A Previously Unrecognized System of Folds and Related Faults in Stable Platform Limestones of the El Rufuf and Drunka Formations, Western Desert, Egypt

Barbara Tewksbury[1], Asmaa A. Dokmak[2], Elhamy A. Tarabees[3], Ahmed S. Mansour[2], Tharwat A. Fattah[2] & Mohamed A. Rashed[2]
[1]Hamilton College (Clinton, NY), [2]Alexandria University (Alexandria, Egypt), & [3]Damanhour University (Damanhour, Egypt)

Hamilton
ALEXANDRIA UNIVERSITY
DAMANHOUR UNIVERSITY

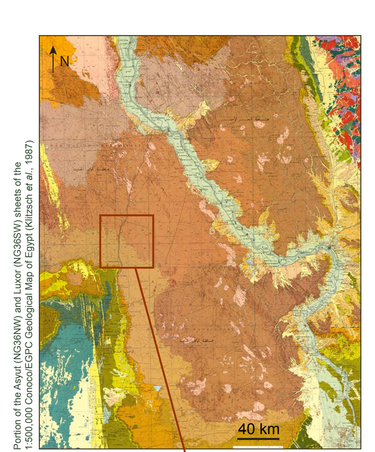
Abstract

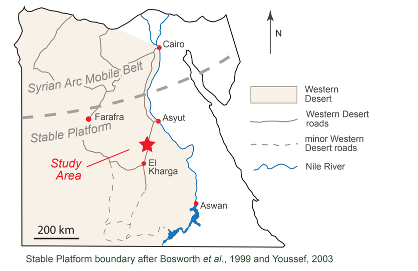
Landsat images of the Western Desert of Egypt show a pervasive and systematic patterning. Our study of recent high resolution satellite imagery in Google Earth, combined with targeted field work, reveals that although some of the patterning results from aeolian erosion and deposition, a remarkable proportion is fundamentally structural over an area of at least 20,000 km2. Eocene carbonates display hundreds of narrow synclinal structures that are typically several 100 meters wide and separated by much broader anticlinal structures. Synclinal structures are generally gentle to open, with shallow but variable plunges and multiple basin closures along their lengths. Although these narrow synclinal structures define many of the lineaments previously shown on regional bedrock maps, they are only rarely accompanied by major faults. Anticlinal structures are generally very different in both geometry and scale from the synclines. They are broad, flat-topped, and up to 10 times wider than the immediately adjacent synclines. In some areas, intersecting sets of WNW-ESE and N-S synclines separate broad, blocky domical structures. In other areas, the WNW-ESE synclines have a sigmoidal pattern, changing trend along their lengths from WNW-ESE to NW-SE.

In contrast to the synclines described above, a small number of narrow N-S synclinal structures spaced 6-10 km apart in the El Rufuf and the Drunka Formations are clearly associated with major faults. The two most prominent of these extend to the south, defining the shape of the Kharga Valley as well as the oasis trends.

As far as we are aware, these fold structures have not been previously recognized. The combination of low dip angles, scale of the structures, and only slight differences in erosional resistance of massively bedded limestones results in structures that are too subtle and too big to be readily noticeable from the ground and too small to be identifiable except in satellite images with resolutions of a few m/pixel. Detection from the ground is also confounded by yardangs, which obscure bedding and structures in many areas.

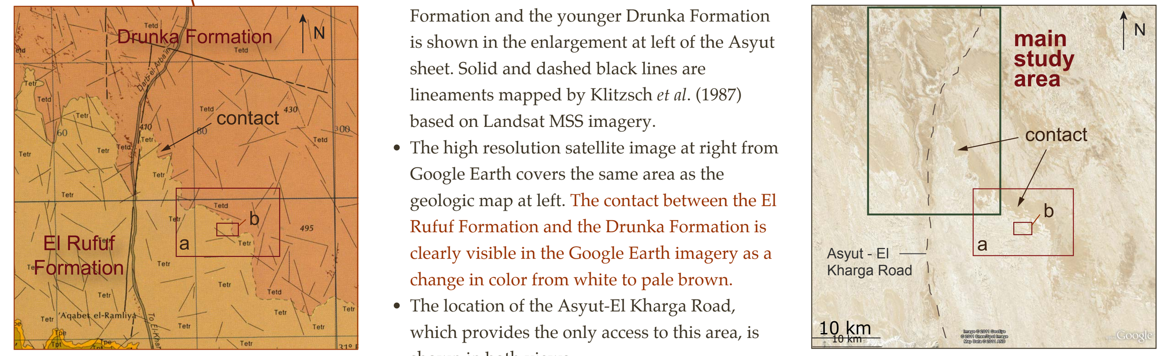
Origin of the project





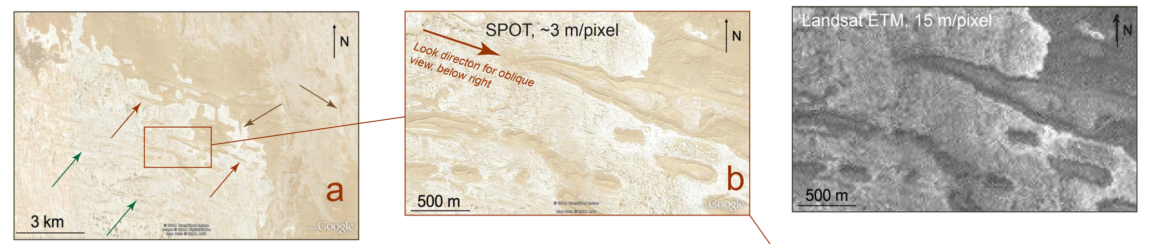
- The Stable Platform of central Egypt (right) consists of a sequence of Late Mesozoic through Miocene sediments lying unconformably on Precambrian basement. The sequence generally dips very gently north, exposing the oldest rocks in the south.
- The Eocene through Miocene section consists almost exclusively of shallow marine carbonates (Said, 1990; Issawi et al., 1999) and is shown on the map at left with shades of brown and tan.
- Our study area (red box at left and red star above right) lies along the contact between two formations in the Thebes Group – the El Rufuf Formation (shown in tan) and the Drunka Formation (shown in rusty brown).

The study area lies in the Western Desert of Egypt, about 150 km southwest of Asyut along the Asyut-El Kharga Road. This is a profoundly remote area – the map above shows literally the only road access in the Western Desert. Lake Ontario would easily fit between the Farafra Road and the Asyut-El Kharga Road.



- The contact between the older El Rufuf Formation and the younger Drunka Formation is shown in the enlargement at left of the Asyut sheet. Solid and dashed black lines are lineaments mapped by Klitzsch et al. (1987) based on Landsat MSS imagery.
- The high resolution satellite image at right from Google Earth covers the same area as the geologic map at left. The contact between the El Rufuf Formation and the Drunka Formation is clearly visible in the Google Earth imagery as a change in color from white to pale brown.
- The location of the Asyut-El Kharga Road, which provides the only access to this area, is shown in both views.

While exploring new high resolution imagery in Google Earth in 2009 along the Drunka-El Rufuf contact, Tewksbury was intrigued by the complexity of patterns that suggests that the contact is not as simple as portrayed on the Asyut geologic map sheet. Images a and b below left and center show pronounced WNW-ESE finger-like patterns both between the white rock at the top of the El Rufuf and the pale brown rock at the bottom of the Drunka (red arrows), as well as a fainter patterning of similar orientation within the El Rufuf (green arrows) and a more widely-spaced NS patterning as well (brown arrows). The locations of images a and b are shown with red rectangles on the geologic map above left and the Google Earth image above right.



- Previous analysis by Tewksbury et al. (2009) using SPOT imagery in Google Earth shows that the pattern results from the presence of many open, shallowly-plunging folds with shallow, gently porpoising hinges. Narrow, open synclines trending both WNW and NS are separated by broader anticlinal or domical structures. The oblique view in Google Earth at right (look direction shown above) shows that the elongate pale brown patches along the contact are the keels of these narrow, open, synclinal folds.
- It is no surprise that these structures were not recognized at the time of creation of the 1:500,000 regional maps by Klitzsch et al. (1987). Even at the highest resolution of the most recent Landsat imagery (15 m/pixel in the panchromatic band), the nature of the patterns remain enigmatic (above right). The 1987 maps were based on even lower resolution imagery, the 79 m/pixel Landsat MSS of the 1970s.

Previous work

- Previous work by others in the Drunka and El Rufuf Formations has targeted general sedimentology, stratigraphy, and paleontology (e.g., Hassan et al., 1993; Kaheila et al., 1990; Rashed and Sediek, 1997) and includes focused studies on the origin of chert in the carbonates (Elshistawy et al., 1997) and unusual large concretions in the Drunka Formation (McBride et al., 1999).
- Measured sections are limited to one drill hole (Barakat and Fakhry, 1965) and to rare areas with significant vertical exposure along the Nile escarpment (e.g., Kenawy et al., 1988), in small quarries along the Asyut-El Kharga Road, and in the escarpment bordering the El Kharga Valley (Hermina, 1967).
- Very limited work has been published on yardangs in the area of the Western Desert (Grolier et al., 1980).
- The contact between the Drunka and El Rufuf Formations has been mapped on the Asyut Sheet of the 1:500,000 Geological Map of Egypt (Klitzsch et al., 1987). Essentially the only structural work that has been done in the study area is the mapping of lineaments for the Asyut regional geology sheet using Landsat MSS imagery.

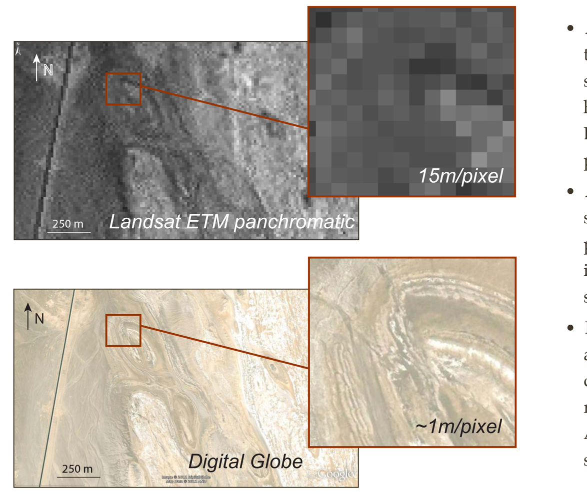
This study

- Our preliminary work in Google Earth described above on structures along the Drunka - El Rufuf contact lies in an area about 20 km east of the Asyut-El Kharga Road – an area not easily accessible in the field.
- When the opportunity arose for Alexandria University Masters student Asmaa Dokmak to do both work in Google Earth and field ground truthing, we chose an area along the same contact but farther west, where the study area is accessible from the Asyut-El Kharga Road and where Digital Globe imagery offers higher resolution than the SPOT images (shown above) that we used previously.
- **The purpose of our work has been to conduct pre-field work mapping and structural analysis over a large area using imagery in Google Earth, to field check critical areas where they are accessible along the road, and to generalize those field results to validate and improve our mapping in the inaccessible portions of the area.**
- **As far as we are able to determine, the structures that are the subject of the work reported here have not been previously recognized and unstudied.**

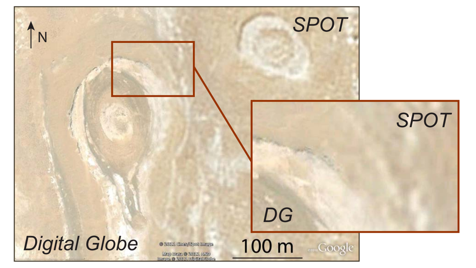
Pre-fieldwork mapping in Google Earth

Google Earth offers a unique combination of freely available, high resolution imagery that enables structural mapping in areas where bedrock is well-exposed, as it is in the Western Desert. Prior to field work, we mapped the structures in our 400 km2 study area using the methods outlined below.

Google Earth imagery for Egypt



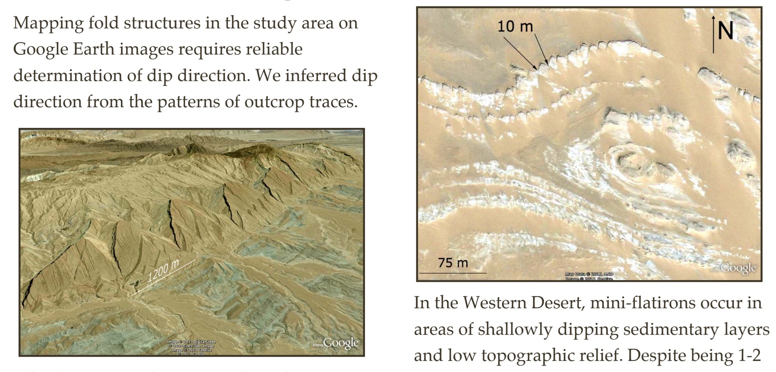
- As Google has replaced older Landsat imagery in Google Earth the last several years with high resolution commercial satellite imagery, it has become possible to study a whole host of features that were too small to be visible in the Landsat, ASTER, and other imagery that has been used previously to study remote areas of the Western Desert.
- At highest Landsat resolution (above left, with inset showing the 15-meter pixels of the Landsat ETM panchromatic band), a portion of our map area shows intriguing patterns. The resolution is not high enough to study them, however.
- Features that are enigmatic at best at Landsat resolution are mappable in Digital Globe images (at left) that are currently up in Google Earth. This imagery has a resolution of ~1m/pixel. Despite proximity to the Asyut-El Kharga road (black diagonal line), these structures have not been previously recognized or studied.



Not all high resolution images of Egypt in Google Earth are currently at a resolution of 1 m/pixel. SPOT imagery at about 3 m/pixel is the best that is available in some places. Although this is a significant improvement over Landsat resolutions, the contrast between what can be seen in Google Earth's highest resolution imagery vs. what can be seen in the slightly lower resolution SPOT images is striking and underscores why structures such as these have not been found previously – they have simply been "invisible" at the resolution of previous images.

Determining dip

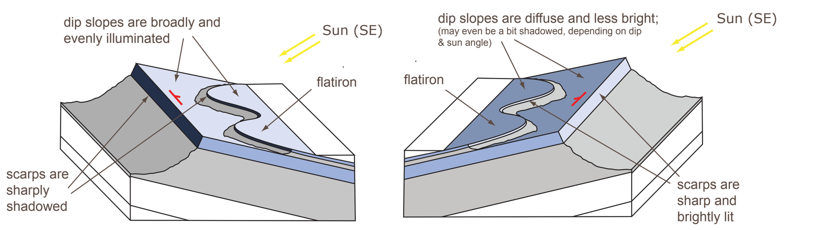
Mapping fold structures in the study area on Google Earth images requires reliable determination of dip direction. We inferred dip direction from the patterns of outcrop traces.



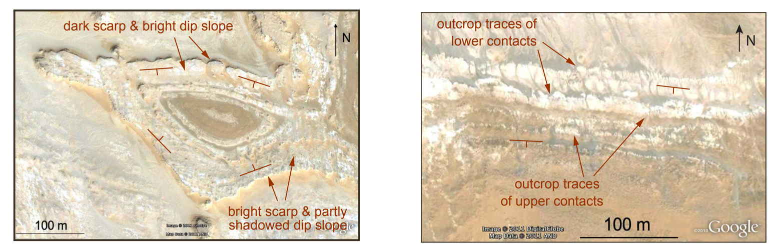
The flatirons on the flank of this whaleback anticline in the Zagros Mountains are typical of those in areas of moderate to steep dips and significant topographic relief.

In the Western Desert, mini-flatirons occur in areas of shallowly dipping sedimentary layers and low topographic relief. Despite being 1-2 orders of magnitude smaller than flatirons seen in mountainous regions such as the Zagros, they serve as good dip indicators in our imagery.

Google Earth Digital Globe images were captured by a sun-synchronous satellite shortly before 10:30 am local time. Sun illumination direction in all of our images is from the SE.



Where layers dip toward the Sun (above left), the sun-facing dip slope is brightly but broadly illuminated, and a very sharp narrow shadow occurs where the scarp that cuts across the unit faces away from the Sun. Where resistant layers dip away from the Sun (above right), the scarp faces the Sun and is narrow and brightly lit (upper arrow); faces away from the Sun, is broad and more diffusely lit (and commonly somewhat shadowed).

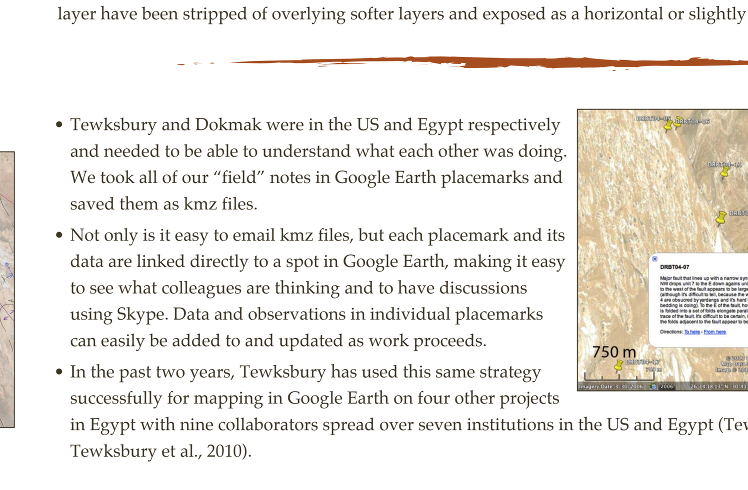


This small eye-shaped structure shows a dark scarp and bright dip slope on the north side, and a bright scarp and partly shadowed dip slope on the south side, indicating dips to the SSE and NW respectively. Both are consistent with the dip direction determined from the Vs in the small wadis, and all of the indicators together suggest that the structure above is a very small, elongate, and somewhat cuspate basin.

Where resistant layers are thin and scarps are too low to cast shadows, upper contacts typically have relatively straight outcrop traces, whereas lower contacts are typically irregular. In the image above, south-dipping, slightly more resistant white layers show ragged and irregular traces of lower contacts and straight traces of upper contacts.

Pre-fieldwork mapping

- We divided our reconnaissance mapping area into sections and used Google Earth Pro to save a high resolution image of each section for printing at 55 cm x 72 cm using a large format color printer.
- We found that having Google Earth up on the computer screen for adding notes in placemarks (see far right), coupled with mapping by hand on an overlay, was a good combination for this complex area. We could zoom in closely on the computer screen but map in a larger context on the paper printout. Hand mapping also allowed us to make tentative mapping decisions in uncertain areas and to make changes easily, both of which are more difficult when mapping digitally.



- Tewksbury and Dokmak were in the US and Egypt respectively and needed to be able to understand what each other was doing. We took all of our "field" notes in Google Earth placemarks and saved them as kmz files.
- Not only is it easy to email kmz files, but each placemark and its data are linked directly to a spot in Google Earth, making it easy to see what colleagues are thinking and to have discussions using Skype. Data and conversations in individual placemarks can easily be added to and updated as work proceeds.
- In the past two years, Tewksbury has used this same strategy successfully for mapping in Google Earth on four other projects in Egypt with nine collaborators spread over seven institutions in the US and Egypt (Tewksbury et al., 2011; Tewksbury et al., 2010).

Determining units & stratigraphy

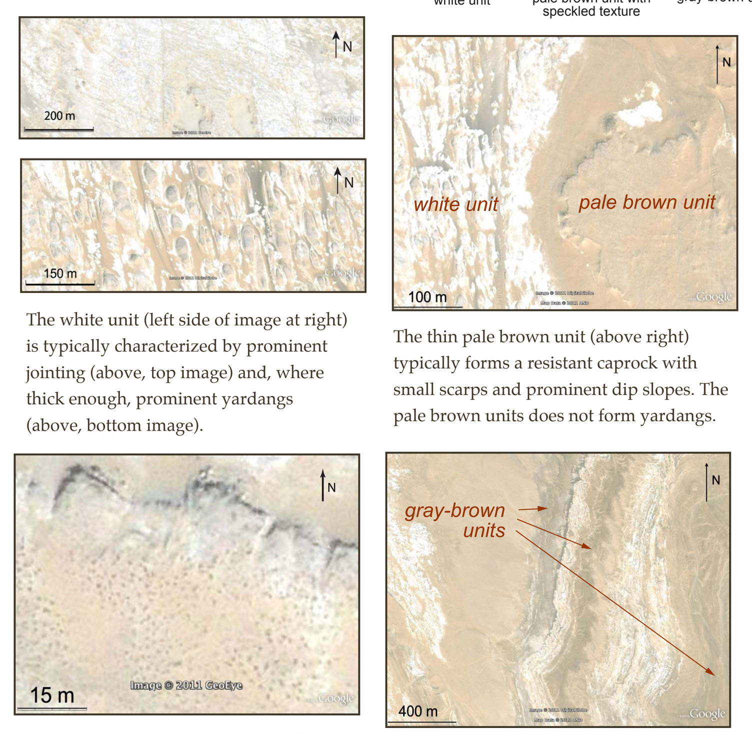
Google Earth images show sub-units of different character and color within the limestones of the Drunka and El Rufuf that can be traced over long distances. We defined a set of mappable unit types and developed a stratigraphy of sub-units in order to map not only the Drunka-El Rufuf contact but also structures within the upper El Rufuf and the lower Drunka Formations in Google Earth images.

We recognized three mappable unit types in Google Earth, a white unit, a pale brown unit with speckled texture, and a gray-brown unit. These three unit types are described below.

Pre-fieldwork strat column

Units Types for Mapping in Google Earth

white unit | pale brown unit with speckled texture | gray-brown unit



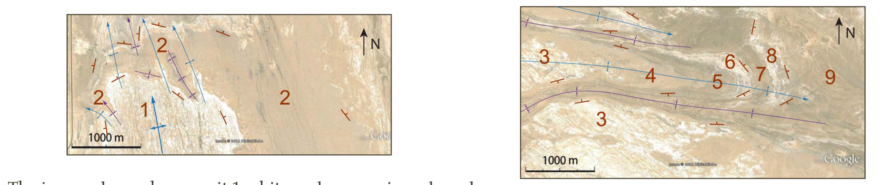
The white unit (left side of image at right) is typically characterized by prominent jointing (above, top image), and where thick enough, prominent yardangs (above, bottom image).

The thin pale brown unit (above right) typically forms a resistant caprock with small scarps and prominent dip slopes. The pale brown units does not form yardangs.

The pale brown unit is decorated with a distinctive, small-scale speckled texture.

The gray-brown unit, shown above between the outcrop areas of white and pale brown units, has no scarps, hogbacks, or yardangs.

By combining dip determinations in Google Earth with mappable unit types, we rapidly realized that our stratigraphy consists of nine sub-units (strat column right) four different white rock units (1, 3, 6, and 8), two different pale tan speckled units (2 and 4), and three different gray-brown units (5, 7, and 9). All but Unit 1 are sub-units within the Drunka Formation.



The image above shows unit 1 white rock occupying a broad, N-plunging anticline, with units 2 and 3 dipping away from the core. Unit 2 outcrop width varies from less than a few 10s of meters on the west side to nearly 2 km on the east.

The image above shows units 3-9 exposed in a broad, ESE-plunging anticline flanked by two narrow synclinal structures.

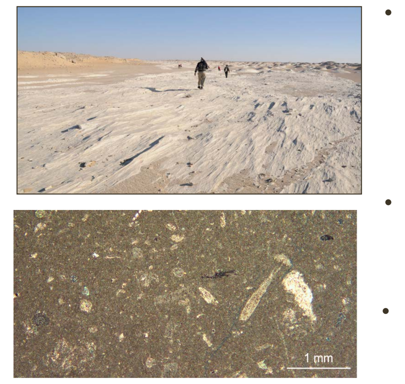
Nothing in the literature suggests significant variation in unit thickness. Variation in outcrop width likely reflects differences in dip amount, with extreme outcrop widths where bedding surfaces of a more resistant layer have been stripped of overlying softer layers and exposed as a horizontal or slightly undulating surface.

Field work along the Asyut-El Kharga Road

Because field access to this area was very limited both in time and in the distance that we could travel from the Asyut-El Kharga Road, our strategy was to choose a small number of carefully targeted areas to validate critical interpretations (dip directions, unit determinations, fold and fault structures) so that we could extend these, in principle, across the inaccessible portions of the study area where similar features occur.

Nature of the units in the field

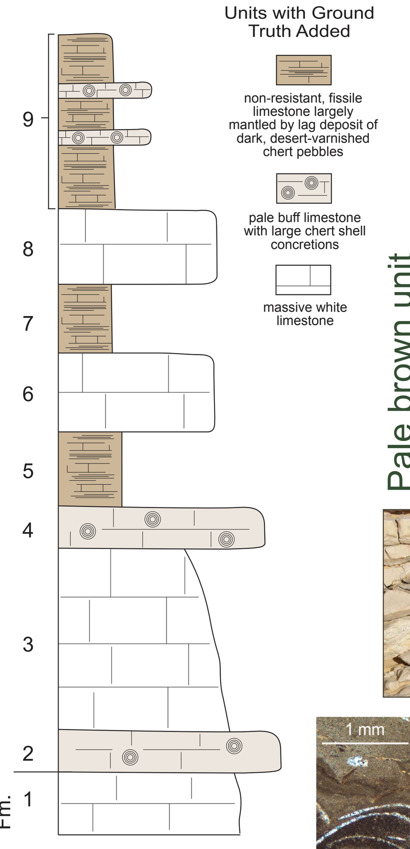
White unit



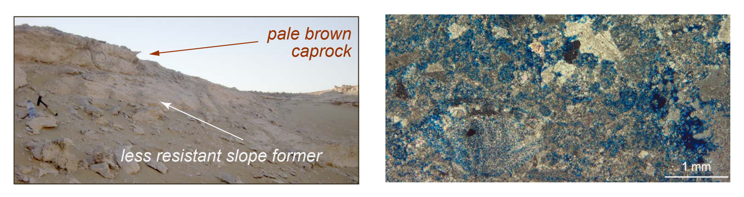
- The white rock of map units 1, 3, 6, and 8 is a dense, white, massive, crystalline limestone that is spectacularly wind fluted in many places (left). Thin sections (below left), plus plus EDAX analysis, indicate that this limestone is essentially 100% calcite and contains little if any silica.
- Where this limestone occurs in thin layers or is dipping more than a few degrees, outcrop exposures are commonly low and wind-scoured (above right).
- Where this limestone is thicker, it is eroded into yardangs ranging from less than a meter to many meters in height (right).

Post-fieldwork strat column

Units with Ground Truth Added

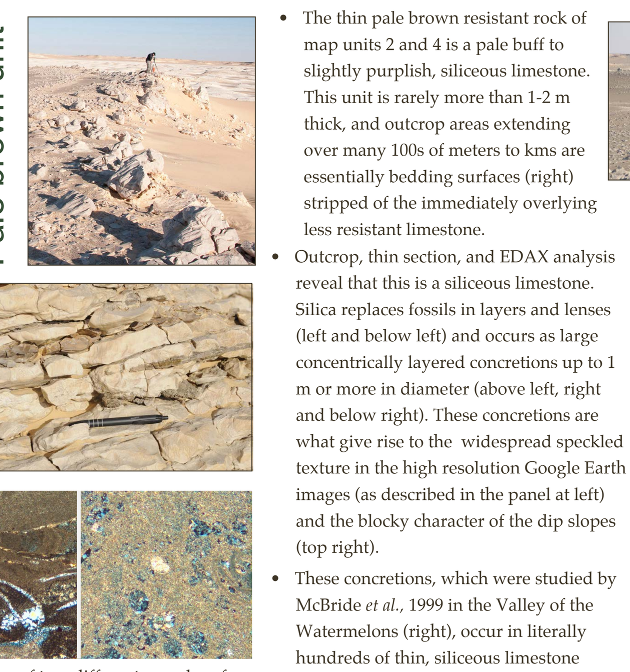


White rock sub-unit



In the field, we discovered that a less resistant white limestone is commonly a slope-former beneath the pale brown caprock of units 2 and 4. Hand samples and thin sections (above right), plus EDAX analysis, indicate that this slope-former is a porous, chalky limestone with no silica. The bright blue areas in the thin section above right is blue epoxy filling pore spaces.

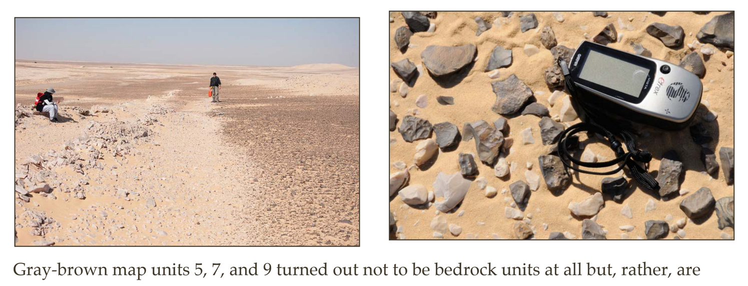
Pale brown unit



- The thin pale brown resistant rock of map units 2 and 4 is a pale buff to slightly purplish, siliceous limestone. This unit is rarely more than 1-2 m thick, and outcrop areas extending over many 100s of meters to kms are essentially bedding surfaces (right) stripped of the immediately overlying less resistant limestone.
- Outcrop, thin section, and EDAX analysis reveal that this is a siliceous limestone. Silica replaces fossils in layers and lenses (left and below left) and occurs as large concentrically layered concretions up to 1 m or more in diameter (above left, right and below right). These concretions are what give rise to the widespread speckled texture in the high resolution Google Earth images (as described in the panel at left) and the blocky character of the dip slopes (top right).
- These concretions, which were studied by McBride et al., 1999 in the Valley of the Watermelons (right), occur in literally hundreds of thin, siliceous limestone layers in the El Rufuf, Drunka, and Minia Formations.

Thin sections of two different samples of partially silicified limestone from the pale brown mapping unit.

Gray-brown unit



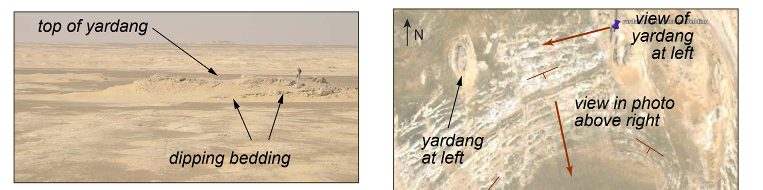
Gray-brown map units 5, 7, and 9 turned out not to be bedrock units at all but, rather, are dark-colored surface lag deposits. The photo above left shows the gray-brown map unit between two sets of outcrops of the dense white limestone bedrock. Up close, it's clear that the dark color is due to abundant dark-colored fragments. Thin section and EDAX analysis indicate that the dark-colored fragments are white chert with a coating of dark desert varnish. Less abundant white fragments are limestone with no desert varnish.

In a few rare places, we encountered small outcrops of pale buff, fissile, slightly marly limestone poking up through the dark surface lag, from which we infer that the chert lag deposits blanket largely non-resistant sequences in the stratigraphy. That non-resistant limestone underlies the dark surface lag is confirmed by the presence of white carbonate powder just beneath the surface, as shown in the tire tracks above right.

Verifying structures mapped in Google Earth

Dips

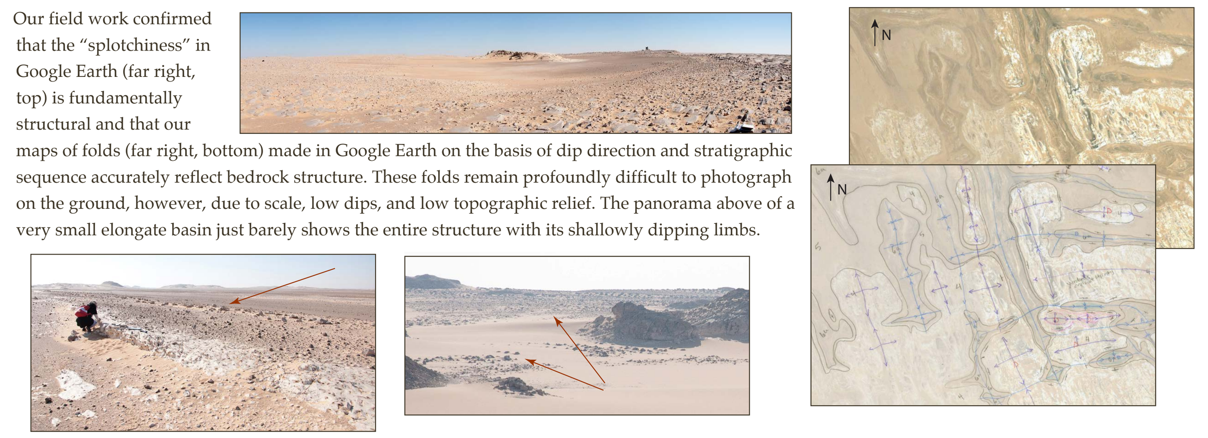
- Most critically, our field work showed that our methods for interpreting dip directions from outcrop patterns in Google Earth images worked well. Mini-Vs in small wadis (above left and center) do, in fact, point in the dip direction in the field. Broad sloping surfaces associated with mini-scarps (above right) are, in fact, dip slopes and cross-layer scarps. Dips are shallow in most places.
- We also learned that, in some areas, dip directions are easier to infer from the satellite imagery than on the ground. Where the massive white limestone is wind-scoured (right), upwind-facing scour surfaces can be mistaken for bedding. In the instance at right, dips are, in fact, away from the observer, toward an elongate basin whose center lies in the dark patch in the background.



The tops of yardangs in the white limestone are typically quasi-horizontal surfaces that lie at approximately the same elevation for a cluster of yardangs in a given area (see middle image at left). This makes it easy to assume that the dips within the limestone are also horizontal. In the yardang above left, however, it is clear that bedding dips to the left, while the yardang top (an old erosion surface?) is horizontal. This explains why the yardangs in the Google Earth image above right appear to truncate the bedding.

- Where the dark surface lag of the gray-brown map unit is confined between the outcrop areas of two adjacent bedrock units (e.g., between the faulted white limestone layers at left), the gray-brown unit is a good proxy for the non-resistant bedrock unit that immediately underlies it and allows accurate mapping of bedrock units in Google Earth images despite the fact that it is a surficial unit.
- In some areas, this dark lag deposit has been redistributed by past sheetwash and fluvial activity and, in such places, is not a good proxy for an underlying non-resistant bedrock layer, which helps explain why structures are commonly difficult to sort out in the gray-brown areas.

Folds and faults



Our field work confirmed that the "splotchiness" in Google Earth (far right, top) is fundamentally structural and that our maps of folds (far right, bottom) made in Google Earth on the basis of dip direction and stratigraphic sequence accurately reflect bedrock structure. These folds remain profoundly difficult to photograph on the ground, however, due to scale, low dips, and low topographic relief. The panorama above is of a very small elongate basin just barely shows the entire structure with its shallowly dipping limbs.

One of the unexpected ways that folds showed up in the field is in the outcrop expression of the thin, concretion-bearing siliceous limestone unit. Where the unit is dipping (above left), concretions form a line, like pearls on a string, outlining the shape of the fold. Where the unit is flat-lying, the bedding surface is exposed for hundreds of meters and is dotted over wide areas with fields of concretions (above center).

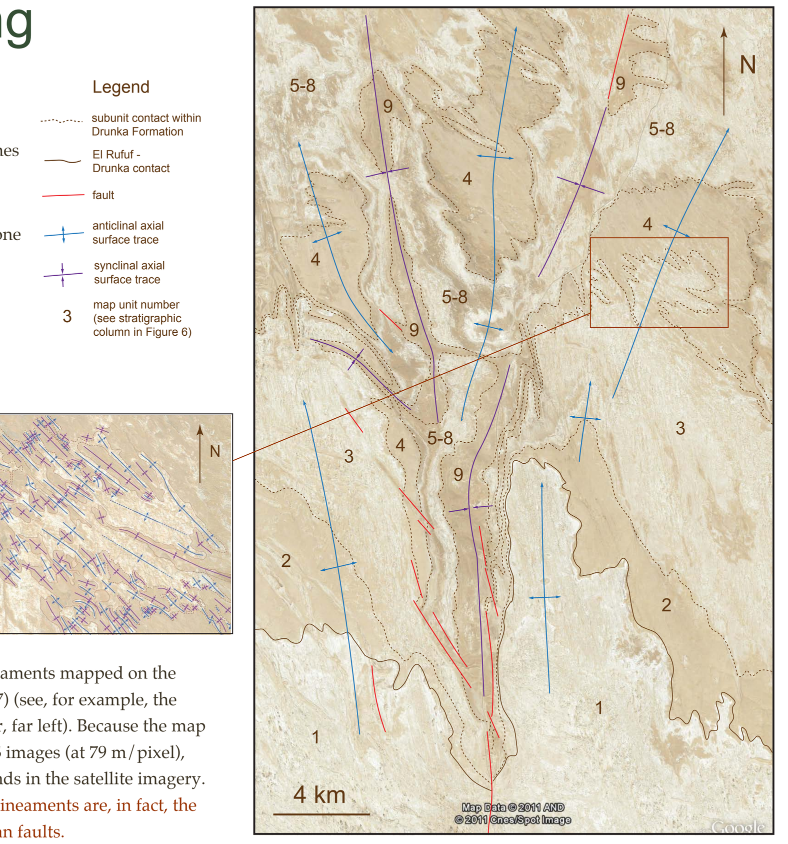
In the field, we also confirmed faults that we had mapped in Google Earth. The major faults that we field-checked typically form resistant fin-like zones (left) marked by densely jointed rock and fault breccia cemented with sparry calcite (right). We were profoundly struck by how hard it would have been to stumble on these faults in the field had we not mapped them ahead of time in Google Earth.

Results of mapping

The geologic map at right shows a generalized version of our mapping results, emphasizing stratigraphy and large-scale structures.

- Unit 4 cores two very broad north-plunging anticlines and one broad, central, low-amplitude dome.
- The central dome is separated from the two broad anticlines by open, narrower, synclinal structures, one trending NNW and one trending NNE, that merge south into one syncline.
- The southern syncline lies parallel to a major NS striking fault that continues south to bound the eastern side of the El Kharga Valley.

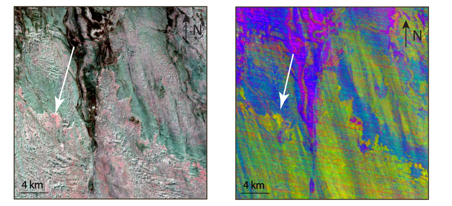
The pervasive "stripiness" of much of the western and northern portions of the study area (and, indeed, much of the Western Desert both here and the Nile) is due to the presence of narrow, open, WNW-ESE trending, synclinal structures that are typically several 100 meters wide separated by broader, low amplitude, anticlinal structures (detail map at right).



Our work also clearly illuminates the nature of the lineaments mapped on the 1987 1:500,000 geologic map sheets (Klitzsch et al., 1987) (see, for example, the lineaments in the geologic map in panel 1 of this poster, left). Because the map authors had access only to low resolution Landsat MSS images (at 79 m/pixel), they mapped lineaments wherever they saw linear trends in the satellite imagery. Our study has revealed that the vast majority of these lineaments are, in fact, the narrow synclinal structures described above, rather than faults.

Revision of Drunka-El Rufuf contact

The 1987 Asyut geologic map (Klitzsch et al., 1987) places the contact between the Drunka and El Rufuf Formations farther north to the W of the road than to the E (map at right). Careful mapping of structure and stratigraphy indicates, however, that the contact mapped by Klitzsch et al. (1987) W of the road actually lies well within the Drunka Formation, at the contact between our Units 3 and 4. Our work indicates that the contact between the Drunka and El Rufuf Formations west of the Asyut-El Kharga Road should be placed farther south, at the contact between our Unit 1 (the top of the El Rufuf Formation) and our Unit 2 (the first subunit in the Drunka Formation).

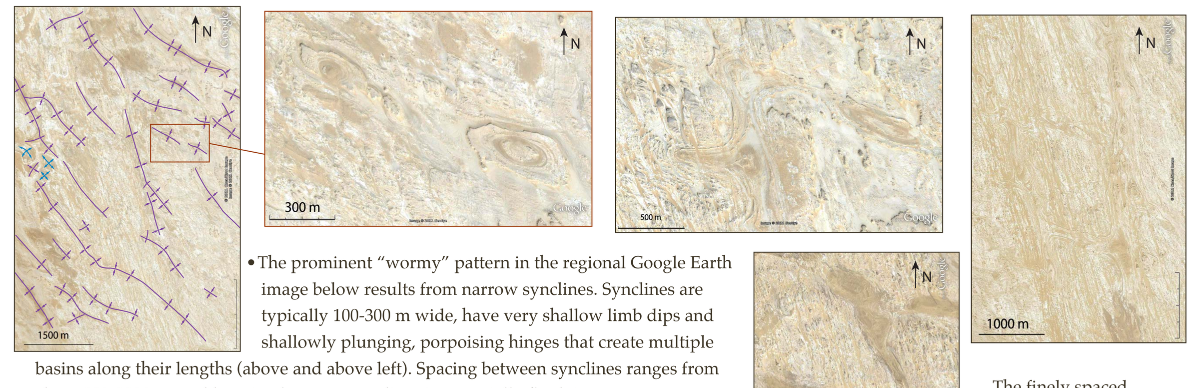


ASTER SWIR (left) and TIR (right) images processed by Dr. Sarah Robinson support our interpretation that Drunka-El Rufuf contact lies at the arrows west of the Asyut-El Kharga Road.

Discussion

We are still very much in the initial stages of regional mapping and interpretation. Based on our detailed mapping, plus additional regional reconnaissance, we have tentatively divided the structures in this area of the Western Desert into four sets.

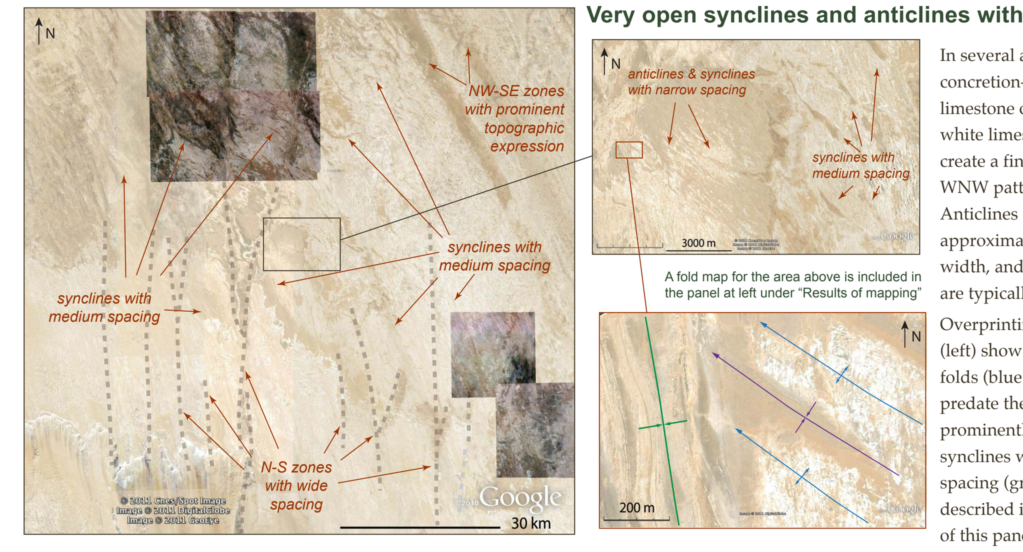
Narrow synclines with medium spacing



- The prominent "wormy" pattern in the regional Google Earth image below results from narrow synclines. Synclines are typically 100-300 m wide, have very shallow limb dips and shallowly plunging, porpoising hinges that create multiple basins along their lengths (above and above left). Spacing between synclines ranges from about 800-2000 m, and layering between synclines is essentially flat-lying.
- Most areas contain two distinct orientations of synclines (e.g., WNW-ESE and NNW-SSE; or NW-SE and NS). Synclines of one trend bend and merge into those of the other trend (right and above right), suggesting that formation of the two sets was related.
- Faults parallel to WNW and NW syncline trends are extremely rare.
- Whatever formed this regional structure is fundamentally a syncline-forming process - these structures are not typical anticline/syncline pairs.

The finely spaced NNW-SSE patterning in these images is a prominent regional joint set.

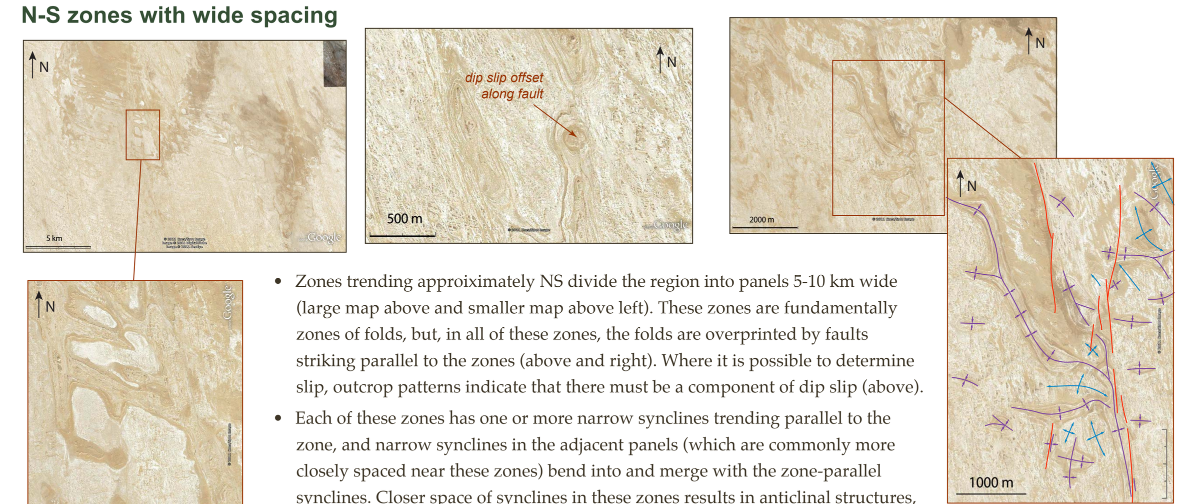
Very open synclines and anticlines with narrow spacing



In several areas where a concretion-bearing siliceous limestone overlies massive white limestone, open folds with a WNW patterning (left). Anticlines and synclines are approximately the same width, and fold wavelengths are typically 100-300 m.

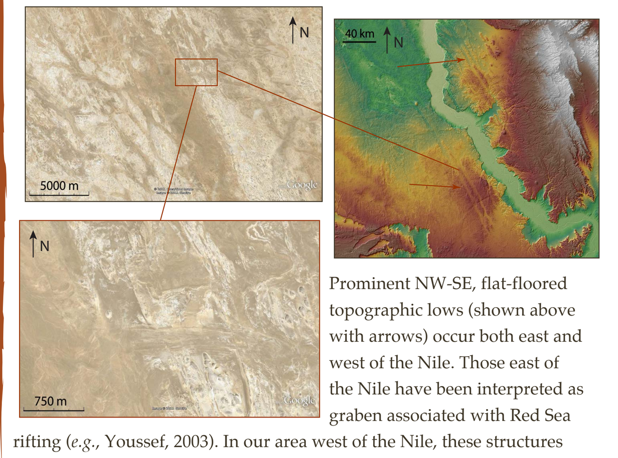
Overprinting relationships (left) show that the fine-scale folds (blue and purple) predate the larger, and more prominently developed synclines with medium spacing (green) that are described in the top section of this panel.

N-S zones with wide spacing



- Zones trending approximately NS divide the region into panels 5-10 km wide (large map above and smaller map above left). These zones are fundamentally zones of folds, but, in all of these zones, the folds are overprinted by faults striking parallel to the zones (above and right). Where it is possible to determine slip, outcrop patterns indicate that there must be a component of dip slip (above).
- Each of these zones has one or more narrow synclines trending parallel to the zone, and narrow synclines in the adjacent panels (which are commonly more closely spaced near these zones) bend into and merge with the zone-parallel synclines. Closer space of synclines in these zones results in anticlinal structures, dominantly rounded to blocky domes (images left and right).
- The major NS fault zone that extends north from the El Kharga Valley branches in our mapping area (our geologic map in panel at left) and coincides with two major synclinal structures trending NNW and NNE and can be traced for at least 40 km north of our mapping area. Faults related to this zone cut older fold structures.

NE-SW zones with prominent topographic expression



Prominent NW-SE, flat-floored topographic lows (shown above with arrows) occur both east and west of the Nile. These lows, where the Nile have been interpreted as grabens associated with Red Sea rifting (e.g., Youssef, 2003). In our area west of the Nile, these structures cut our WNW-ESE narrow synclines (left).

Interpretation

- Because the limestones that host these structures are Early Eocene in age, the structures must be Eocene or younger.
- The oldest structures appear to be the closely spaced, open synclines and anticlines that are overprinted by a prominent set of narrow synclines with medium spacing.
- The narrow synclines with medium spacing don't have companion anticlines of comparable geometry. It's almost as if the anticlines are a geometric accident of a process that actively formed synclines.
- Widely spaced zones of more complex intersecting fold structures appear to be synchronous with development of the narrow synclines, have the most prominent late fault development, and have "real" anticlines with geometries more like those of adjacent synclines.

Although this project at a regional scale is still in its infancy, we are struck by how different these structures, which lie in the Stable Platform of Egypt, appear to be from folds typical of contractional folds belts. Might NE-SW extension associated with Red Sea opening have produced small amounts of extension along NW-SE striking zones of basement weakness, causing the widely spaced narrow synclines? NE-SW extension would also put left lateral transtension on pre-existing NS basement faults. Small amounts of slip might have produces initial synclines that were co-eval with NW/NNW synclines, with later more complex structures developing, particularly where stepovers occur. Mobility of underlying shales might have been involved as well. Continued regional assessment might have been involved as well of the synclines with major graben, particularly in the eastern portion of our area.

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