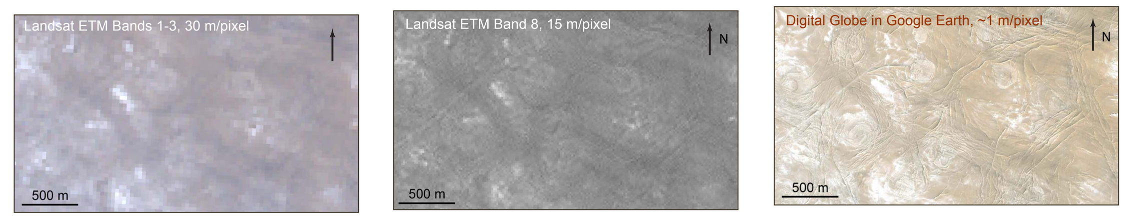
- Our area of study in the Western Desert lies in what has been termed the Stable Platform of Egypt. The Cretaceous and Tertiary stratigraphic section of the Stable Platform has been well-studied (*e.g.*, Said, 1990; Hermina, 1990; Issawi, 1999).
- Structures in the Syrian Arc Mobile Belt have received considerable attention by previous workers and by the oil industry (*e.g.*, Bosworth *et al.*, 1999; Guiraud *et al.*, 2001; Youssef, 2003).
- 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 are able to determine, the small-scale structures that are the subject of our research have been previously unrecognized and unstudied. We are currently doing reconnaissance mapping on satellite imagery in Google Earth and plan to study these structures in the field in December, 2011 and January, 2012.**

Our work in Egypt aims to address the following questions

- What are the characteristics and geometries of these small scale bedrock structures? In what ways do these structures vary with host rock type and age?
- How and when did these structures form? Are they "tectonic" structures, or are they features that formed penecontemporaneously with sediment deposition
- Why is the overall scale and geometry of the bubble wrap terrain strikingly similar to that of the polygonal ridge terrain at Farafra, despite the fact that the structures themselves are different ?
- What role did reactivation of long-lived basement faults play in the location, formation, and subsequent modification of these structures?

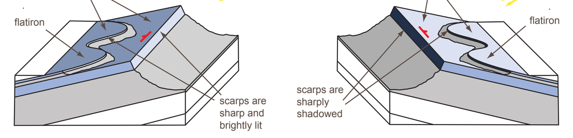
Data sources and methodology

Freely available, high resolution imagery in Google Earth has revolutionized our ability to find and study these structures.



The primary reason that the small-scale structures that are the subject of this study 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.

- Until recently, Landsat ETM imagery was the best resolution imagery that was freely available. Both in color, at 30 m/pixel (above left), and in the panchromatic band at 15 m/pixel (above middle), a small part of our study area at Farafra looks splotchy, but it is impossible to determine the nature of the splotchiness.
- A Google Earth Digital Globe image (above right, ~1 m/pixel) shows the polygonal ridge network at Farafra in startling clarity with enough detail that it can not only be recognized as a potentially interesting research problem but can also be studied in this imagery.
- High resolution Digital Globe imagery in Google Earth is captured by a sun-synchronous satellite that images this portion of Egypt at shortly before 10:30 am local time. Because this part of Egypt is north of the Tropic of Cancer, sun illumination direction in all of our imagery is from the SE.
- Although there is very little topographic relief in the areas we are mapping, we use the same techniques commonly employed to determine dip directions from topographic features, only on a much smaller scale. Minor erosion of slightly more resistant layers produces mini-flatirons, mini-scarps, and mini-hogbacks.

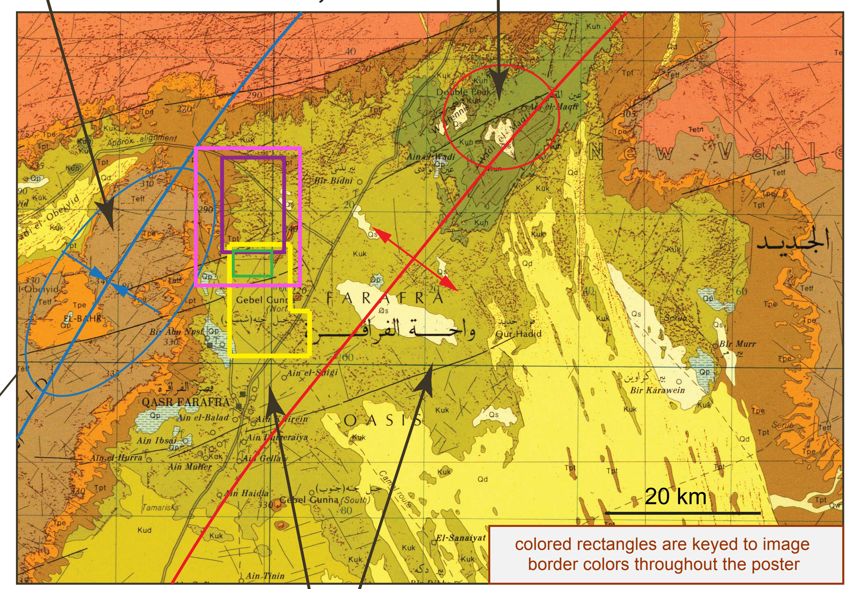


- Existing elevation data (SRTM DEM data at 90 m/pixel) are inadequate, however, for determining dip amounts for these small features.

Polygonal ridge networks and eyes in the Khoman Fm., Farafra Oasis

youngest rx in Farafra area (Tertiary Tarawan, Esna, and Farafra Formations) – overlie Khoman chalk; **no ridges or eyes**

oldest rx in Farafra area (Cretaceous Wadi Hennis and El Hefhuf Formations) – underlies Khoman chalk; **no ridges or eyes**



A portion of the 1:500,000 Geological Map of Egypt, Farafra Sheet (NG35NE) (Klitzsch et al., 1987); locations of Farafra Anticline and El-Guss Syncline based on Barakat and Hamid (1974).

Late Cretaceous Khoman Chalk

Near Farafra Oasis, Late Cretaceous massive neritic chalks and chalky limestones of the Khoman Formation (light olive green below left) contain **polygonal ridge networks and eye-shaped features**. Nearly continuous exposures allowed us to conduct reconnaissance mapping using high resolution satellite imagery in Google Earth.

We defined three terrain types for mapping on satellite imagery:

Polka dot mesa terrain (described in detail at **right**)

- The "eyes" in this terrain consist of approximately 150 small elliptical mesas each less than 200 m across and typically having a concave cap of resistant rock.

Terrain with low-relief eyes (described **below right**)

- The "eyes" in this terrain are the same size and shape as the eyes in the polka dot mesa terrain and have the same concavity in the centers, but the eyes do not stand above the level of the surrounding terrain as they do in the polka dot mesas.

Polygonal ridge terrain (described **below left**)

- This terrain consists of dense clusters of very low relief, slightly resistant ridges arranged in networks that define polygons containing few ridges in their interiors.

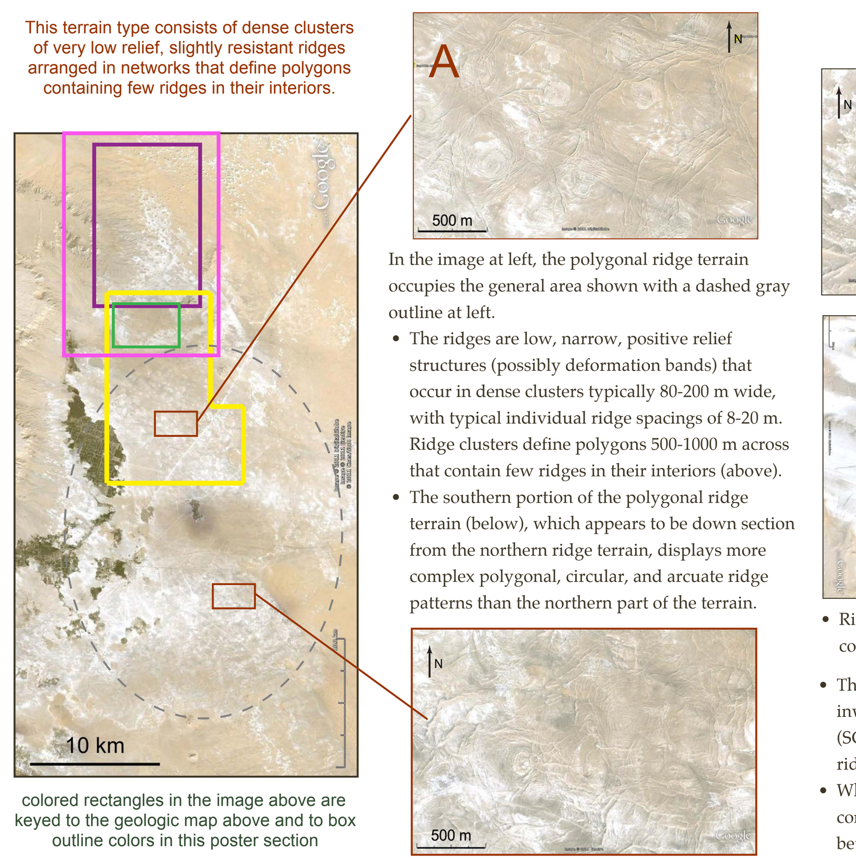
Overall distribution of the features:

The Khoman Formation is exposed in the eroded core of the broad NE-SW trending regional Farafra Anticline (left). The Khoman Formation is conformable with underlying Cretaceous layers. Overlying Paleocene layers lie unconformably on the Khoman.

- Polygonal ridge networks and eyes occur **only** in the Khoman Formation and do **not** occur in sandstones and shales of the underlying Wadi Hennis or El Hefhuf Formations (darker green) nor in overlying limestones and shales of the Early Tertiary Tarawan, Esna, and Farafra (Thebes) Formations (browns and orange).
- Virtually every exposed part of the Khoman Formation in the map area at left contains either polygonal ridge networks, low-relief eyes, or polka dot mesas. Fairly continuous exposure of these features covers an area of about 2000 km^2, but we have found polygonal ridge networks and low-relief eyes in interdune patches over an additional area of at least 5000 km^2.
- Tawadros (2001) indicates that the type section of the Khoman Formation at Ain Khoman southwest of Bahariya is at least 50 m thick.
- The extraordinary area over which these polygonal ridge networks and eyes are exposed in a fairly thin unit is a function of the very low relief of the area and the very low dips of the Khoman Formation on both flanks of the Farafra Anticline.

Polygonal ridge terrain type

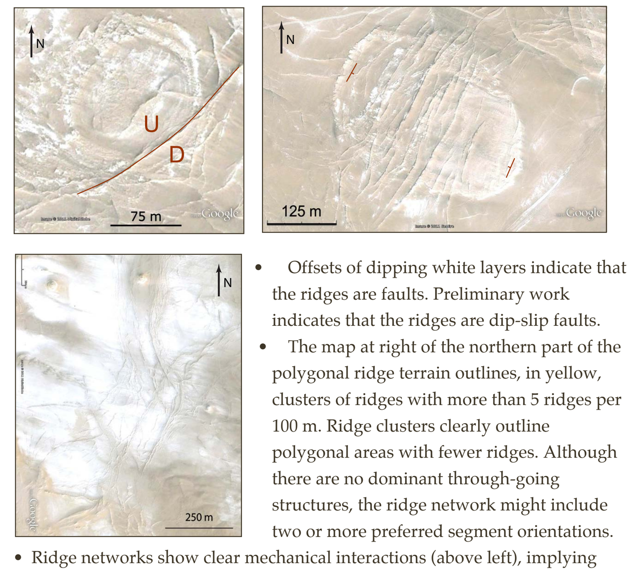
This terrain type consists of dense clusters of very low relief, slightly resistant ridges arranged in networks that define polygons containing few ridges in their interiors.



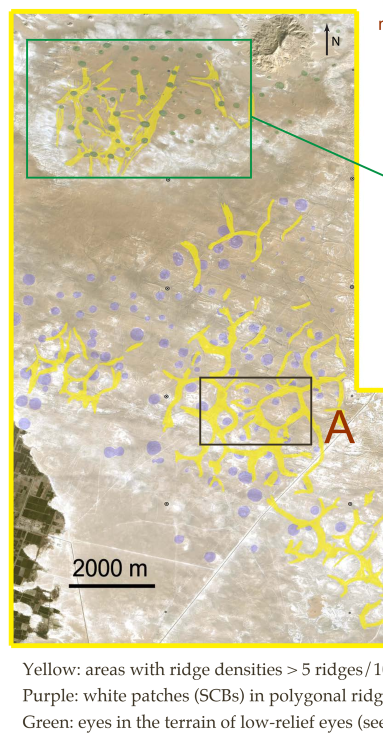
colored rectangles in the image above are keyed to the geologic map above and to box outline colors in this poster section

In the image at left, the polygonal ridge terrain occupies the general area shown with a dashed gray outline at left.

- The ridges are low, narrow, positive relief structures (possibly deformation bands) that occur in dense clusters typically 80-200 m wide, with typical individual ridge spacings of 8-20 m. Ridge clusters define polygons 500-1000 m across that contain few ridges in their interiors (above).
- The southern portion of the polygonal ridge terrain (below), which appears to be down section from the northern ridge terrain, displays more complex polygonal, circular, and arcuate ridge patterns than the northern part of the terrain.



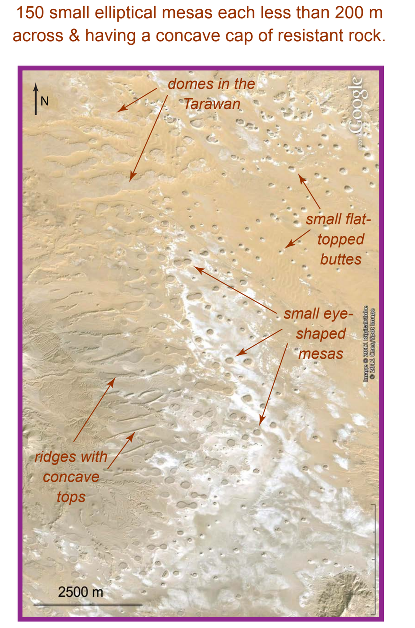
- Offsets of dipping white layers indicate that the ridges are faults. Preliminary work indicates that the ridges are dip-slip faults.
- The map at right of the northern part of the polygonal ridge terrain outlines, in yellow, clusters of ridges with more than 5 ridges per 100 m. Ridge clusters clearly outline polygonal areas with fewer ridges. Although there are no dominant through-going structures, the ridge network might include two or more preferred segment orientations.
- Ridge networks show clear mechanical interactions (above left), implying contemporaneous growth of ridge networks having different orientations.
- The polygonal ridge terrain contains quasi-circular white patches with inward dips. Based on crosscutting relationships, these small circular basins (SCBs) pre-date the ridges in this portion of the stratigraphy. This causes the ridge geometries to be affected in places by the edges of the SCBs.
- White SCBs are shaded purple at right. SCBs vary in size, polygons can contain more than one SCB, and there is no obvious spatial relationship between the white SCBs and the ridge network polygons.



Yellow: areas with ridge densities > 5 ridges/100 m
Purple: white patches (SCBs) in polygonal ridge terrain
Green: eyes in the terrain of low-relief eyes (see right)

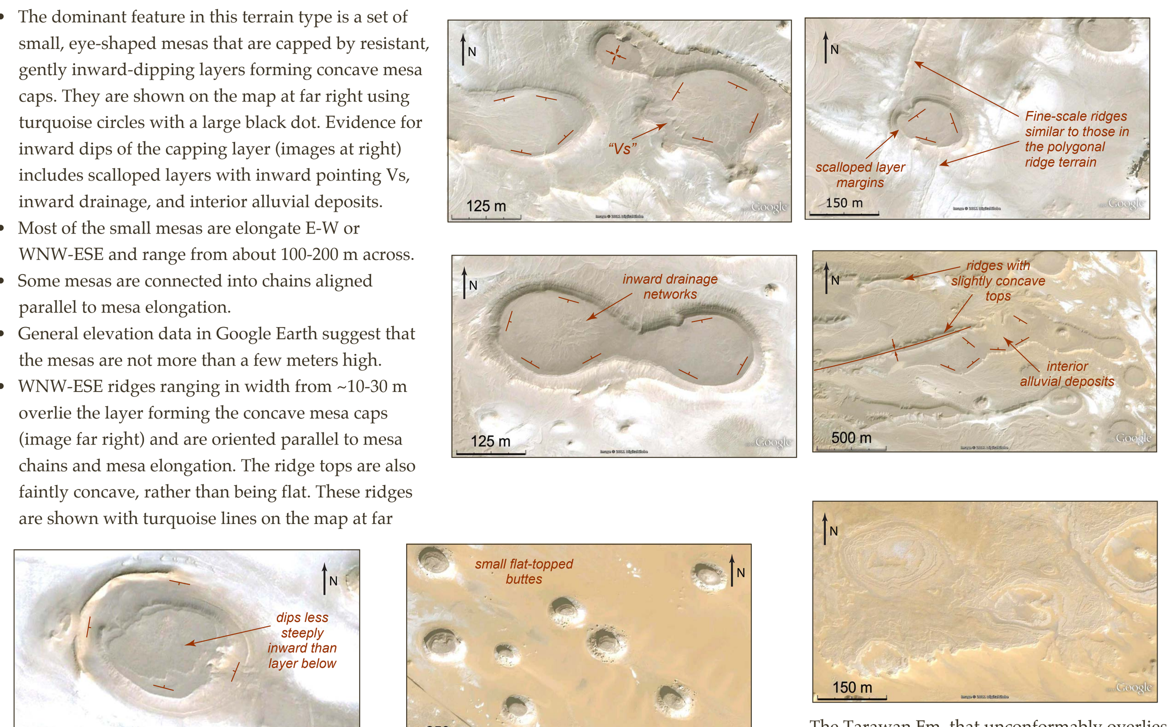
Polka dot mesa terrain type

The "eyes" in this terrain type consist of approximately 150 small elliptical mesas each less than 200 m across & having a concave cap of resistant rock.



The polka dot mesa terrain has its highest elevation in the west. The terrain is characterized in the west by narrow EW ridges and fingers, in the center by EW chains of small mesas 100-200 m in diameter and elongate ~EW, and, at the lowest elevations to the east, by small flat-topped buttes.

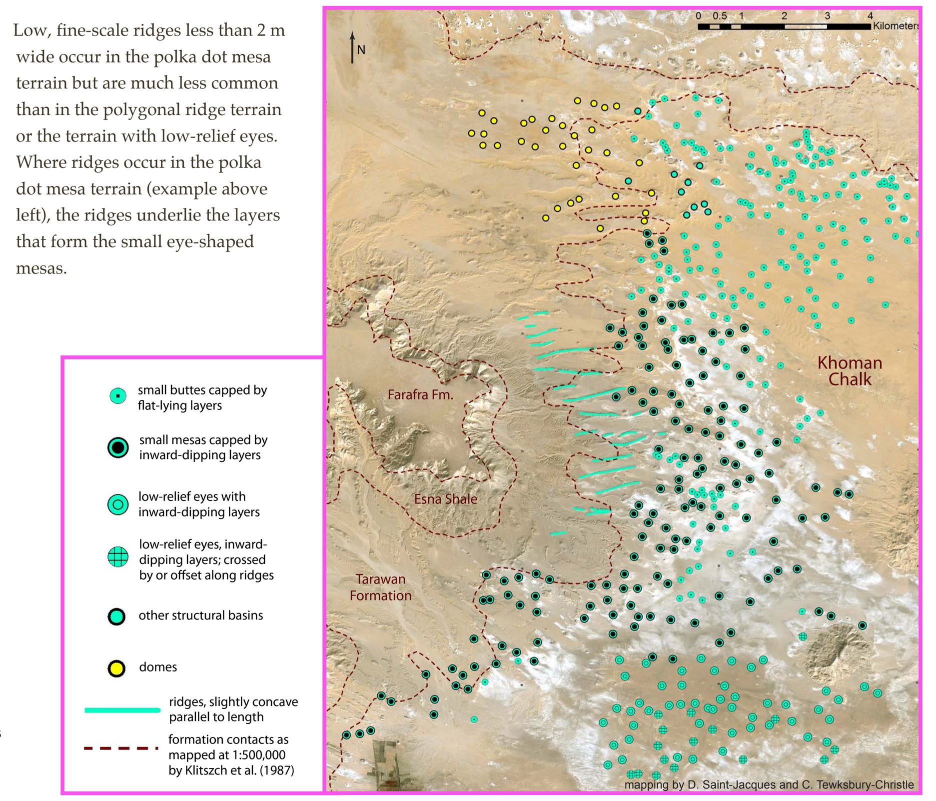
- The dominant feature in this terrain type is a set of small, eye-shaped mesas that are capped by resistant, gently inward-dipping layers forming concave mesa caps. They are shown on the map at far right using turquoise circles with a large black dot. Evidence for inward dips of the capping layer (images at right) includes scalloped layers with inward pointing Vs, inward drainage, and interior alluvial deposits.
- Most of the small mesas are elongate E-W or WNW-ESE and range from about 100-200 m across.
- Some mesas are connected into chains aligned parallel to mesa elongation.
- General elevation data in Google Earth suggest that the mesas are not more than a few meters high.
- WNW-ESE ridges ranging in width from ~10-30 m overlie the layer forming the concave mesa caps (image far right) and are oriented parallel to mesa chains and mesa elongation. The ridge tops are also faintly concave, rather than being flat. These ridges are shown with turquoise lines on the map at far right.



In some small mesas, older layers cropping out around the central cap appear to dip more steeply than the central younger layers (*e.g.*, above left). The small buttes (above right), which appear to have flat-lying caps, may capture this transition up-section from inward dips to flat-lying layers. The small buttes are shown on the map at far right as turquoise circles with a small central black dot.

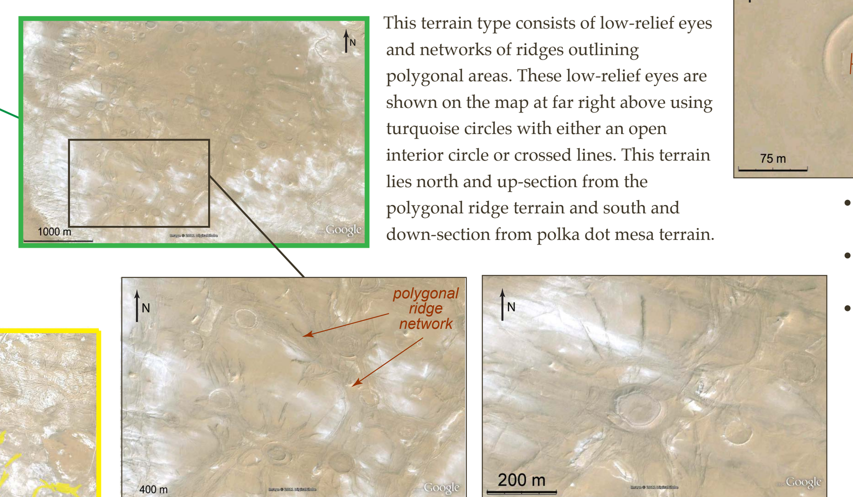
The Tarawan Fm. that unconformably overlies the Khoman to the north of the polka dot mesa terrain contains domes several hundred meters across and separated by narrow interconnected synclines.

Low, fine-scale ridges less than 2 m wide occur in the polka dot mesa terrain but are much less common than in the polygonal ridge terrain or the terrain with low-relief eyes. Where ridges occur in the polka dot mesa terrain (example above left), the ridges underlie the layers that form the small eye-shaped mesas.



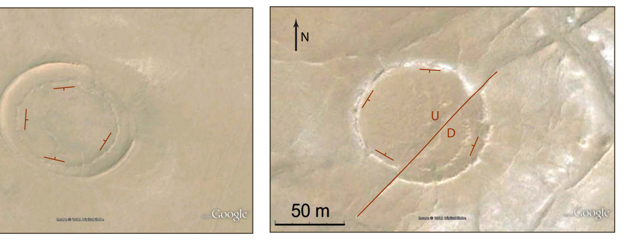
Terrain type with low-relief eyes

The "eyes" in this terrain type are the same size and shape as the eyes in the polka dot mesa terrain and have similar concavity in the centers, but the eyes do not stand above the level of the surrounding terrain as they do in the polka dot mesas.

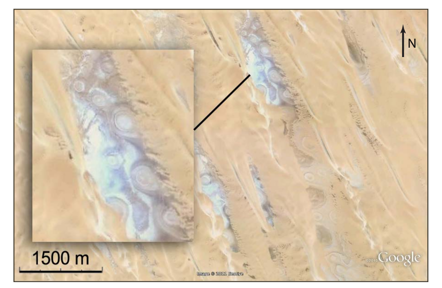


This terrain type consists of low-relief eyes and networks of ridges outlining polygonal areas. These low-relief eyes are shown on the map at far right above using turquoise circles with either an open interior circle or crossed lines. This terrain lies north and up-section from the polygonal ridge terrain and south and down-section from polka dot mesa terrain.

- Unlike the polka dot mesa terrain, this terrain type contains polygonal networks of ridge clusters. The map outlined in yellow at left and the image above left show that the polygonal ridge networks are similar in size to those in the polygonal ridge terrain.
- The low-relief eyes are spatially related to the ridge networks and occur both along arms and intersections in the polygonal ridge network.
- Radial ridges are common around the eyes and typically extend outward two or more eye diameters (above right).



- Eyes are 100-200 m across and defined by inward-dipping layers. Some eyes have a saucer-shaped resistant layer in the center.
- The ridges in this terrain clearly lie along faults that cut up through and offset layers in the eyes. Offsets are consistent with dip slip.
- As in the polka dot mesa terrain, the eye-shaped structures with inward dips in this terrain are not accompanied by adjacent structures with outward dips. As far as we can determine from the satellite imagery, layers in the country rock surrounding the eyes appear to be flat-lying.



Low relief eyes occur even in the narrow patches of Khoman Chalk exposed in the sand sheet southeast of Farafra, suggesting extensive development of this terrain beneath the sand.

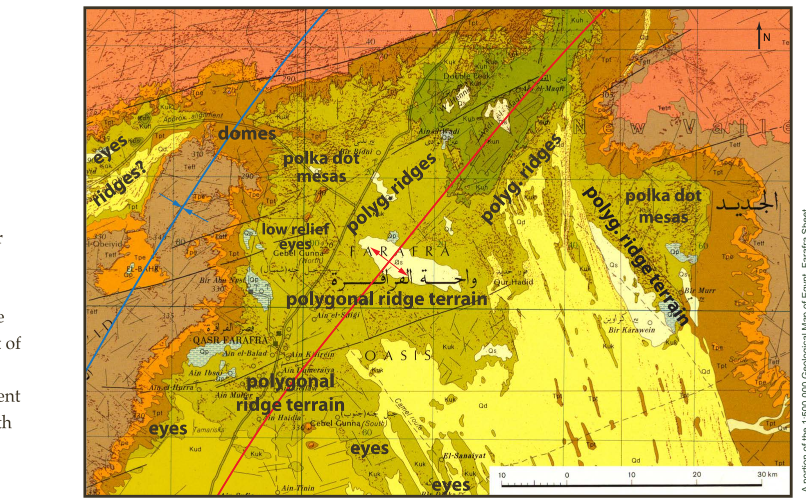
Summary of distribution of features

Map **above**, which shows *only* polka dot mesas and low relief eyes

- The southern part of the area shown above is characterized by low-relief eyes spatially associated with arms and intersections of polygonal ridge networks.
- The central part of the area, which is higher in the section, is dominated by small mesas and chains of mesas with caps of inward-dipping layers. Ridges are present but form only weak patterns.
- The youngest part of the Khoman Formation contains EW slightly concave ridges in the west and small, flat-topped buttes in the north.

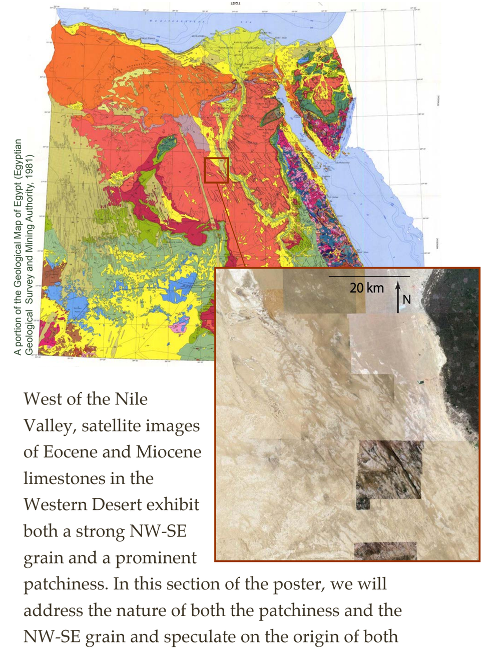
Map **below**, showing the distribution of all three terrain types across the region

- The polygonal ridge terrain occurs in the oldest part of the Khoman Formation in the core of the Farafra Anticline; the most complex part of the polygonal ridge terrain appears to be in the oldest part of the Khoman Formation.
- Polka dot mesas and low relief eyes occur in the Khoman Formation everywhere that we have looked between the polygonal ridge terrain and the overlying Tarawan Formation.



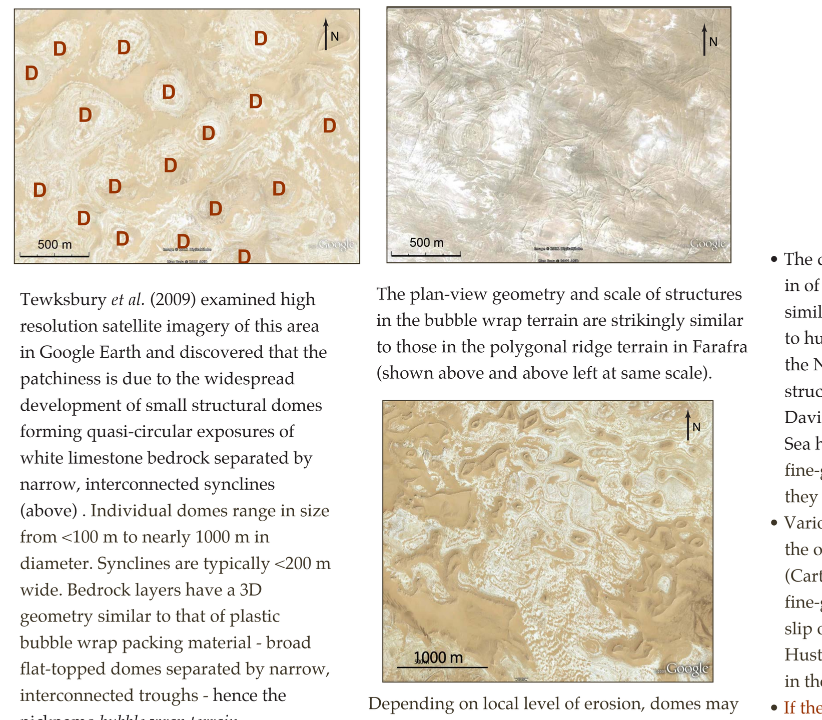
A portion of the 1:500,000 Geological Map of Egypt, Farafra Sheet (NG35NE) (Klitzsch et al., 1987); locations of Farafra Anticline and El-Guss Syncline based on Barakat and Hamid (1974).

The bubble wrap terrain



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

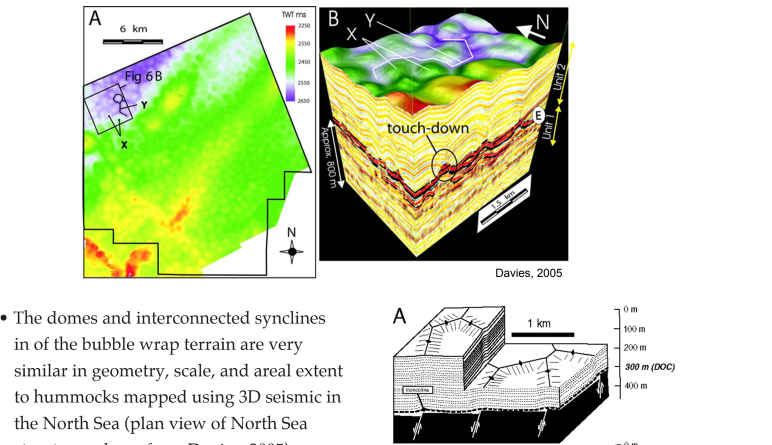
West of the Nile Valley, satellite images of Eocene and Miocene limestones in the Western Desert exhibit both a strong NW-SE grain and a prominent patchiness. In this section of the poster, we will address the nature of both the patchiness and the NW-SE grain and speculate on the origin of both patterns in the context of the possible existence of polygonal fault systems in carbonates of other ages in the Western Desert, as described in the main section of the poster.



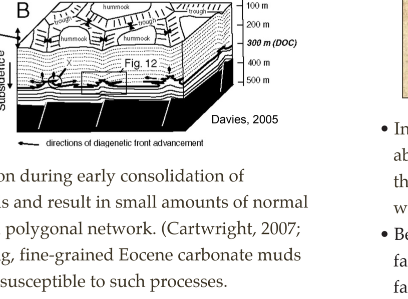
Tewksbury *et al.* (2009) examined high resolution satellite imagery of this area in Google Earth and discovered that the patchiness is due to the widespread development of small structural domes forming quasi-circular exposures of white limestone bedrock separated by narrow, interconnected synclines (above) . Individual domes range in size from <100 m to nearly 1000 m in diameter. Synclines are typically <200 m wide. Bedrock layers have a 3D geometry similar to that of plastic bubble wrap packing material - broad flat-topped domes separated by narrow, interconnected troughs - hence the nickname *bubble wrap terrain*.

The plan-view geometry and scale of structures in the bubble wrap terrain are strikingly similar to those in the polygonal ridge terrain in Farafra (shown above and above left at same scale).

Depending on local level of erosion, domes may be coalescing rather than isolated, with cuspate basins preserving keels of synclinal troughs.

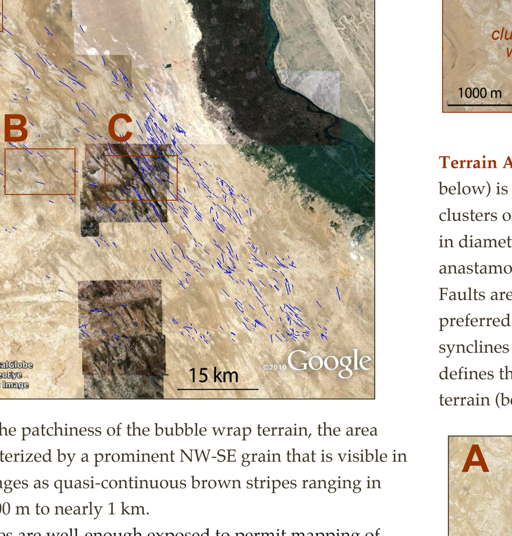


- The domes and interconnected synclines in of the bubble wrap terrain are very similar in geometry, scale, and areal extent to hummocks mapped using 3D seismic in the North Sea (plan view of North Sea structures above from Davies, 2005). Davies provides evidence that the North Sea hummocks occur in young fine-grained marine sediments and that they overlie a polygonal fault network.

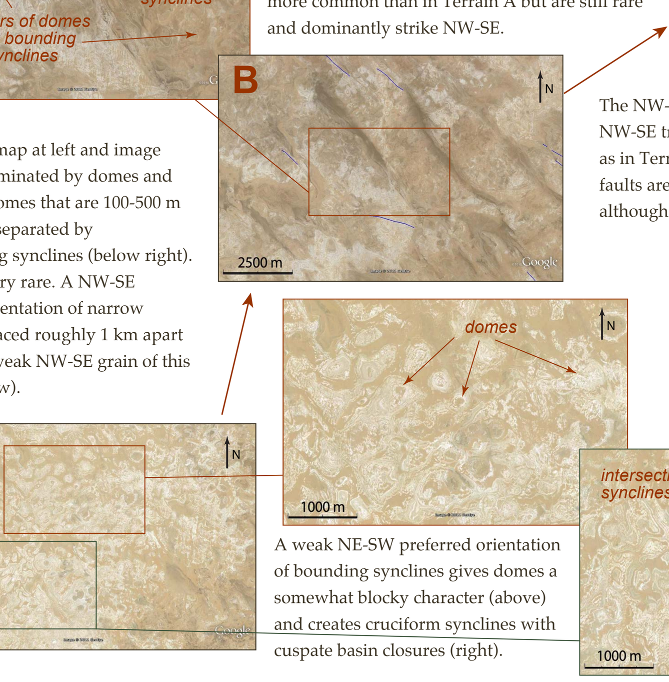


- Various models have been proposed for the origin of polygonal fault networks (Cartwright *et al.*, 2003), and all call for formation during early consolidation of fine-grained sediments such as chalks and muds and result in small amounts of normal slip on faults in an interconnected, layer-bound polygonal network. (Cartwright, 2007; Hustoft, 2007; Gay and Berndt, 2007). The young, fine-grained Eocene carbonate muds in the bubble wrap terrain may well have been susceptible to such processes.
- If the structures at Farafra described in the main part of the poster also turn out to be polygonal faults and related structures, Egyptian shelf carbonates may have undergone repeated episodes of polygonal faulting from the Late Cretaceous onward.

The character of the bubble wrap terrain changes markedly from SW to NE (from A to B to C), across the trend of the NW-SE patterning in the satellite images.



- In addition to the patchiness of the bubble wrap terrain, the area above is characterized by a prominent NW-SE grain that is visible in the satellite images as quasi-continuous brown stripes ranging in width from <200 m to nearly 1 km.
- Bedrock surfaces are well-enough exposed to permit mapping of faults in high resolution images in Google Earth. The strikes of most faults lie parallel to the prominent NW-SE patterning in the satellite images, and there is a marked increase from SW to NE in the number and length of faults exposed at the surface **even though the regional grain remains prominent in areas with few faults.**

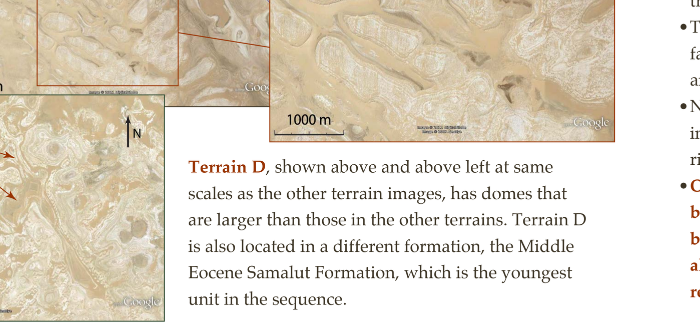


Terrain A (map at left and image below) is dominated by domes and clusters of domes that are 100-500 m in diameter separated by anastamosing synclines (below right). Faults are very rare. A NW-SE preferred orientation of narrow synclines spaced roughly 1 km apart defines the weak NW-SE grain of this terrain (below).

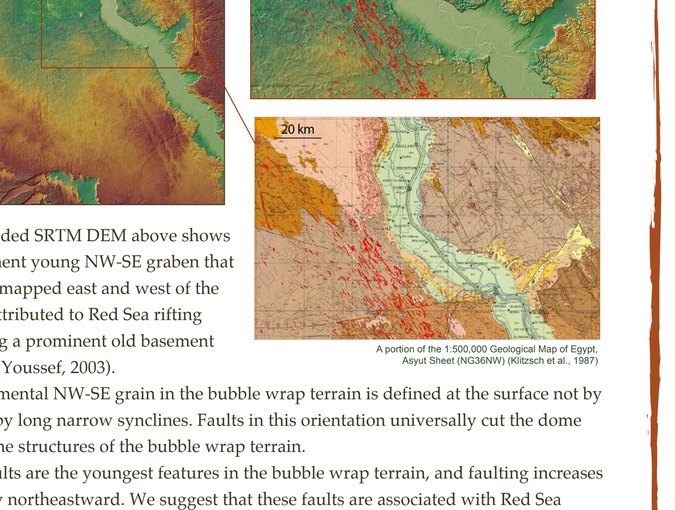
Terrain B (below and left) has clusters of 100-500 m domes separated by prominent NW-SE synclines that define the NW-SE grain. The long synclines are continuous with the synclines separating domes in the dome clusters. Faults are more common than in Terrain A but are still rare and dominantly strike NW-SE.

A weak NE-SW preferred orientation of bounding synclines gives domes a somewhat blocky character (above) and creates cruciform synclines with cuspate basin closures (right).

The NW-SE grain of **Terrain C** (above and above right) is fundamentally defined by long, narrow, NW-SE trending synclines. Domes occur in the panels between faults, but they are not as prominent as in Terrains A and B. Where domes occur, they are similar in scale to domes elsewhere. NW-SE faults are common and are preferentially located within and at the margins of the NW-SE synclines, although faults also occur in the panels in between. Faults cut both domes and synclines.



Terrain D, shown above and above left at same scales as the other terrain images, has domes that are larger than those in the other terrains. Terrain D is also located in a different formation, the Middle Eocene Samalut Formation, which is the youngest unit in the sequence.



A portion of the 1:500,000 Geological Map of Egypt, Asyut Sheet (NG36NW) (Klitzsch et al., 1987)

- The hillshaded SRTM DEM above shows the prominent young NW-SE graben that have been mapped east and west of the Nile and attributed to Red Sea rifting reactivating a prominent old basement trend (*e.g.*, Youssef, 2003).
- The fundamental NW-SE grain in the bubble wrap terrain is defined at the surface not by faults but by long narrow synclines. Faults in this orientation universally cut the dome and syncline structures of the bubble wrap terrain.
- NW-SE faults are the youngest features in the bubble wrap terrain, and faulting increases in intensity northeastward. We suggest that these faults are associated with Red Sea rifting and were superimposed on preexisting structures of the bubble wrap terrain.
- **Our working hypothesis is that the orientation of original bubble wrap domes and bounding synclines, however they formed, were controlled in part by pre-existing basement weaknesses, most prominently NW-SE weaknesses, causing the preferential alignment of bounding synclines in the bubble wrap terrain and the pronounced regional grain. Extension during Red Sea rifting exploited these same structures.**

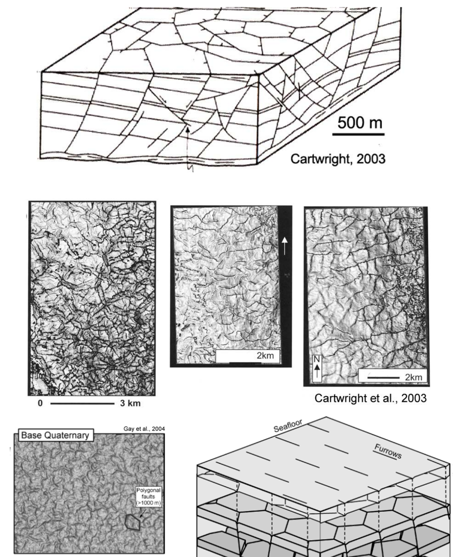
Some initial thoughts on models to test

We are still very much in the initial stages of this project and, to date, have only done reconnaissance work on these structures using high resolution satellite image. The ideas in this panel are presented as models that we will test with additional field, remote sensing, and lab analysis.

Although this project is still very much in its infancy, we are struck by similarities between the features that we have observed in the Khoman Formation and features of polygonal fault systems and overlying fluid escape structures that have been imaged in 2D and 3D seismic in many marine basins around the world. We outline a bit about these features below and speculate on possible correlations with structures in the Khoman Formation.

Polygonal fault systems

Polygonal fault systems are sets of layer-confined, low-displacement extensional faults arranged in networks that are broadly polygonal in map view (diagram at right). Polygonal fault systems typically occur in fine-grained sediments such as muds and chalks and have been reported from over 200 basins world-wide (*e.g.*, Cartwright and Dewhurst, 1998; Cartwright *et al.*, 2003).

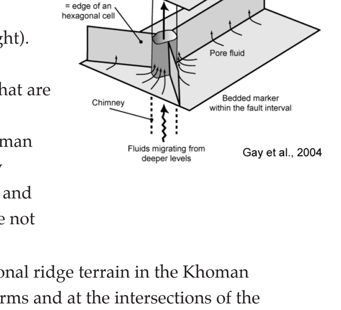


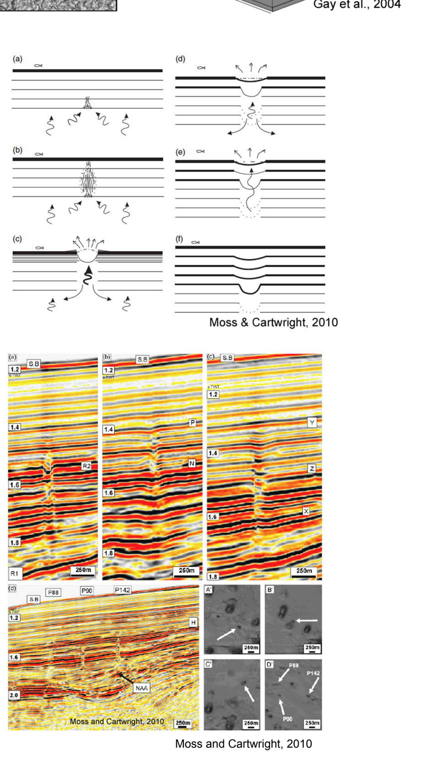
- The Khoman Formation consists of chalk, a rock type common in polygonal fault systems.
- The polygonal ridge networks in the Khoman Formation consist of faults that, where it can be determined, have dip slip.
- The polygonal regions defined by the network of faults in the Khoman Formation have dimensions of 500-1000 m in map view, similar to dimensions in polygonal fault systems studied in 3D seismic (plan views at right from Cartwright *et al.*, 2003 and Gay *et al.*, 2004).
- The features in the Khoman Formation are layer-confined and, at least from what can be seen in satellite imagery, appear not occur in either the underlying or overlying formations near Farafra.
- Portions of the Khoman Formation have more complex polygonal patterns of faults than others, and the complex portions appear to be slightly lower in the section than the simpler sections. Polygonal faults reported from the Lower Congo Basin by Gay et al. (2004) show a similar pattern, with more complex "polygons within polygons" deeper in the section (plan view and perspective views at right).
- Are the polygonal ridge networks in Farafra an example of a polygonal fault system??

Pockmarks and fluid escape structures

Fluid escape structures have been reported in close association with polygonal fault systems from many areas of the world. Pockmarks and furrows at the sediment-water interface, and chimneys in the underlying sediments, have been reported from the North Sea, offshore Namibia, the Lower Congo Basin, and Lake Superior (e.g., Andresen and Huuse, 2011; Moss and Cartwright, 2010; Hustoft *et al.*, 2010;Gay and Berndt, 2007; Gay *et al.*, 2004; and Cartwright *et al.*, 2004).

- In models proposed by Gay *et al.* (2004) and Moss and Cartwright (2010), fluid escape through pipes and tabular zones creates pockmarks and furrows at the seafloor. Pipes are typically less than 100 m to a few hundred meters across (right) and commonly slightly oblong (below right). Over time, pockmarks fill in as sedimentation proceeds, but continued fluid flow keeps the pockmarks as negative features until fluid flow ceases (far right). As sedimentation proceeds, seafloor sediments drape the pockmarks, creating layers with small inward primary dips that are visible in seismic profiles (below right).





- The fact that we see no evidence in the upper part of the Khoman Formation for any fold structures other than the small, nearly circular basins that form the eyes of the low-relief eye terrain and the overlying small saucer-topped mesas suggests that we are not dealing with typical mechanisms of folding.
- The low-relief eye terrain stratigraphically overlies the polygonal ridge terrain in the Khoman Formation, and the eyes are located preferentially along the arms and at the intersections of the polygonal network of faults. The low-relief eyesare similar in size (100-200 m) to fluid escape pockmarks that are associated with an underlying polygonal fault system and that have been imaged with 3D seismic in the North Sea and elsewhere (right).
- The small eye-shaped mesas of the polka dot mesa terrain also have inward-dipping layers. The small mesas are all elongate roughly E-W, are linked in EW chains of shallow basins, and underlie slightly concave EW ridges.
- Are the low-relief eyes, eye-shaped mesas, and concave ridges examples of furrows and chains of fluid-escape pockmarks associated with polygonal fault networks?

Plans for 2011-2012 field work

As we indicated above, the Desert Eyes Project is very much in its infancy. We have funding from the National Science Foundation through the IRES program to conduct field work this winter through NSF grant OISE-1030224.

Our field work will be aimed at addressing the following:

- Nature of the polygonal ridge network. Are the ridges deformation bands? Mineralized faults and fractures?
- Nature of the low-relief eyes and small eye-shaped mesas, including evidence for fluid flow.
- Range in lithologies and properties of different parts of the Khoman Formation.
- Accuracy of our interpretations of dips, structures, and stratigraphy.
- Seismic refraction profiles to provide data on these structures in the subsurface.
- Relationship, if any, between the features that we see in the satellite images and the karst features that have been reported at smaller scale in the Farafra area.
- And answering the vexing question of why we don't see the polygonal ridges in any of the tourist photos we've seen of the White Desert near Farafra...

The work will be carried out as a collaborative project among researchers and students from Hamilton College, Missouri University of Science and Technology, University of Idaho, University of Vermont and, from Egypt, Damanhour University, Alexandria University, Sohag University, Asyut University, and South Valley University, Aswan.