In southern Egypt, basement faults of Precambrian age have been repeatedly reactivated and cut Cretaceous to Eocene rocks in a wide region west of the Nile River. Faults in Cretaceous siliciclastic rocks of the Nubian Plain and Kharga Valley display a different range of structures from those in the overlying Early Tertiary carbonates that cap the Sinn el-Kaddab Plateau. In the carbonates capping the Plateau, faults have little topographic expression but are characterized by spectacular eyeshaped domes and basins aligned along fault strike. In the Cretaceous siliciclastic rocks of the Nubian Plain and Kharga Valley, faults are commonly more resistant than surrounding rocks and are characterized by sets of discontinuous ridges several meters wide and rising a few meters above the surrounding countryside. "Eyes"

are present along these faults as well but are much less common than along faults in the overlying carbonates. Southwest of Aswan, the E-W-striking Seiyal Fault cuts a sequence of siliciclastic rocks containing friable, porous quartz sandstone. The discontinuous resistant fins marking the surface expression of the fault consist of a core zone of deformation bands overprinted by joints and sheared joints cemented by calcite, with poikilotopic calcite extending from the veins into cement halos adjacent to the veins. Damage zones containing deformation bands lie adjacent to the fault core. The deformation bands, veins, and related cement halos combine to make the fault zones more resistant than the surrounding country rock.

E-W and NNE-SSW faults cut siliciclastic rocks of the Six Hills area of the Kharga Valley over a distance of at least 200 km west of the Sinn el-Kaddab Plateau. High resolution satellite imagery reveals that the faults are characterized by en echelon major ridges and intersecting subsidiary ridges in ladder-like linking band and conjugate geometries. Geometries are consistent with predominantly strike-slip movement, dextral on EW faults and sinistral on NNE-SSW faults, with a compression axis oriented NW-SE. Based on our field work along the Seiyal Fault, we infer that slip along basement faults in the Six Hills area was likely accommodated in the overlying siliclastic units by formation of deformation band arrays and that basement faults focused fluid flow in the overlying siliciclastic cover.

## Introduction

The sedimentary bedrock of the Western Desert of Egypt displays a remarkable set of eye-shaped structures ranging in size from <100 m to several 10s of kilometers. Field mapping and satellite image analysis show that these are structural domes and basins. Some are spatially associated with faults at the surface; others are not.

Medium scale eyes along fault

The long-term aim of our work in Egypt is to address the following questions • What is the location and geometry of eyes of various types, and in what ways do

- eyes vary with size, host rock type, and location relative to faults?
- How and when did the eyes form, and what do they tell us about regional tectonics?
- What role did reactivation of long-lived basement faults play?
- What role did the character of underlying sedimentary lithologies play? • What do these extraordinary exposures tell us in general about the response of a
- sedimentary cover sequence to slip along pre-existing basement faults?

### This study

- In southern Egypt, Precambrian basement is overlain unconformably by a
- sequence of Early Cretaceous through Eocene Stable Platform sediments. • The youngest rocks in the sequence are Eocene limestones (salmon color on the map at right) that cap the broad, high, and remote Sinn el-Kaddab Plateau
- standing between the Nile Valley and the Kharga Depression. • Beneath the carbonates lie shales, marly shales, marls, and chalks of Late
- Cretaceous and Paleocene age (red and lime green at right). • The bottom of the section consists of Cretaceous sandstone and siltstone of the "Nubian Group" (green at right), which lies unconformably on Precambrian
- basement. These oldest sedimentary rocks are exposed in the Kharga Valley and the Nubian Plain but extend beneath the Sinn el-Kaddab Plateau. Prior to erosion, they were covered by the younger shales, chalks, and carbonates. • Eyes are present in all of the sedimentary lithologies, although they are most
- spectacularly developed in the carbonates of the Plateau. • Because mobility of shales underlying the carbonates may have played a
- significant complicating role in formation of eyes in the carbonates, we chose to study the faults and their eyes in the rocks immediately above the basement in the El Sett Tellaal (Six Hills) Region of the Kharga Valley and in the Nubian Plain SW of Aswan. By first establishing the response of the siliciclastic rocks at the base of the section to slip along basement faults, we will be better able to determine why eyes are so much more common in the Eocene carbonates and to assess the role of mobility in the shales between the two sequences.
- El Sett Tellaal lies in one of the remotest parts of Egypt, and we have studied the area exclusively using satellite imagery. The area southwest of Aswan is accessible, however, and we have collected field data and samples from this area.

### Previous work

- The eyes of the Western Desert were first studied by Hume (1908) in the area south of the Sinn el-Kaddah Plateau, and he recognized them as structural domes and basins. Areas where faults and eyes have been previously mapped by others are shown with colored outlines on the simplified geologic map above right.
- Eyes and related faults were carefully mapped by Issawi (1968) along the Kalabsha and Seiyal Faults, as well as along several other un-named faults in the southernmost Sinn el-Kaddab region (blue outline above) as part of a project to establish whether major east-west faults in the region posed a seismic hazard to the Aswan High Dam. El-Hinnawi *et al.* (1978) mapped eyes along faults cutting the escarpment on the east side of the Kharga Depression (magenta outline). Barakat (1972) used aerial photos to map faults and lineaments in a large area (cyan outline) overlapping with that covered by Issawi and a 1950s study by the Yugoslavian Enterprise for Applied Geophysics. Barakat was the first to systematically inventory the eyes in a portion of the region, and he mapped about 100 eyes in the area outlined in cyan; he identified one eye in El Sett Tellaal. Alfarhan *et al.* (2006) used ASTER imagery to map several stretches of the Kalabsha and Seiyal Faults and proposed that eyes formed in stepover regions of strike-slip faults.
- The major EW faults (and less prominent NS ones) cutting central Egypt (heavy black lines on map above) have been recognized for many years, and their role in regional tectonics, as well as their repeated reactivation, have been discussed by many authors (*e.g.*, Guiraud, 1985; Guiraud and Bellion, 1995; Guiraud, 1999; Guiraud et al., 2001; Youssef, 2003; Stern and Abdelsalam, 1996; Adamson et al., 1992).
- Previous work in El Sett Tellaal was compiled on the 1987 regional geologic maps by Conoco/EGPC, who used Landsat imagery to supplement field data in remote areas. Landsat imagery (above right) clearly shows a swarm of linear features in El Sett Tellaal. These linear features were mapped simply as "fractures or faults" (geologic map at right) and were not interpreted beyond this general characterization.

Opportunities Presented by Availability of New Data



The primary reason that the 1987 Geological Map of Egypt (previous section above) does not provide useful information about the network of linear features in El Sett Tellaal is that the resolution of Landsat imagery is inadequate to determine what the features actually are other than to use sun illumination direction to determine that the features are ridges (above left). At the resolution of the Digital Globe/SPOT images now up in Google Earth (1-2 m/pixel, color images above and right), however, it is possible to see spectacular

detail not only in the major ridges but also to see subsidiary features (*e.g.*, right) that allow interpretation of these features and their significance. Furthermore, the region is only very locally covered by obscuring sand, which provides an opportunity to map these features in detail in a region nearly 10,000 km<sup>2</sup> in area.



# Eyes Along Faults on the Sinn el-Kaddab Plateau

As described in the introduction below left, previous workers had recognized the presence of both faults and eyes in southern Egypt, but inaccessibility of large parts of the area, coupled with lack of good quality aerial photography or high resolution satellite imagery, precluded detailed mapping and analysis of structures in large parts of the area. Last year, we used high resolution imagery recently posted in Google Earth to do an inventory of eyes along faults of the Sinn el-Kaddab **Plateau and surrounding areas** (Tewksbury *et al.,* 2009; Pandey, 2009). The inventory is shown below, and important conclusions are summarized at right.



# Faults and Eyes in the El Sett Tellaal Region

The extraordinary network of ridges in El Sett Tellaal shows clearly on the hillshaded SRTM DEM below



• We intepret the majority of the ridges to be fault ridges analogous to the resistant ridges that we mapped in the field along the Seival Fault. We suggest that these ridges likely also consist of core zones of veins in joints and sheared joints bordered by damage zones containing deformation bands developed in the porous sandstones of the Cretaceous Six Hills Formation. • Below, we provide evidence for our interpretation of the ridges.

#### Fault ridges

Long continuous ridges



Conjugate ridges



#### Dike ridges

- Some ridges in El Sett Tellaal are likely to be dikes, rather than fault ridges.
- We suggest that long straight to broadly curved and continuous ridges
- such as those at right are dikes. • The features that we interpret as dikes (e.g., A at right) do not display the en
- echelon geometry with linking bands that are displayed by the fault ridges (B). In several areas, the ridges that we
- interpret as dikes form crude radial complexes centered on broad domes in the bedding.









Hillshaded SRTM DEM colorized by elev





# Deformation Bands and the Expression in Siliciclastic Cover Rocks of Slip on Basement Faults in Southern Egypt

- Eye-shaped domes and basins are ubiquitous on faults in this region our current inventory stands about 500 domes and basins > 500 m in long dimension – and they occur on faults of all orientations • Domes and basins along faults occur in rocks as old as the Cretaceous (Kharga and Tushka Depressions and Nubian Plain) and as young as the Middle Eocene (Sinn el-Kaddab). Field mapping by others (*e.g.*, Issawi, 1968) indicates that some of the domes in the Kharga and Tushka Depressions
- are cored by Precambrian crystalline basement. • Eyes are most common and most complex in the Eocene carbonates (green on the map below), occurring both along faults and in country rock between faults (B below).
- Eves are least common and least complex in the sandstones at the bottom of the sedimentary sequence (pale yellow on the map below) and are spatially related to faults.
- Large eyes 15-40 km in diameter (A below) occur only in the shales/marly shales/chalks in the middle of the sedimentary sequence (tan on the map below).

Eyes and faults in the carbonates

ASTER DEMs indicate that the most prominent of the ridges at left are 10-20 m in height. The highest resolution images in Google Earth reveal that the smallest of the ridges are only a meter or so wide and spaced less than 10 m apart (below), similar in scale to those that we observed in the field along the Seiyal Fault.





Variations in resolution of current Google Earth imagery from extraordinary (A) t (merely!) great (B). Most of the imagery on this poster is from areas with resolution B.

Bedding ridges

low ridges with small-scale

hogbacks and flatirons that allow

determination of dip direction. In

the example below right, beds

dip generally NW. The "eye"

above right is a complex of a

number of folds in bedding

is horizontal, typically eroding in a "dendritic"

basins along faults, however, differences in

pattern, as shown by the darker, resistant unit at



We suggest that the following types of ridges developed along faults: • Long continuous ridges many kilometers in length (above left and below right) that lie parallel to the fault trend and truncate and/or

- offset domes or basins in the sedimentary layering. • Sets of en echelon ridges (above and above right) with segments approximately 1 km or less in length, commonly connected at stepovers by linking bands. The stepover and linking band geometries enables us to determine the horizontal component of slip (right lateral in the two images above and left lateral above right).
- Sets of conjugate ridges, as shown at left.









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# Seiyal Fault in Cretaceous Sandstone

The Seival 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 (below). The Seiyal Fault cuts Lower Eocene carbonates 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. Presence of fissures in surficial deposits along the trace of the fault (shown with arrows at right) suggests that the Seiyal Fault, like the seismogenic Kalabsha Fault to the south, is still active.



East of the escarpment, the Seiyal Fault bends orth and crosses Cretaceous sandstone and iltstone (green above right). Precambrian basement lies less than 100 m beneath these

- Just west of the Aswan-Abu Simbel Road, the fault and several small branches cut a 2-km eye in the sedimentary layers (right).
- The eve is a domical structure with generally shallow dips. Bedding is horizontal in the country rock away from the dome and the fault.
- The bedrock consists of porous, friable tan sandstone interlayered with siltstone and layers of dense, ferruginous sandstone.
- The fault and its branches cut the dome and truncate dipping layers within the dome.
- The purpose of our field work was to characterize the nature of the Seiyal Fault where it cuts the sedimentary units.





Generalized map of faults, eyes, and dikes in El Sett Tellaal



Based on the imagery in Google Earth, we have defined and mapped three families of faults (described below and at right) and one set of dikes. The map above is generalized and does not show small-scale features such as linking bands or small splays and subsidiary faults. Colors are as follows:

- **EW faults with domes and basins.** These faults are parallel to the major EW faults of the Sinn el-Kaddab Plateau. The central set connects eastward to the Gebel Abu Bayan Al Wastani and Ge Abu Bayan Al Bahari faults that cut the western side of the Sinn el-Kaddab. The southern group connects to major faults in the Tushka Depression to the east. • **NNE-SSW faults** parallel to prominent bedrock fault trends throughout central Egypt.
- **NW-SE** faults.

### Characteristics of EW faults with eyes

© 2010 Cross/Spot Image Map Data © 2010 AMD left). These exceptions display eyes but are

100 m Lings © 3010 Birth Ginks

- A Start I M

© 2010 Cnes/Spot Image Map Data © 2013 AND

#### Sense of slip

- The geometry of en echelon ridges and linking bands plus the apparent offsets of a number of the eyes (e.g. left and below left) is consistent with a large
- component of right lateral strike slip on the EW faults. • The offset dome at left appears to require a component of dip slip as well (in this case, down to the south) to account for the wider outcrop exposure of the basin on the south side of the fault.



Barbara Tewksbury, John Hogan, Stephen Kemp, Tucker Keren, Carolyn Tewksbury-Christle, Richard Schultz, & Charlotte Mehrtens Hamilton College, Missouri University of Science and Technology, University of Nevada, & University of Vermont







The trace of the Seival Fault is characterized by many discontinuous resistant ridges (black arrows above and below left), rather than one continuous, through-going fault Ridges range from less than 1 meter to several meters in both height and width and from a



#### In outcrop



- The discontinuous ridges along the fault trace have dense, resistant cores with a prominent verti structure defining fins (upper left, center, and upper right at A). Bedding in the adjacent sandstones dips shallowly (blue Sharpie above and C above right), and the fins truncate bedding.
- Polished vertical surfaces with shallowly plunging lineations occur in some of the resistant fin zones. • The resistant fins (A above right) are bordered by zones with vertical deformation bands in a damage zone extending many centimeters to several meters away from the fin zones (B above right).
- Deformation band damage zones along the main branches of the Seiyal Fault have linking band geometries consistent with a large component of right lateral strike slip (above right).
- Deformation band zones without core zones are common in the country rock away from the mair trace of the fault (right) and cross-cut dipping layering in the dome.
- A set of parallel ridges (light dashes far right) at a moderate angle to the main trace of the fault (heavy dashes far right) are defined by deformation bands with linking band geometries (right) onsistent with motion conjugate to the main fault









### Summary of our initial work on the Seiyal Fault

- bands suggests a large component of right lateral strike slip on the Seiyal Fault.
- In this hyper arid desert climate, the combination of deformation band damage zones and calcite veins with calcite cement halos creates fault zone segments that are more resistant than the porous, friable country rock. • The dense core zones contain deformation bands overprinted by calcite-filled joints and sheared joints with cement halos, suggesting accommodation of slip along basement faults first by formation of discontinuous zones of deformation
- been proposed by Eichubl et al. (2009) for the Moab Fault.



- The central image above shows the three fault families that we have identified in El Sett Tellaal.
- EW faults with eyes are generally characterized by prominent, long straight ridge segments. • NNE-SSW faults are generally characterized by complex stepover and linking band geometries
- and a lack of eyes. • NW-SE faults are generally characterized by en echelon geometries with linking bands and a lack
- Details about each of the three types are presented below and at right.

• Eyes are characteristic of this fault set and distinguish this set from the other two. Eyes include both domes and basins ranging from well-defined small domes and basins a few 100 m in size to broad subtle domes and basins many kilometers in diameter (examples at right and below left). We have inventoried a total of 257 domes and basins in El Sett Tellaal along the EW faults. • Faults in this set trend generally EW and are dominated by long, continuous ridges a kilometer or more in length and parallel to the fault trend. Several important exceptions to this general rule exist however (*e.g.*, at characterized by en echelon ridges at a low angle to the

fault trend, rather than by through-going, continuous



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- Everywhere we have mapped eyes and ridges associated with the EW faults, both the main ridges and subsidiary ridge splays cross cut and postdate formation of the domes and basins of the eyes (images at left and right).
- In these images, the main EW faults and subsidiaries are shown with solid lines; bedding traces are outlined with light dashed lines.



Cooperation Cooperation Cooperation



# Characteristics of the NNE-SSW faults



Characteristics and sense of slip

- Typical portions of NNE-SSW faults are shown at two different scales in the two images above left.
- The NNE-SSW faults in the map area are dominated by right stepovers with linking band geometries as shown above, indicating a significant component of left lateral strike slip. The presence of the dark resistant unit to the west of the fault but not to the east (image above far right) suggests a component of dip slip as well.
- Eyes are extremely rare on the NNE-SSW faults. The basin above right is the only example that we found, and its potential association with other faults is unclear.





- **Fiming relative to dikes** • Dikes are offset both along the major EW faults with eves
- above) and along the minor EW faults (below). • Offsets are right lateral
- consistent with slip sense determined from stepover and linking band geometries.



The key map above center shows progressive northward steps in one of the main EW faults. Enlarged images a-e show that eyes and eye complexes are located broadly in fault bend and stepover areas. In every instance that we have examined here and elsewhere in El Sett Tellaal, the domes and basins that form the eyes are cut by straight fault ridges that developed later than the domes and basins, offsetting and truncating the eyes. We interpret this to indicate that the domes and basins formed in the sedimentary cover *before* the basement fault propagated up through the cover rocks.











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mpletely filling pore spaces adjacent to the veins

1 mm

reliminary petrographic work suggests that the sandstones were weakly cemented by an Fe-rich carbonate cement, possibly in the vadose zone, and experienced several subsequent cementation events. Cross cutting relationships indicate that calcite vein fill and blocky calcite in poikilotopic cement halos postdate formation of deformation bands (db, above left) and, in some cases, form in zones adjacent and parallel to preexisting deformation bands (db, above right).

• The Seival Fault is characterized in the Nubian Plain by discontinuous resistant ridges consisting of dense core zones bordered by damage zones containing deformation bands. Initial work on linking band geometries in the deformation

bands followed by fracture and slip in the cores of the segments, localized fluid flow, and precipitation of calcite, as has





- 2010 Case/Spot Image Map Cate 2010 AND **Relationship to other features**
- Along one NNE-SSW fault (left), a NWfault appears to be offset along the NNE-SSW fault. It is far more common however, to see no clear offset of one by
- In many places, the main ridge and linking band trends of the NNE-SSW and NW-SE faults have the same conjugate geometries (above).
- There is no place in the map area where clear relationship can be demonstrated between the NNE-SSW faults and the EW faults with eyes.
- The dikes appear to be younger than the NNE-SSW faults (left).

### Characteristics of the NW-SE faults



Characteristics and sense of slip • Typical portions of NW-SE faults are shown at two different scales in the two images above.

• The NW-SE faults in the map area are dominated by en echelon geometries with linking bands as shown above. We interpret this as a Riedel geometry, developed over a basement fault. • Although the geometry of fault segments and linking bands consistently indicates a large component of right lateral strike slip, the pattern of eroded resistant layers **Relationship to the other fault sets** in some of the stepovers indicates a component of dip slip for these faults as well (image at right).





• As mentioned in the section above on the NNE-SSW faults, the main ridge and linking band trends of the NNE-SSW and NW-SE faults have the

same conjugate geometries (left). • Where NW-SE faults are in close proximity to the EW faults with eyes, the relationship between the two is ambiguous, and it is common for NW-SE faults to appear to either die out or merge with the EW faults.

### Discussion

#### Summary of critical observations

- Faults and stresses
- The NNE-SSW and NW-SE faults in El Sett Tellaal consist of en echelon segments, not through-going fault planes. The Seival Fault where we examined it in sandstones is similar in surface expression (albeit with smaller and lower relief ridges) and is not characterized by a through-going fault plane.
- The only faults that appear to have long segments of through-going faults are the EW faults in El Sett Tellaal and the portion of the Seival Fault where it cuts carbonate rock on the Sinn el-Kaddab Plateau.
- EW and NW-SE faults in El Sett Tellaal have features consistent with right lateral strike slip. NNE-SSW faults have features consistent with left lateral strike slip. Both appear to have non-zero, but undetermined, dip slip components.
- Deformation bands along the EW Seival Fault suggest largely right lateral strike slip, with left lateral strike slip along subordinate conjugate structures.
- Slip sense, fault orientations, and orientations of conjugate structures are consistent with a maximum horizontal compression direction oriented NW-SE (approximately 325-145°).

- On the Sinn el-Kaddab Plateau, eyes are common along faults of all orientations and are commonly complicated and multiple. Eyes also occur in the country rock away from faults. • In El Sett Tellaal, only the EW faults have eyes, and they are generally simpler and fewer in number than
- those along faults on the Sinn el-Kaddab. Faults of other orientations in El Sett Tellaal do not have eyes, nor does the country rock in El Sett Tellaal. • Late Cretaceous through Eocene shaly, marly, and chalky rocks exposed over large areas between the Sinn el-Kaddab escarpment and El Sett Tellaal have very large eyes only loosely related to faults.

- Deformation bands in sandstones along the Seival Fault are overprinted in fault cores by joints, sheared joints, and calcite vein filling.
- Eyes in Cretaceous sandstones in El Sett Tellaal and along the eastern Seival Fault predate faults and are cut by en echelon fault segments, by linking bands, and by through-going faults.
- Faults and eyes in the sandstones of El Sett Tellaal must postdate deposition in the Late Cretaceous. • Faults and eyes in carbonate rocks of the Sinn el-Kaddab Plateau must postdate deposition in the Middle Eocene • Dikes in El Sett Tellaal are offset by slip along the EW faults with eyes but crosscut the NNE-SSW faults. The age of the dikes is unknown, but major magmatic events in SW Egypt occurred during the Late Cretaceous (83-78 Ma) and the Middle to Late Eocene (41-45 Ma, with some dolerite dikes as young as 32 Ma) (Meneisy, 1990).

#### The response of Cretaceous cover to slip along reactivated basement faults in El Sett Tellaal

Our current working hypothesis is as follows:

- Reactivation of major EW basement faults resulted first in the formation of forced folds in the Cretaceous sandstones and siltstones immediately overlying the basement – these are the domical and basinal "eyes".
- Continued or later slip on the major EW basement faults in response to NW-SE regional compression caused localized brittle deformation resulting in deformation band formation, overprinting by joints and sheared joints in high strain zones, localized fluid flow, and precipitation of calcite in veins in fault core zones. In the hyper arid Sahara, these fault segments now form resistant ridges.
- The presence of en echelon segments with linking bands, rather than through-going faults, suggests that slip was limited along the NNE-SSW and NW-SE fault sets in El Sett Tellaal and that through-going faults had not propagated upward from the basement to this level along these faults.
- The fact that the EW faults are the only ones with both eyes and long, through-going fault ridges suggests that the EW faults are the main faults accommodating deformation in El Sett Tellaal.

#### Implications for structures in Eocene carbonates of the Sinn el-Kaddab Plateau

Our current working hypothesis is as follows:

- The huge eyes in the shales and related rocks that overlie the Cretaceous sandstones and underlie the Eocene carbonates of the Sinn el-Kaddab suggest widespread mobility in the shales.
- Mobility in the shales underlying the carbonates could help explain why dome and basin structures are more common and more complicated both along faults and in the country rock in the carbonates of the Sinn el-Kaddab than they are in the underlying Cretaceous sandstones.
- Several huge questions immediately emerge and will drive our future work: • When were these faults active? Our working hypothesis suggests that the bulk of the deformation forming
- the eyes and faults postdates the Middle Eocene. The conundrum is that statements about major right lateral slip along EW faults during the Santonian (Late K) are ubiquitous in the literature (*e.g.*, Guiraud and Guiraud et al., 1985, 1995, 1999, 2001; Youssef, 2001). On the other hand, we have yet to find a published source that describes the actual evidence for major Cretaceous slip on the basement faults in this part of
- Egypt, so the amount of slip and the nature of structures produced remain legitimately open questions. • Did Cretaceous slip accomplish only forced folding in the cover rocks (which could have been thin), with
- post-Middle Eocene reactivation responsible for the vast majority of the structures we now see? • The age of dikes in El Sett Tellaal holds great promise for determining the timing of development of both the
- eves and the faults. How old are they?
- How thick was the cover rock when the faults in El Sett Tellaal were active?
- Can detailed chronologies of formation of structures, veins, and cements help constrain the model? • If the Cretaceous cover rocks experienced at least two episodes of slip on underlying basement faults, why
- are the structures less complex than those in the younger rocks, which experienced only one episode of slip?
- Is it reasonable to suggest that the shales were mobile? If so, what caused them to mobilize, and when? • What role did processes that formed the "bubble wrap terrain" (Tewksbury, 2009) in Eocene rocks north of the Sinn el-Kaddab Plateau play in the formation of domes and basins of the Sinn el-Kaddab, and can those processes help explain the greater complexity of structures in rocks higher in the sequence?

### Implications for fluid flow in the Nubian aquifer

The section of the Seival Fault in our study lies in Cretaceous siliciclastic rocks that form the extensive Nubian aquifer in Egypt and elsewhere in North Africa. The presence of fault damage zones with extensive deformation band formation may have a complicated impact on fluid flow in rocks of the Nubian aquifer.

- Because deformation band formation reduces porosity and permeability, and hence reducing saturated hydraulic conductivity (*e.g.*, Antonellini and Aydin, 1994; Sigda *et al.*, 1999), the presence of deformation bands may inhibit the flow of groundwater both along faults and across faults in the saturated zone. The contours on groundwater head strike at a high angle to the axis of the Kharga Valley, and the groundwater flow is generally toward the north (Thorweihe and Heinl, 2002). The presence of major EW faults with deformation bands in El Sett Tellaal might well influence groundwater flow rates and directions, especially
- Work by Wilson *et al.* (2006) and Sigda and Wilson (2003) suggests that the opposite is typically true in the vadose zone, where low-porosity deformation bands can be up to six orders of magnitude more hydraulically conductive than surrounding porous sandstone. Although this is unlikely to have an impact on aquifer recharge, capillarity in these hydraulically conductive zones might preferentially wick groundwater to the surface along deformation band zones.

#### Seeking students for Desert Eyes Project

We have received NSF funding to study the origin of domes and basins in the Western Desert. Our grant provides funding for several undergraduate students to participate in field research in Egypt. For more information and application instructions, please contact Barbara Tewksbury via email at btewksbu@hamilton.edu