Reconnaissance Study of Domes and Basins in Tertiary Sedimentary Rocks in the Western Desert of Egypt Using High Resolution Satellite Imagery

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Abstract

High resolution satellite imagery of the remote Western Desert of Egypt reveals spectacular small scale dome and basin structures in Early Tertiary limestone, marl, shale, and chalk. Although domes and basins occur from the southern end of the Sinn el-Kaddab Plateau at least as far as 27.75N (over 500 km), the character of structures changes from south to north.

On Sinn el-Kaddab, elongate domes and basins ranging from <250 m to >1.5 km in length occur as prominent “eyes” both along major E-W faults and along minor faults and linear zones of other orientations. Many aspects of these domes and basins are consistent with the geometry produced by extensional fault-propagation folding, and offsets of fold layering on many of the faults require dip slip. This is consistent with normal slip mapped in the field by others. Focal mechanisms along the Kalabsha Fault at the southern end of Sinn el-Kaddab indicate modern right-lateral strike slip movement. Because the Kalabsha has structures similar to those along the other E-W faults of the Plateau, however, strike slip may represent modern reactivation.

In contrast to the linear alignment of domes and basins on the Sinn el-Kaddab Plateau, these features between the latitude of Asyut and 27.75N cluster in roughly equidimensional fields approximately 1-2 km across. Dome fields are dominated by clusters of 100-500 m diameter domes characterized by very low dip angles. Adjacent dome fields are separated from one another by narrow zones (100-200 m wide) that typically contain doubly-plunging, dominantly synclinal structures.

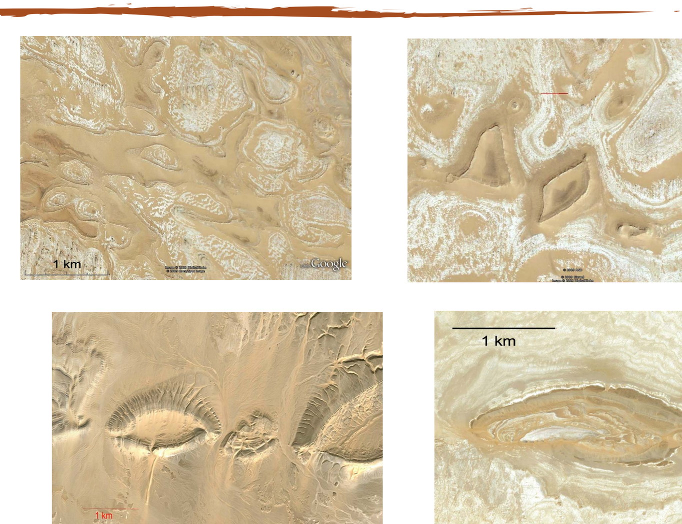
Between southern Sinn el-Kaddab and the area in the north, structures are a hybrid. Folds (primarily narrow, doubly plunging synclines) occur along prominent structural trends, with only minor evidence of faulting and minor occurrences of domes and basins in the tracts in between.

The presence of dome fields in the north and domes and basins away from the main faults on the Sinn el-Kaddab suggests a model that is more complex than localized folding associated with fault propagation. We are exploring whether subsurface sediment mobilization may have been responsible for the dome fields, which are strikingly similar to structures related to polygonal faulting in the North Sea, and whether such processes may have played a role in formation of structures along the major faults.

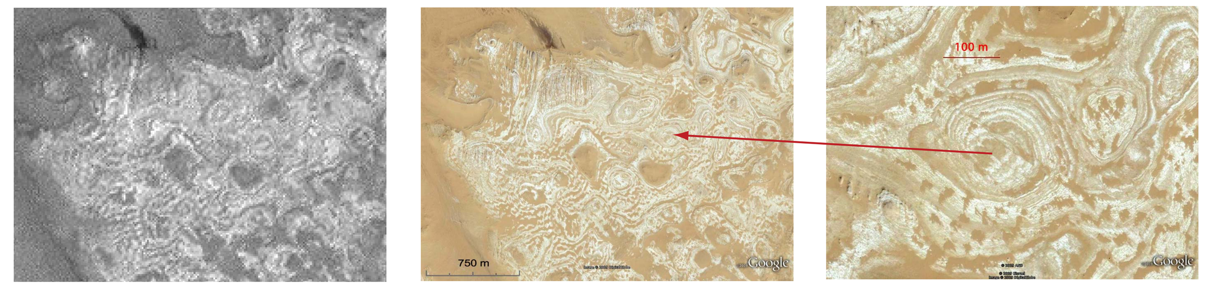
Purpose of the study

High resolution satellite imagery of the remote Western Desert of Egypt reveals spectacular small scale dome and basin structures, along with extensive faulting in many places, in a region stretching over 500 km from the southern end of the Sinn el-Kaddab Plateau at least as far as 27.75N.

The purposes of this study are to use newly posted satellite imagery in Google Earth to:
- determine the nature and geometries of the structures.
- determine how the character of the structures changes across the region.
- establish initial models for the origin of the structures.

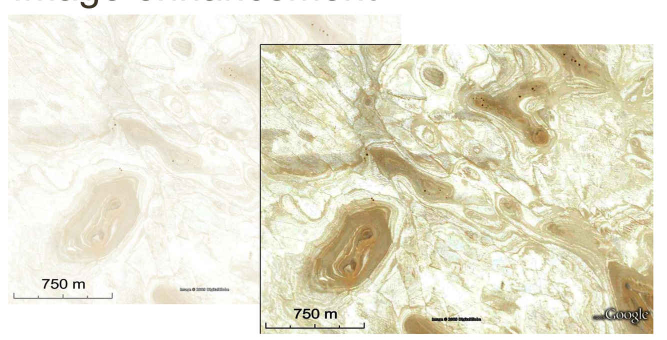


Data and techniques



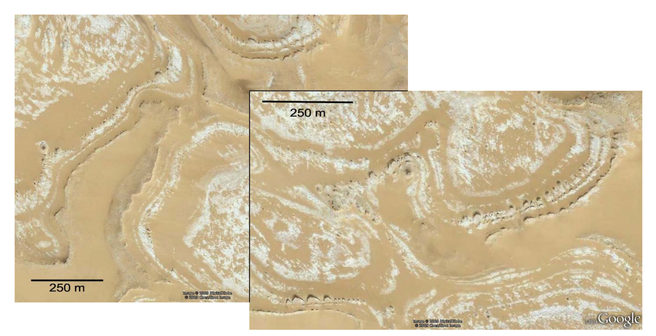
The smallest of these structures are only 100-500 m across, and it is almost impossible to tell what they are at ASTER/Landsat scale. Even at the scale of the Landsat panchromatic band (15 m/pixel, above left), they are frustratingly enigmatic. But, at the scale of the Digital Globe/SPOT images now up in Google Earth (1-2 m/pixel, above center), it’s possible to see outcrop patterns of contacts and faults at a level of detail that confirms that they are indeed structures (*e.g.*, the faulted dome, above right) and not surface features or simply erosional patterns in horizontal units. At Landsat scales, the faulted dome above right would be scarcely 10 pixels across....

Image enhancement



Contrast is low in many of the Egypt images in Google Earth. Enhancing image contrast using PhotoShop is crucial for determining the nature and relationships of structures.

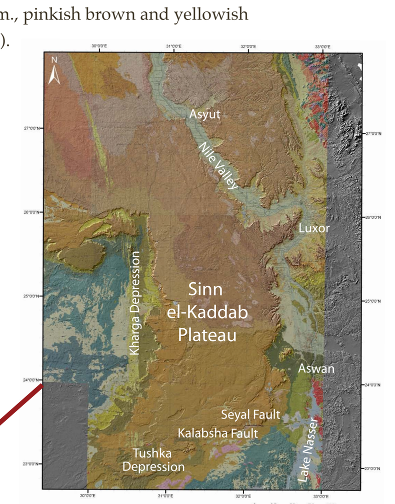
Determining dip directions

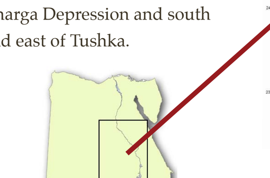


Very low dip angles combine with extremely low topographic relief to produce mini-flatirons and hogbacks that can be used to determine dip directions in the high resolution Google Earth images.

Regional geology

- The Sinn el-Kaddab Plateau in the Western Desert of Egypt is a broad, flat-topped, remote region standing 300-350 m above the Nile Valley to the east and the Kharga Depression to the west. A scarp to the south separates the Plateau from the Tushka Depression. The Plateau decreases in elevation to the north and merges with the low relief region west of the Nile.
- The Eocene bedrock at the surface of the Sinn el-Kaddab Plateau and the flat plains to the north is dominated by stable shelf marine limestone and chalk, with lesser amounts of marly limestone and shale (Thebes Group and Minia Fm., pinkish brown and yellowish brown on the geologic map below).
- Cretaceous to Eocene units that underlie the plateau are exposed west, south, and east of the Plateau and in the bordering scarps. These include shales of the Dakhla and Esna Formations; shale, marl, and limestone of the Kurkur and Garra Formations; and chalk of the Tarawan Formation.
- Cretaceous sandstone and siltstone lie in the floor of the Kharga Depression and south and east of Tushka.





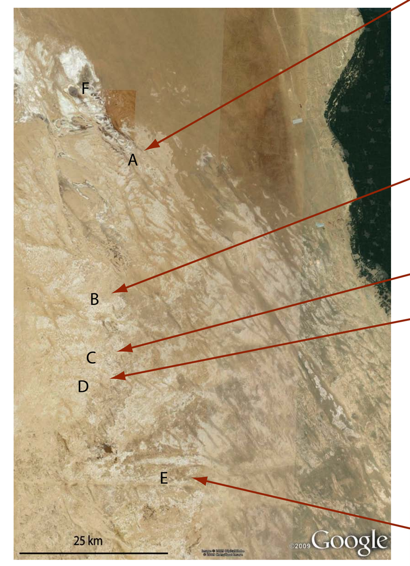
Geological Map of Egypt (1987), Bahariya, Farafra, Asyut, Dakhla, Luxor, and El-Saad El-Ali sheets draped over hillshaded SRTM DEM. Key map at left from www.maproom.psu.edu/dcw/

Previous work

- Fold structures in sedimentary units in Egypt have been well studied in several regions: 1) the northern Sinai, 2) immediately west of Cairo (the Abu Roash folds), and 3) northwest of the Fayum Depression (the El Kataniya fold belt). All appear to be contractional tectonic structures associated with Tethyan convergence. To our knowledge, however, the published literature provides no indication that anyone has recognized the presence of a spectacular set of dome and basin structures in the huge area NW, W, and SW of Asyut nor the anticlines and synclines along the Drunka-El Rufuf contact east of the northern end of the Kharga Depression.
- Spectacular eye-shaped structures along some of the major E-W faults at the southern end of the Sinn el-Kaddab Plateau were first recognized by Hume (1908). Both the faults and the eyes were carefully mapped by Issawi (1968) along the Kalabsha and Seyal Faults, as well as along several other un-named faults in the southernmost Sinn El Kaddab region, and by El-Hinnawi *et al.* (1978) along faults cutting the escarpment on the east side of the Kharga Depression. Alfarhan *et al.* (2005) used ASTER imagery to map several stretches of the Kalabsha and Seiyal Faults and proposed that the eyes formed in stepover regions as a result of strike slip motion. To our knowledge, no one has previously done a systematic inventory of the dome and basin structures along these faults, nor has anyone studied the structures of the remote central and northern parts of the plateau or the structures of the Western Desert NW, W, and SW of Asyut.

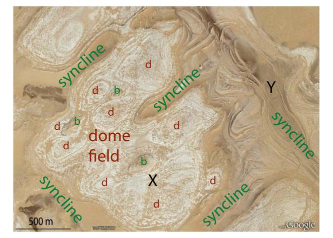
“Bubble wrap” structures in the Minia and Samalut Formations

West of the Nile Valley, satellite images of limestones of the Middle Eocene Samalut and Minia Formations exhibit both a strong NW-SE grain and a prominent patchiness (image below). High resolution satellite imagery reveals that the NW-SE structural grain is defined primarily by narrow synclinal structures and that the light-colored patches are complex small-scale domes and dome fields with a “bubble wrap” geometry.



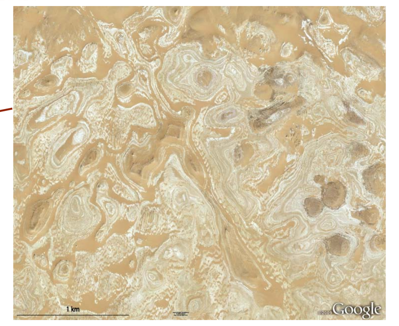
Two interesting things emerge in a high resolution view of the hazy EW structure at “E” above (detailed images at right).
- The patchy character is due to the same scale of “bubble wrap” structure seen farther north.
- The EW structure is a narrow alignment of elongate basins locally cut by EW faults, a geometry remarkably similar to the “fault and eye” geometry in the Sinn el-Kaddab.

- Individual domes and clusters of domes are cored by “white rock” and are separated from one another by networks of narrow synclines in “brown rock”. Basinal closures form where synclines intersect.
- Individual domes range in size from <100 m to about 500 m in diameter. Synclines are typically less than 200 m wide. The three images below and the image at right are all at the same scale.
- Many of the white patches are dome fields (X at left and right) consisting of dome culminations (d) separated by narrow synclinal networks that locally intersect in basinal closures (b).
- The image at right also shows a portion of one of the major regional NW-SE stripes (at Y) and reveals that it is a synclinal structure in the brown rock.

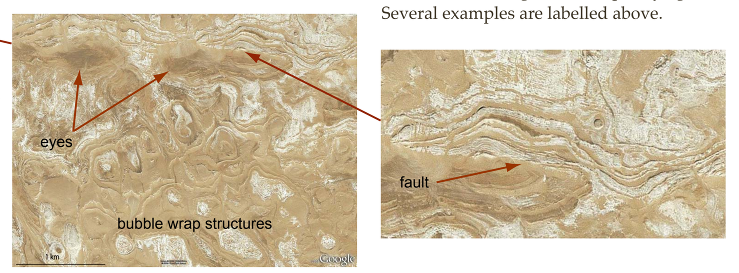


The geometry of the structures, with broad quasi-circular domes in the white rock separated by narrow interconnected synclines in brown rock, has a “bubble wrap” character.

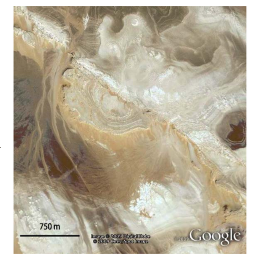
The domes have broadly convex margins, whereas the basins, which fill the spaces between domes, typically have concave margins and a “pointy” geometry. Several examples are labelled above.



In some parts of the region, (examples above and far left), the synclines define a prominent structural grain oriented NW-SE and ENE-WSW. In other areas (example at left), the synclinal structures are not prominently aligned.



In a very few places, the prominent NW-SE structural grain is not only the locus of narrow synclinal structures but also of faults that cut the synclines. The faulted basin at right (location F on the key map) is strikingly similar to the “eyes” along faults much farther south on the Sinn el-Kaddab Plateau.



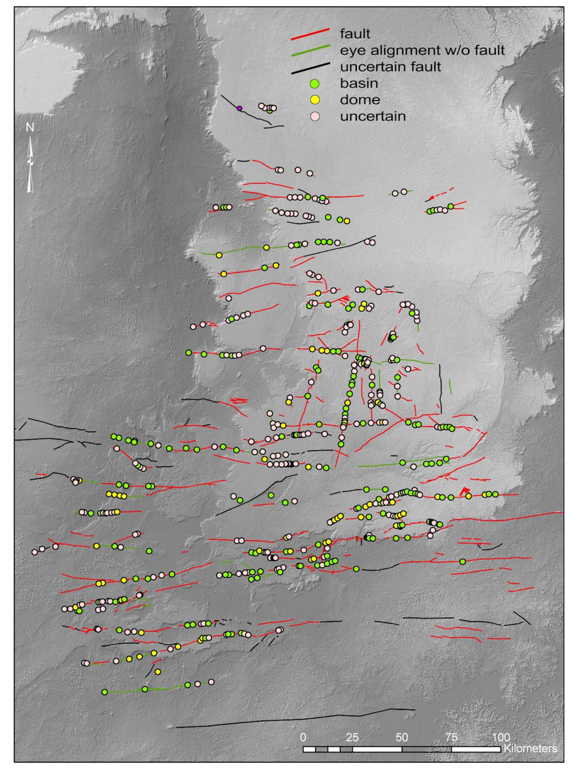
Mobility of shales underlying the Sinn el-Kaddab Plateau

Shales of both the Dakhla and Esna Formations, which underlie the dominantly limestone caprock of the Sinn el-Kaddab Plateau, display spectacular mass movement features where they are exposed in both the eastern (Doliber *et al.*, in press) and western scarps of the plateau.

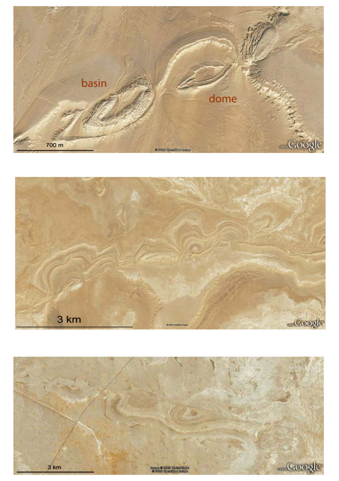
The Garra Formation displays large circular structures 5-30 km across along the western side of the Sinn el-Kaddab that may be related to subsurface mobility of the Dakhla Formation.

Fault inventory in Sinn el-Kaddab Region

The faults of the Sinn ed-Kaddab region are decorated with a remarkable set of eye-shaped structures. Both field mapping and satellite image analysis reveals that they are structural domes and basins. Sections of the poster to the right describe some of these features in detail. The map below shows an inventory of faults and “eyes” based on high resolution imagery in Google Earth. We are still in the process of refining the inventory of domes and basins and have not yet analyzed their distributions.



Examples of domes and basins

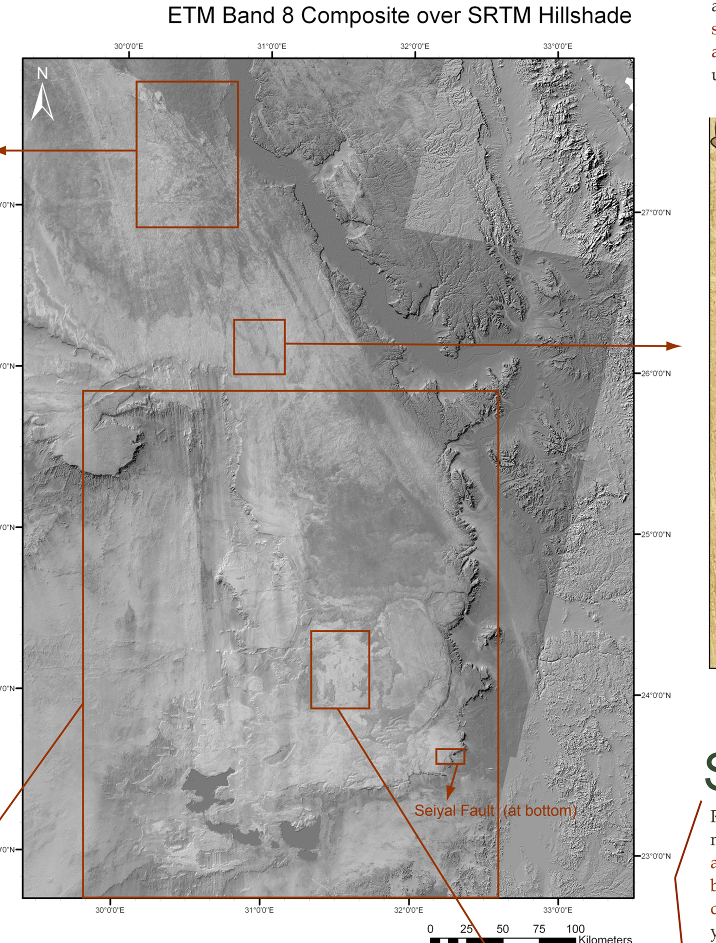


- Eye-shaped domes and basins are ubiquitous on faults in this region – our current inventory stands at 479 domes and basins – and they occur on faults of all orientations.
- Eye-shaped domes and basins are not restricted to the Sinn el-Kaddab Plateau and occur both on the eastern margin of the Kharga Depression and in the Tushka Depression.
- Domes and basins along faults occur in rocks as old as the Cretaceous (Kharga and Tushka Depressions) and as young as the Middle Eocene (Sinn el-Kaddab). A few domes in the Kharga and Tushka Depressions are cored by Precambrian crystalline basement.
- The faults are predominantly oriented E-W, and faulting decreases in intensity from south to north, dying out by the north end of the Kharga Depression.

Hundreds of nearly levelled square kilometers extend endlessly as a bare and dazzling white limestone rock surface, sometimes veneered by limestone rubble. No vegetation, no traces of any kind of life, absolutely nothing but the bare rock and the sun.

Bahay Issawi, 1968, The Geology of the Kurkur Dungul Area

ETM Band 8 Composite over SRTM Hillshade

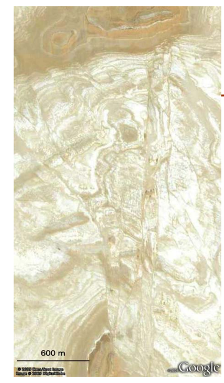


fault inventory bottom left

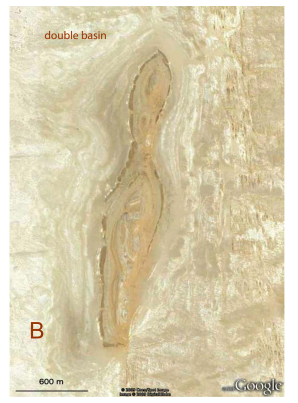
Structures along a N-S fault with “eyes”

The fault strikes N-S, steps westward from north to south, and does not have significant overlap in some of the overstep regions. The fault is marked by elongate eye structures consisting of nine basins and two domes, shown with layer form lines at right. The domes and basins lie along the fault segments rather than in the overstep regions (geologic map at right) and predate the most recent movement along the fault. The dip reverses between the two domes in the southern part of the fault.

- The eyes along the fault include both basin and domes that can be readily identified by the scalloped edges on the basins (far left) and the hogbacks and flatirons around the domes (left).
- Though the folding involves the white country rock, the folding is spatially related to the fault and dies out away from the fault segments.
- Layer offsets cannot be restored by pure strike slip and require dip slip along the main fault segments (left).

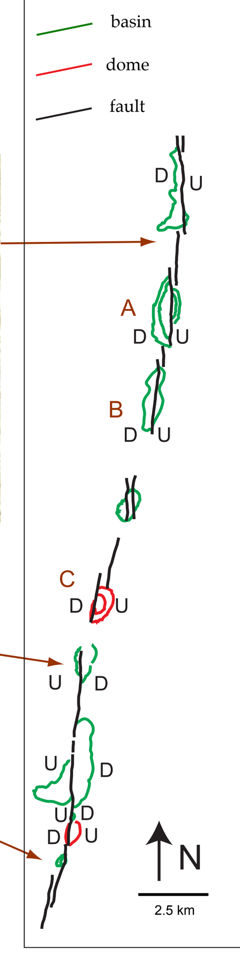


- The fault is dramatically different in the overstep regions. Several closely-spaced, predominantly N-S striking faults cut the white country rock in the overstep region, whereas the “brown rock” of the basins and domes is cut by a single fault.

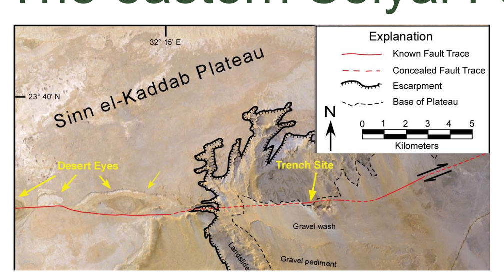


Though formation of the basins and domes pre-dates the most recent movement on the fault, two of the basins are only partially cut by the main fault, with slip dying out along strike at the northern end.

In the northern and far southern parts of the fault, the eastern block is the footwall (above left). Between the two domes, however, the dip reverses – the western block is the footwall (right above). If slip is normal, this suggests that the fault dips west throughout most of its length except between the two domes, where it dips to the east.

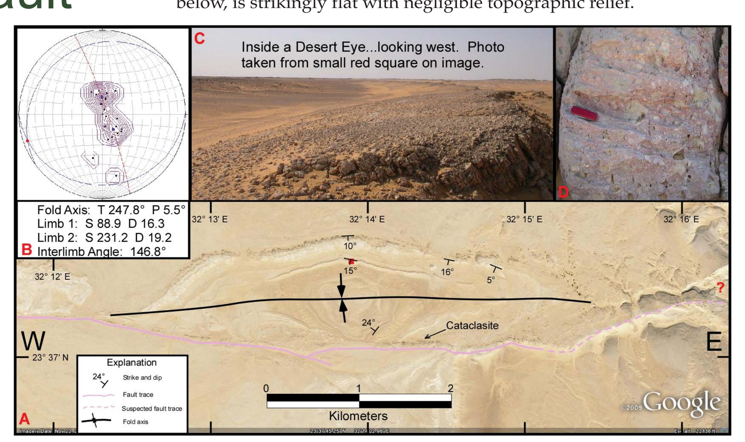


The eastern Seiyal Fault

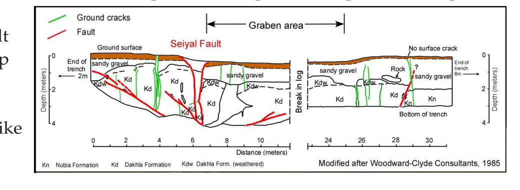


The Seiyal Fault stretches for over 90 km EW across the southern end of the Sinn el-Kaddab Plateau. Elongate eyes (both domical and basinal) up to 5.5 km long decorate the trace of the fault and are cut by the fault. The Seiyal Fault cuts Lower Eocene units on the Plateau and Upper Cretaceous through Upper Paleocene rocks east of the escarpment. The fault dies out on the Nubian Plain west of Lake Nasser.

The surface of the Sinn el-Kaddab Plateau, shown in the photo below, is strikingly flat with negligible topographic relief.

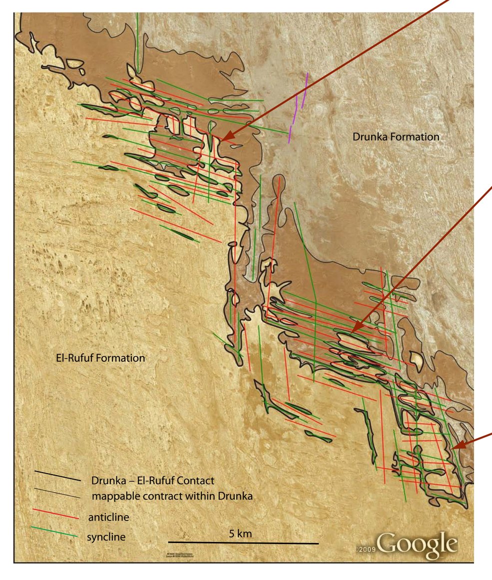


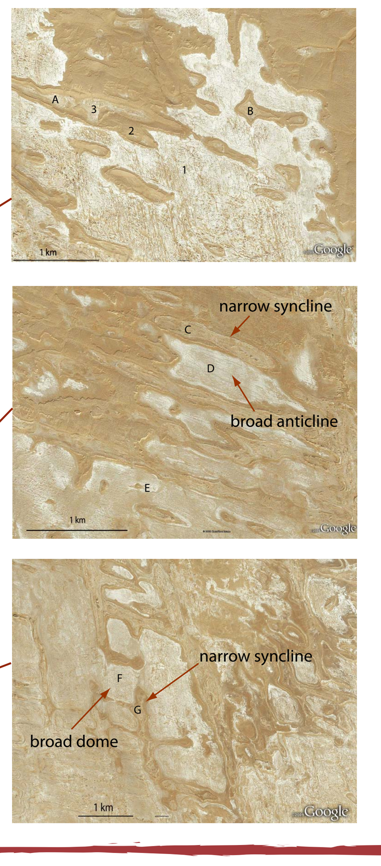
- Limb dips in the eye shown at left are shallow (5-15°), with slightly steeper dips on the side of the basin adjacent to the fault. The micro-hogback and flatiron topography produced by a combination of shallow dips and very subdued topography is clearly visible in Google Earth and is consistent with field-determined dip directions.
- Cataclasite is exposed along the fault on the south side of the basin (photo left).
- Some aspects of the Seiyal Fault suggest dip slip and some suggest strike slip. The layer contacts of the dome and basin shown at right that are cut by the fault cannot be restored by pure strike slip. On the other hand, results from 1985 trenching along the fault (location shown on map at far left) suggest recent slip and are most consistent with strike slip and development of a palm-tree duplex. This may suggest that the Seiyal Fault was originally a dip slip fault that has been recently reactivated as a strike slip fault.



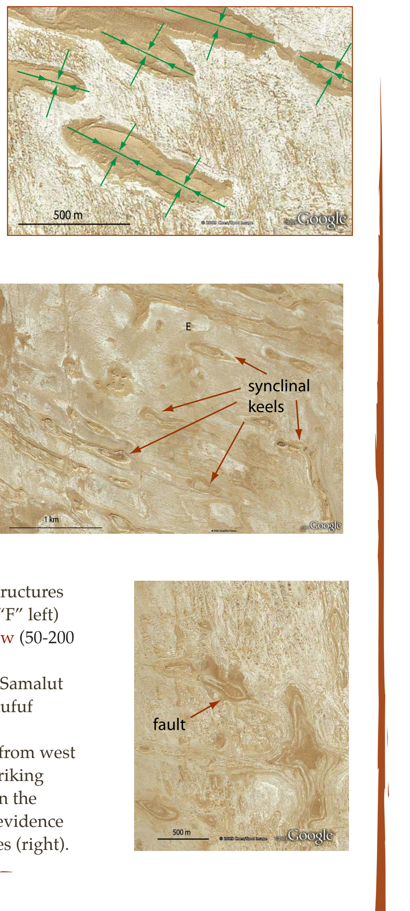
Synclines and anticlines along the Drunka–El-Rufuf contact

Northeast of the end of the Kharga Depression, Eocene limestones of the Drunka Formation overlie Eocene limestones of the El-Rufuf Formaton. Tracing the contact and mappable units near the contact reveals a surprisingly complex geometry given the fact that the area has essentially no topographic relief. The complexity stems from the fact that units are folded into anticlines and synclines with very low limb dips, which repeats the units locally and complicates the outcrop trace geometry.





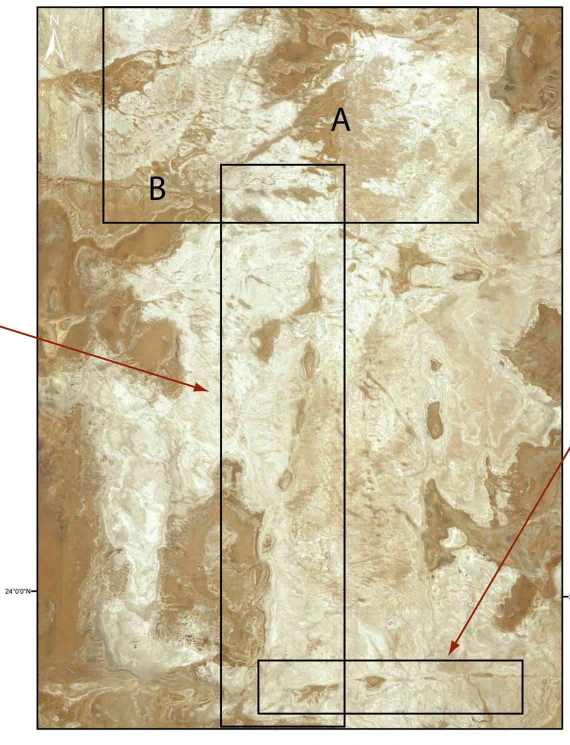
- The stratigraphic sequence is easily distinguishable on contrast-enhanced high resolution imagery and consists of a “white rock” unit (1) overlain by a “brown rock” unit (2) and a beige unit (3).
- A close-up view (right) reveals that the brown elongate patches are the keels of doubly plunging synclines.
- All folds are characterized by gently porpoising hinges; *e.g.*, the fold marked “A” at left has six basinal closures along its length.
- The stellate basin at “B” is simlar to those in the Minia and Samalut Formations to the north (poster section far left) where a narrow WNW-ESE syncline is crossed by a narrow NS syncline.
- The WNW-ESE synclines are sharply defined and spaced 100-500 m apart (cored by beige rock at left, e.g. at “C”). Anticlinal structures are broader and less sharply defined (shown most clearly where cored by white rock at left, *e.g.*,at “D”).
- The image at right shows an area immediately south of the image at the left (”E” is the same place in both images). South of the Drunka–El-Rufuf contact, the overlying Drunka Formation reappears repeatedly in the keels of WNW-ESE trending synclinal structures. The surrounding country rock of the El-Rufuf displays little evidence of folding.
- As is common on the Sinn El Kaddab Plateau to the south, “white rock” is cut by pervasive WNW-SSE fractures with spacings of 10-20 m, whereas the “brown rock” is not.
- Portions of the contact region are prominently crossed by NNW-SSE structures (left). Broad (500-1000 m) domical structures in the white rock (*e.g.*, at “F” left) are separated from one another by an interconnected network of narrow (50-200 m) synclinal structures in the brown and beige rock (*e.g.*, at “G” left).
- The geometry is similar to the “bubble wrap” terrain of the Minia and Samalut Formations to the north, except that the domes along the Drunka–El-Rufuf contact are not dome fields.
- The simplest explanation for the fact that the contact steps southward from west to east (key map, left) is a small amount of dip slip along NNW-SSE striking faults. Faults are absent in the imagery, however. Blind faults may lie in the subsurface beneath the narrow NNW-SSE synclinal structures. Direct evidence for faulting is rare in this area; where it occurs, it crosscuts all structures (right).



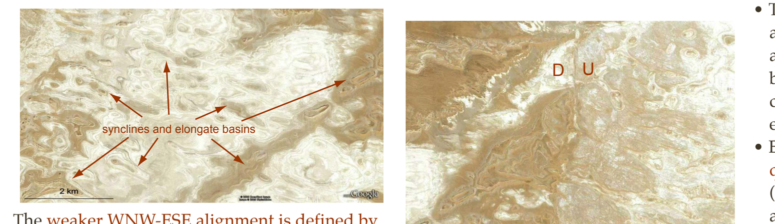
Structures in the country rock of the Sinn el-Kaddab Plateau

Rocks of the Eocene Dungul Formation east and west of the major fault described below left display prominent structural alignments that are defined by the keels of synclines and basinal closures in “brown rock” that appear to die out downward in the “white rock” and are cut by pervasive younger faults.

- Two major faults cut the area, one striking NS (described in detail at left) and the other EW (A and B below). Both are decorated by dominantly basinal eyes.
- The eastern (footwall) block of the NS fault exposes deeper levels of the stratigraphy in the Dungul Formation. The oldest units are grayish brown in the contrast-enhanced image below. The middle units are white, and the youngest units, exposed more prominently on the western side of the fault, are medium to dark brown.

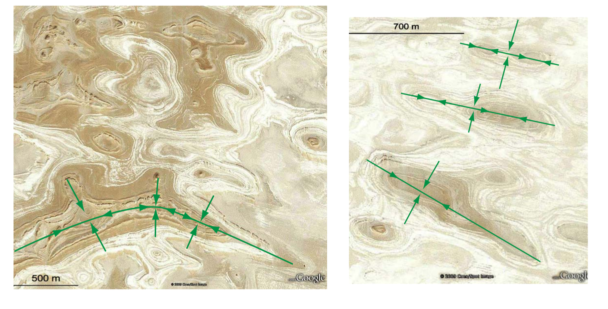


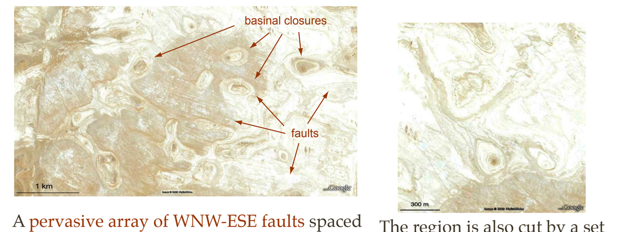
- Prominent WNW-ESE and NNE-SSW, and NE-SW structural alignments occur in the country rock between the main faults.
- High resolution images (below) reveal that these alignments are, in fact, doubly-plunging fold structures with shallow limb dips. The prominent brown NE-SW structure (above right) is a continuous narrow syncline with elongate basinal closures along its length.



The weaker WNW-ESE alignment is defined by the keels of elongate basinal structures (enlarged below) exposed at a deeper structural level than the continuous brown synclinal structures.

- The same structural alignments occur both east and west of the main NS fault, but the structures are less continuous and more isolated east of the fault.
- East of the fault, elongate and quasi-circular structures (below and below left) are almost exclusively basins that preserve just the very keels of eroded synclinal structures.



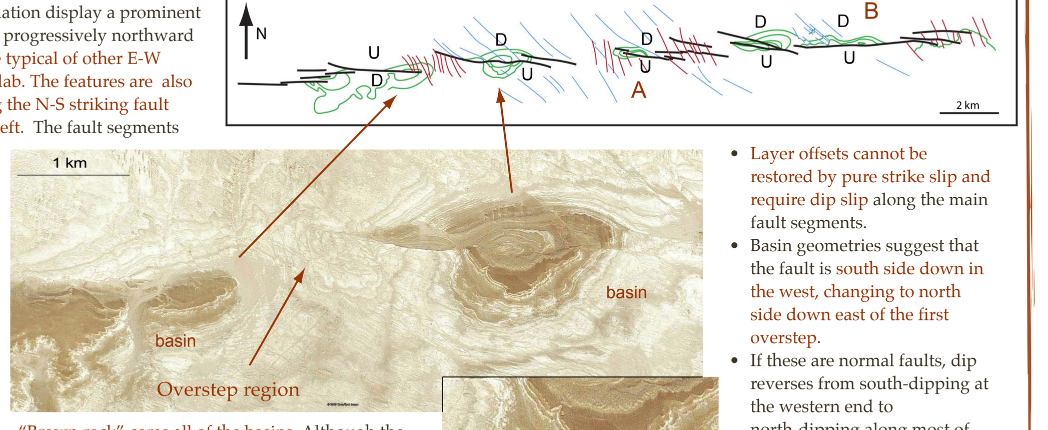


A pervasive array of WNW-ESE faults spaced 10-15 m apart is most prominently developed in the gray and white rock across the entire region (above and left). These faults postdate formation of the domes and basins.

The region is also cut by a set NNW-SSE striking faults spaced 230-240 m apart that appear to postdate the pervasive set described at left.

Structures along a representative E-W fault with “eyes”

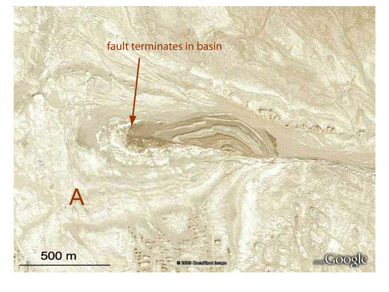
Rocks of the Eocene Dungul Formation display a prominent set of E-W dip slip faults that step progressively northward from west to east. The features are typical of other E-W striking faults on the Sinn el-Kaddab. The features are also essentially identical to those along the N-S striking fault described in the poster section at left. The fault segments are decorated by a series of seven distinct eyes or eye complexes elongate parallel to the fault and ranging in long dimension from 1-3 km. The eyes are all basins, with no domes along this fault.



- The basins lie along the faults *between* the overstep regions, rather than *in* the overstep regions (map above right).
- The overstep regions are characterized by NNW-SSE striking faults (in red on map above right), most of which die out in the adjacent rocks.

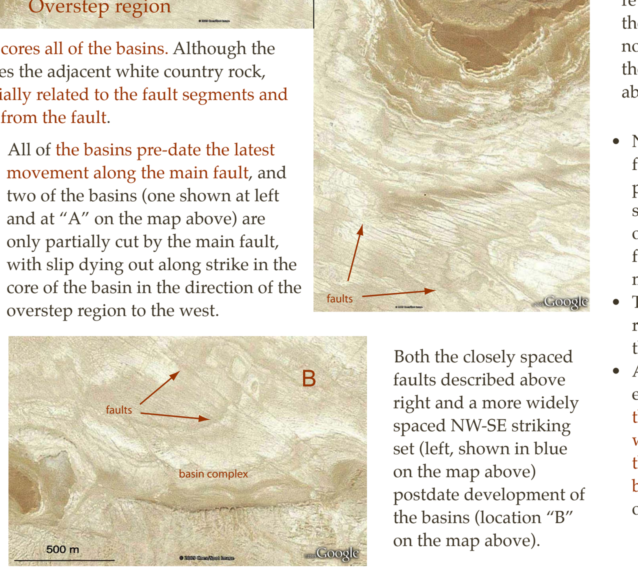
“Brown rock” cores all of the basins. Although the folding involves the adjacent white country rock, folding is spatially related to the fault segments and dies out away from the fault.

- Layer offsets cannot be restored by pure strike slip and require dip slip along the main fault segments.
- Basin geometries suggest that the fault is south side down in the west, changing to north side down east of the first overstep.
- If these are normal faults, dip reverses from south-dipping at the western end to north-dipping along most of the fault shown on the map above.



The majority of the basins along this fault have structural expression on both sides of the fault, although one of the basin sets (right, area “B” on the map above) is confined to one side of the fault.

All of the basins pre-date the latest movement along the main fault, and two of the basins (one shown at left and at “A” on the map above) are only partially cut by the main fault, with slip dying out along strike in the core of the basin in the direction of the overstep region to the west.



Both the closely spaced faults described above right and a more widely spaced NW-SE striking set (left, shown in blue on the map above) postdate development of the basins (location “B” on the map above).

- North and south of the main fault, the white rock is pervasively cut by closely spaced faults (10-25 m) oriented WNW-ESE. These faults are not shown on the map above.
- The main fault overstep regions do not appear to have this pervasive set of faults.
- As is true elsewhere on Sinn el-Kaddab, the small faults that are so pervasive in the white rock largely die out in the brown rock coring the basins and offset only the outermost layers of the basins.

Summary and implications

Topography

The surface of the Sinn el-Kaddab and the areas to the north have very little topographic relief, and we find it striking that individual mappable units are exposed at the surface over huge distances. Low amplitude folding brings the same unit back to the surface again and again, and the level of erosion appears to be controlled by the same slightly more resistant layer over large areas. Much of the area exhibits essentially no dissection by running water, which would obscure the very subtle features such as those in the bubble wrap terrain. The common occurrence of yardangs points to the dominance of wind scouring.

Nature of structures

The geometry of structures in the bubble wrap terrain coupled with the spatial relationship between domes, basins, and faults on the Sinn el-Kaddab, suggests that these folds are not typical contractional fold belt structures.

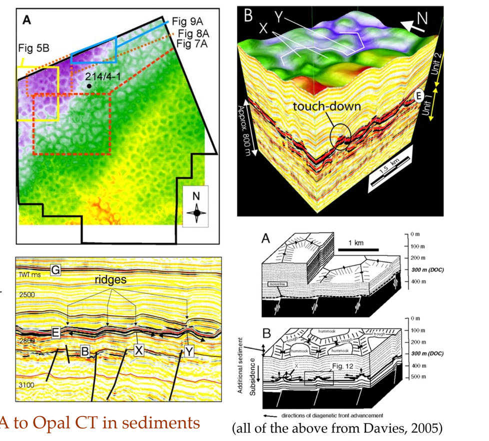
Age of structures

These structures are young - folds and faults occur here in rocks as young as the Middle Eocene.

The bubble wrap structures

Low amplitude folds in a wide area west of the Nile and north of the Kharga Depression are dominated by white-rock domes 100-550 m across, commonly clustered in dome fields and separated by narrow, interconnected brown-rock synclines, many of which are aligned either NW-SE or roughly EW.

- These “bubble wrap” structures are strikingly similar both in scale, geometry, and areal extent to hummocks imaged by 3D seismic in the North Sea (images at right, Davies, 2005). In the North Sea, the hummocks occur in sediments overlying a network of polygonal faults.
- Various models have been proposed for the origin of polygonal fault networks, which occur in sedimentary basins worldwide. These models include gravity collapse, density inversion, syneresis, and compational loading (Cartwright *et al.*, 2003). All proposed models occur 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. Polygonal fault networks have been shown to be important conduits for fluid flow during compaction and diagenesis (Cartwright, 2007; Hustoft, 2007; Gay and Berndt, 2007).
- An intriguing model for the origin of low amplitude hummocks in the North Sea (Davies, 2004) proposes differential compaction and subsidence during diagenesis due to the volume-reducing conversion of biogenic Opal A to Opal CT in sediments directly overlying the faults of a polygonal network, causing a local volume decrease and forming narrow synclinal troughs in sediments immediately overlying the faults (figures at right). Because the conversion is temperature-dependent, they suggest that warm fluids rising along the faults might be responsible for localized volume reduction and formation of a network of synclines surrounding hummocks containing unconverted Opal A.
- Fine-grained Eocene carbonate muds in Egypt may well have been susceptible to such a process. Microfossils are ubiquitous in these muds, and many authors have pointed to siliceous organic remains as the likeliest source for silica in chert nodules that occur in many of the Egyptian Eocene limestones (*e.g*, McBride *et al.*; 1999; Rashed and Sediek, 1997).



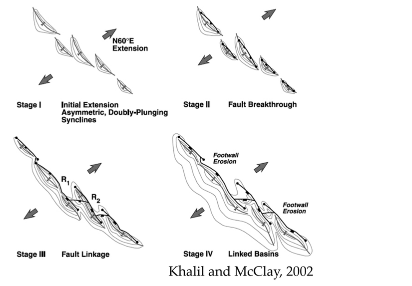
(all of the above from Davies, 2005)

Eyes along the faults of the Sinn el-Kaddab Plateau

Our detailed mapping of several major faults plus reconnaissance observations along other faults indicates that:
- Eyes are ubiquitous along Sinn el-Kaddab faults and have similar geometries and features along EW and NS faults.
- Eyes along the faults are cut by the faults and predate the latest fault movement.
- Eyes typically lie *along* fault segments, rather than in overstep regions between fault segments.
- Both basins and domes occur along the faults, but they do not typically alternate. Many long stretches of faults show only (or dominantly) basinal eyes.
- Offsets of layering in the eyes require dip slip along many of the faults.
- Eye alignments that do not lie along faults occur in the bedrock between major faults on the Sinn el-Kaddab Plateau, but the country rock is not characterized by bubble wrap structures.

And work by others shows the following:
- Issawi (1968) and El-Hinnawy *et al.* (1978) mapped faults and related eyes on the eastern side of the Kharga Valley, in the southernmost Sinn el-Kaddab, and in the Tushka Depression. Their work indicates that limb dips in the eyes are typically low (<5°-15°), that most of the faults are normal faults, and that basement rock cores the domical eyes exposed where faults cross the deepest part of the section.
- Focal mechanism and GPS data, along with offset drainages, indicate modern right lateral strike slip along the Kalabsha Fault (Alfarhan *et al.*, 2006; Mekkawi *et al.*, 2005; Mohamed *et al.*, 2001).

Interpretations and remaining questions:
- The geometries of the eyes and faults are in many ways what one would expect from extensional fault propagation folding, as modeled by Khalil and McClay (2002). Such a model is consistent with our observations that eyes occur *along* faults, rather than in overstep regions between them, that some eyes are only partially cut by faults, and that many faults are dominated by basinal eyes.
- Extensional fault propagation folding is also consistent with narrow synclinal structures and alignments of basinal keels in the country rock – these may be extensional fault propagation folds related to blind subsurface normal faults.
- Domical eyes are less easy to explain with this simple model, as are many basins that sit astride faults rather than lying on only one side of the fault.
- Rock rheology may have played a significant role in the development of these structures. Across the regions, faults dramatically change character as they pass from “white rock” to the “brown rock”. We don’t yet know anything about the compositions of these two rocks types nor how their respective rheologies might have influenced development of structures.
- In addition, we don’t yet know to what extent the development of structures might have been affected by subsurface mobilization in the shales of the Dakhla and Esna Formations.
- Modern strike slip on the Kalabsha Fault likely represents modern reactivation of an older normal fault.



Khalil and McClay, 2002

Between the Sinn el-Kaddab and the bubble wrap terrain

We are struck by the elements that these widely separated areas have in common and propose that the two areas grade into one another over distances of many hundreds of kilometers.
- The area along the Drunka–El-Rufuf contact is in many ways a hybrid of the bubble wrap structures to the north and the fault-and-eye terrain to the south. It has the same roughly EW structural grain as the Sinn el-Kaddab, but the grain is defined by narrow, brown-rock synclines with elongate basinal closures, rather than by faults. Crossing structures oriented N-S create broad white rock domes that are approximately the same scale as the white rock dome fields in the bubble wrap structures.
- Farther north, bubble wrap structures are cut by a narrow EW regional synclinal structure with elongate basinal closures, some of which are cut by EW fault segments that are reminiscent of the fault-and-eye structure of Sinn el-Kaddab faults.
- Regional basement fault patterns might well be superimposed on an otherwise polygonal network and might have localized fluid flow and have created the long synclinal belts in the north if the faults remained blind.

The fact that the same pair of rocks (white rock and brown rock) make the same kinds of structures in the Dungul, the El-Rufuf, the Drunka, the Minia, and the Samalut Formations suggests that something is repeated in the section that promotes these structures. With the exception of the Dungul Formation, all are resported in the literature as consisting of limestone and chalky limesone, with subsidiary marl. We would very much like to know whether the brown rock and the white rock, which differ so markedly in their structures, have differences that might be relevant to formation of the structures. We are currently examining ASTER multispectral data and planning field work to address this, and other, questions.