Insights About Polygonal Faults and Related Structures from Extensive Exposures of the Cretaceous Khoman Formation, Western Desert, Egypt

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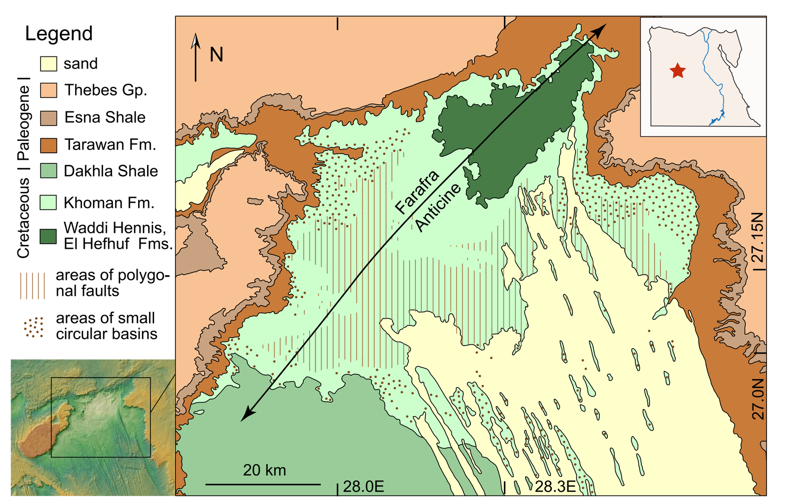
Seismic investigations over the 15 last years in marine basins around the world have revealed the common occurrence of sets of extensional faults that intersect to form networks of large polygons, each hundreds of meters to more than a kilometer across. Although polygonal faults been studied remotely in well over 100 basins worldwide, extensive on-land exposures that lend themselves to field study have remained elusive. We report on discovery of a polygonal fault system in chalk near Farafra Oasis, Egypt. A unique combination of regional structure, topography, and a hyperarid climate has resulted in almost continuous exposure of polygonal faults over an area of nearly 1000 km^2.

We first discovered the faults in high resolution satellite imagery in Google Earth, where their polygonal pattern is spectacularly revealed. Our subsequent field work established contemporaneous activity of faults of different orientations, provided evidence for the role of elevated fluid pressures in initiating the faults, and documented the small-scale features of polygonal faults that are difficult, if not impossible, to study remotely using seismic data. Our field observations provide new insights into polygonal fault systems in marine environments and may assist in the recognition of on-land exposures elsewhere.

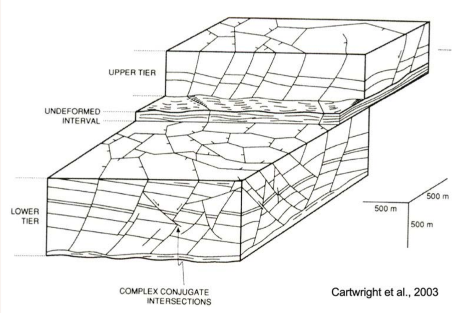
General geologic setting

The Khoman Formation is exposed in the eroded core of the broad NE-SW regional Farafra Anticline (below).

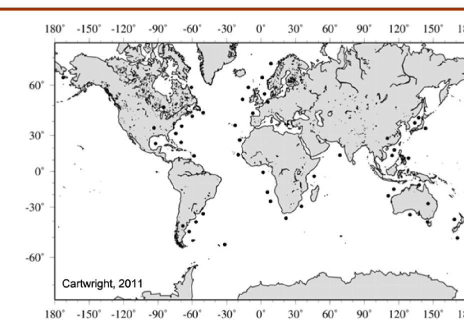


- The Khoman Formation (pale green at right) conformably overlies sandstones and shales of the Wadi Hennis and El Hefhuf Formations (dark green) and is overlain by limestones, shales and chalk of the Early Tertiary Tarawan and Esna Formations and Thebes Group (browns and peach). The cumulative surface and subsurface thickness of the chalk is at least 220 m (Barakat and Hamid, 1974) .
- The low relief of the broad Farafra Valley (inset DEM), coupled with very low limb dips on the Farafra Anticline (and lack of vegetation and surficial cover!) combine to create what are essentially widespread bedding surface exposures over hundreds of square kilometers. This is an extraordinary and fortuitous situation for us, because polygonal faults are best studied on bedding surfaces (which is akin to having map view seismic images of particular horizons) rather than cross section exposures.

Background



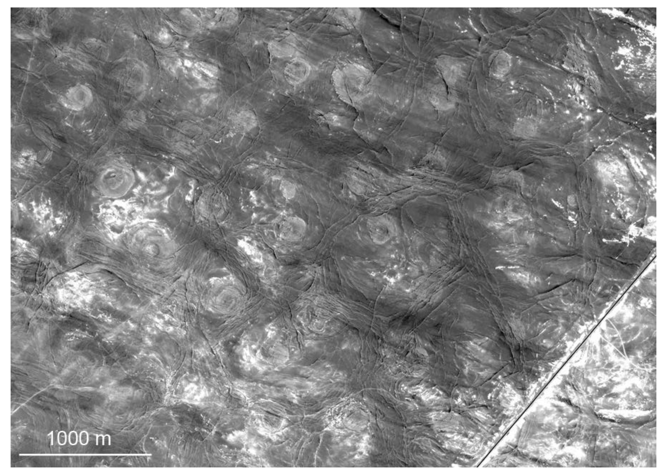
- Polygonal faults are an array of layer-bound normal faults with diverse strikes partially or fully intersecting in a polygonal pattern.
- Polygonal faults occur only in fine-grained sediments (muds, chalks).
- The origin of polygonal faults is still much debated (Cartwright, 2011), but proposed mechanisms involve early consolidation and diagenesis in fine-grained sediments, volume decrease and layer contraction, and significant pore fluid release.



- Polygonal fault systems occur in >100 marine basins worldwide.
- Virtually all polygonal fault systems have been studied remotely by the oil industry using 3D seismic and drilling. Even the ones shown at left in China and Australia represent polygonal faults studied in the subsurface (Nicol *et al.*, 2003; Sun *et al.*, 2010).
- The only on-land exposures of polygonal faults that have been previously studied occur in discontinuous and widely separated outcrops in Cretaceous chalks of the UK and France (Hibsch, 2003).

Overall distribution of polygonal faults and small circular basins

- The Khoman Formation exhibits polygonal ridge networks that we interpret as polygonal faults (vertical brown lines on map at left; evidence below) and small circular basins that we hypothesize are overlying fluid escape structures (brown dots on map at left, evidence below).
- Polygonal faults and small circular basins occur **only** in the Khoman Formation and do **not** occur in units above and below. Eye-shaped structures occur stratigraphically higher in the Khoman than the polygonal faults.
- Virtually every exposed part of the Khoman Formation contains either polygonal faults or small circular basins. Fairly continuous exposures of these features cover an area of about 2000 km^2, but we have found these features in interdune patches over an additional area of at least 5000 km^2.

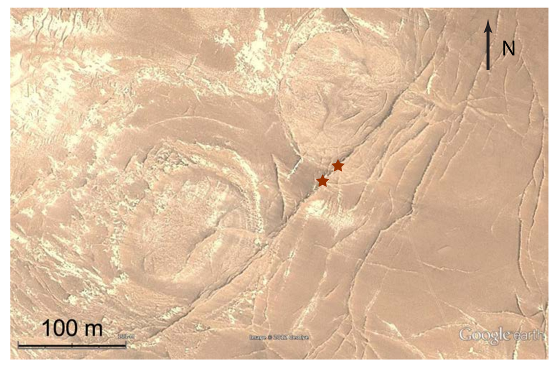


Polygonal ridge networks

Large tracts of the Khoman Formation exhibit dense clusters of very low relief, slightly resistant ridges that are arranged in networks defining polygonal areas 500-1000 m across.

- Ridges of multiple orientations in the Khoman arranged in clusters that define polygonal areas 500-1000 m across with fewer faults in the polygon cores.
- Faults appear to be prominent ridges in the satellite imagery (illumination from the SE in image at left). Field exposures (right) reveal that this is an illusion produced by the concentration of dark surface lag on the upwind (NW) sides of low calcite veins.

Summary of evidence for polygonal faulting

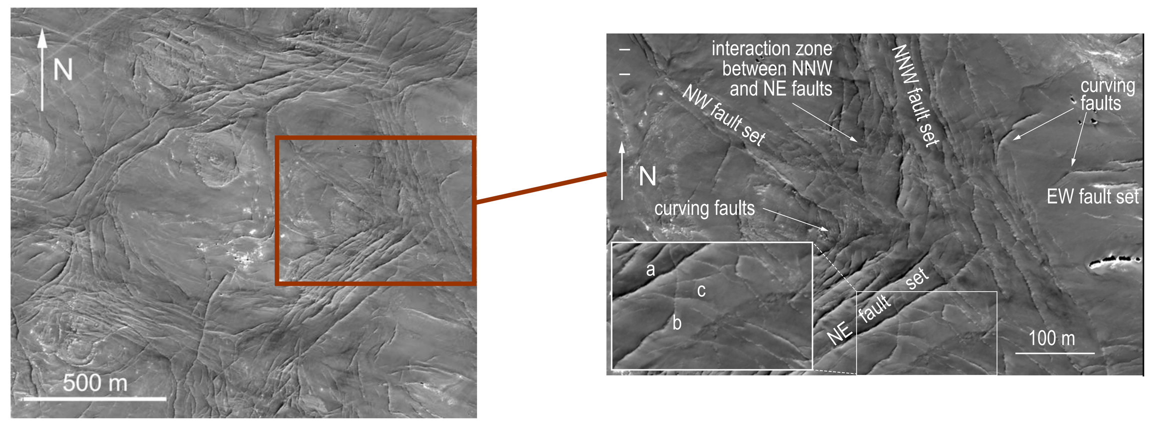


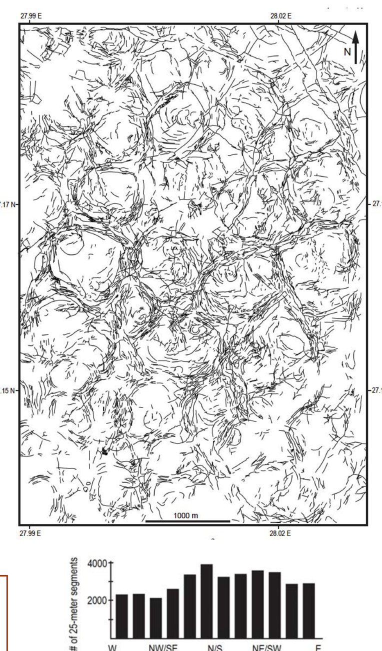
Steeply dipping normal faults with calcite veins

- Ridges in the Khoman are formed by differential erosion of more resistant calcite veins up to 25 cm thick that occur along faults in the soft chalk country rock.
- Fault surfaces are strongly grooved (red arrows above). Coarse calcite forms casts of the grooves along the fault surfaces, crystallized both parallel and perpendicular to fault surfaces and commonly extending into dilatant space (above right). Calcite veins commonly exhibit multiple phases, some with slivers of chalk between veins.
- Faults dip steeply (70 - nearly 90°), slip indicators indicate dip slip, and rare offsets of planar features (left at stars) indicate that slip is normal. Slip calculated from strike offset and dip of layering at left is 2-3 m.

Appropriate rock type: polygonal faults are found only in fine-grained sediments (muds and chalks). The Khoman Formation is the right kind of lithology to host polygonal faults.

Layer-bound character: we see no evidence that these faults occur in either underlying or overlying units; they appear to be confined to the Khoman Formation.





Polygonal geometry and isotropic horizontal stress field

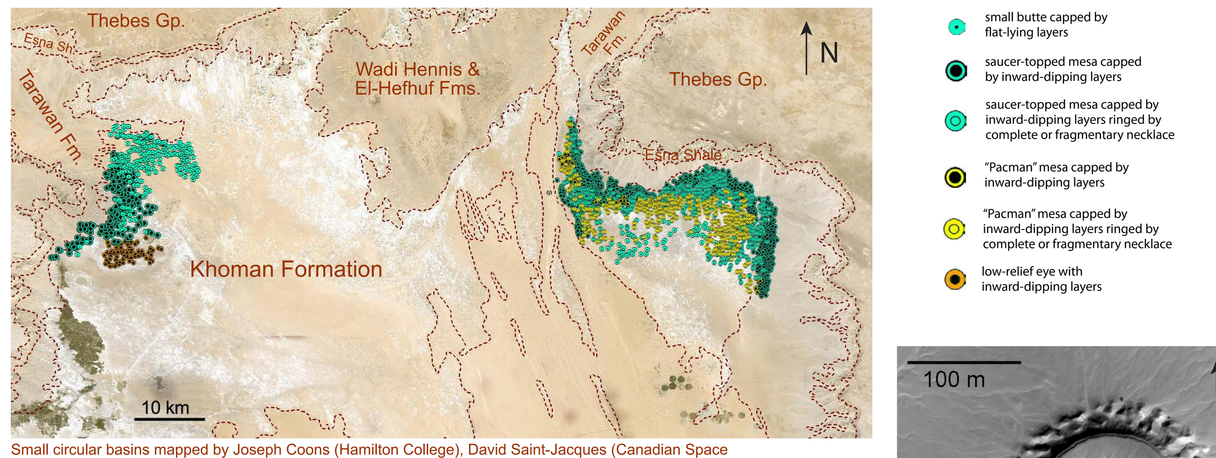
- Mapping of all faults in a 25 km^2 area (left) using ~1 m/pixel satellite imagery reveals a linked polygonal network at a scale typical of polygonal faults imaged in marine basins with 3D seismic. A histogram of fault azimuths (determined using the Polyline Get Azimuth in ArcGIS) reveals no dominant or characteristic fault orientation.
- Geometries indicate that faults of multiple orientations were contemporaneously active. In the area shown above left, faults in the NNW, NE, and NW sets (which define individual polygon sides) commonly curve from one polygon side into an adjacent one. Multiple fault orientations occur where polygon sides meet and interact, with inconsistent crosscutting patterns related to overlap in the timing of fault growth. For example, faults a, b, and c (above right) were each influenced by the others in terms of mechanical interactions (curving of one fault into another) and crosscutting, implying overlap in the timing of growth of each fault orientation. All of these features suggest contemporaneous activity of faults of different orientations, rather than intersection of sets of faults of different ages.
- These features imply simultaneous activity of normal faults with distinctly different strikes and no dominant extension direction.

Combined evidence suggests that the Khoman Formation displays the first extensively exposed polygonal fault system that has been recognized in an on-land field setting.

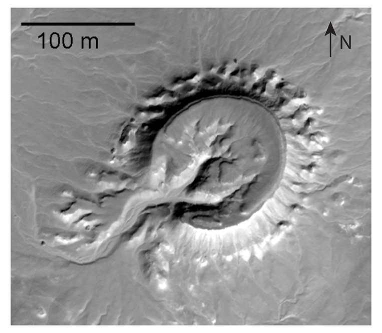
Small circular basins stratigraphically above the polygonal faults

The upper part of the Khoman Formation is characterized by nearly 2000 small circular basins (map below) each less than 200 m across and characterized by inward dipping layers.

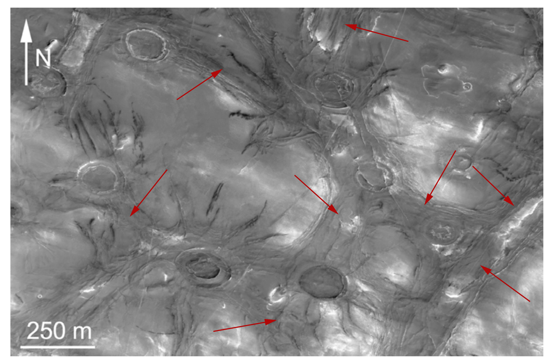
down elevation, down section

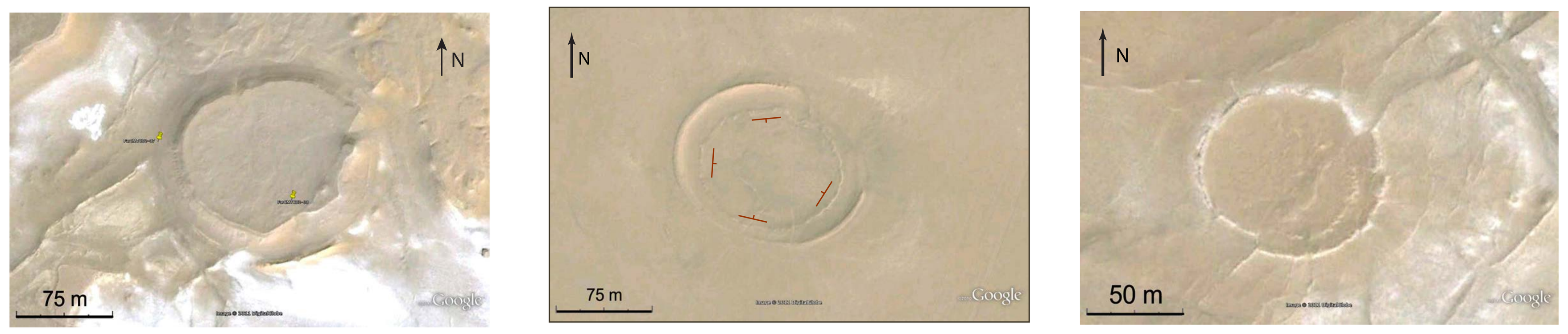


Small circular basins mapped by Joseph Coons (Hamilton College), David Saint-Jacques (Canadian Space Agency), & Carolyn Tewksbury-Christle (United States Air Force); regional geology after Klitzsch *et el.*, 1987)

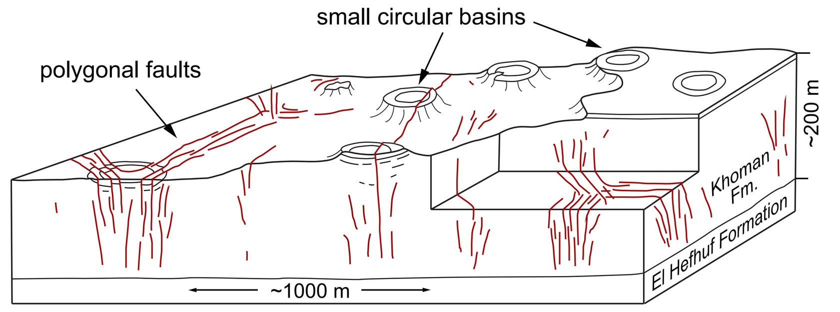


- Eye-shaped features have a consistent size (100-200 m in diameter) and are characterized by layers that dip inward a few degrees.
- Most of the small circular bains mapped above are small saucer-topped mesas < 10 m high with concave caps of slightly more resistant limestone (images left and below left).
- Low-relief small circular basins have similar sizes and inward dips (below). Some low-relief small circular basins have rays (right).
- Some small circular basins are cut by normal faults (left and below) that are similar in character to the polygonal faults described at left.



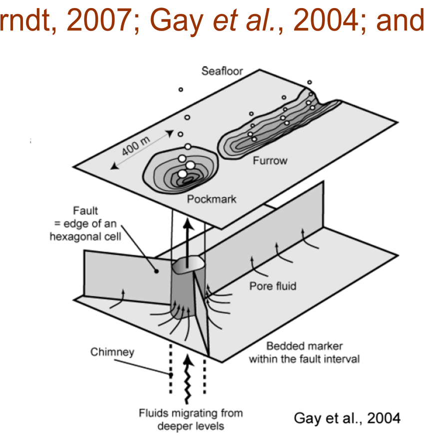


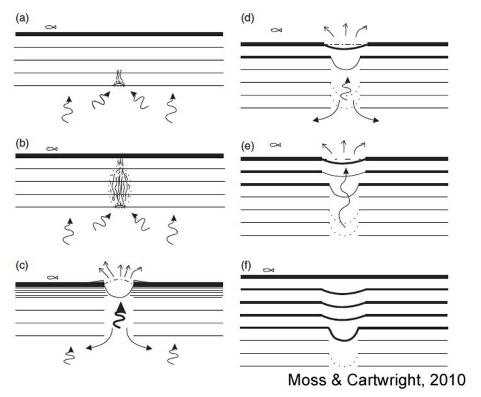
Most of the small circular basins are located stratigraphically above the horizon in the Khoman Formation that hosts the polygonal faults. The stratigraphically lowest eyes are cut by and spatially associated with polygonal fault clusters.



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

- In models proposed by Gay *et al.* (2004) and Moss and Cartwright (2010), fluid escape through pipes and tabular zones creates pockmarks and furrows at the seafloor. Pipes are typically less than 100 m to a few hundred meters across (right) and commonly slightly oblong. Over time, pockmarks fill in as sedimentation proceeds, but continued fluid flow keeps the pockmarks as negative features until fluid flow ceases (middle right). As sedimentation proceeds, seafloor sediments drape the pockmarks, creating layers with small inward primary dips that are visible in seismic profiles. Flow of bottom currents can result in both local unconformities and irregularities in the sediment infill in pockmarks (Andresen *et al.*, 2008).
- Our current working hypothesis is that the eye-shaped structures in the Khoman Formation are fluid escape features developed above the polygonal faults in the chalk.

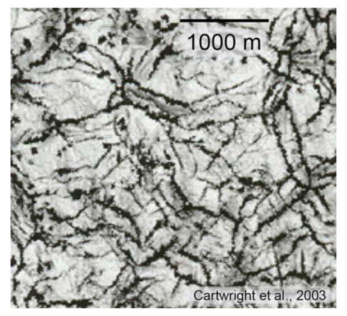




Insights about polygonal faults

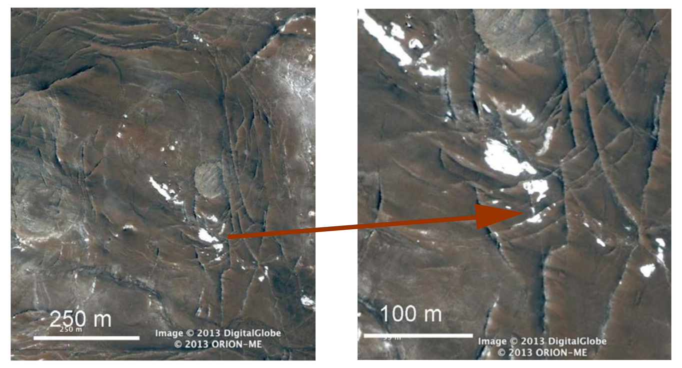
Features below seismic resolution

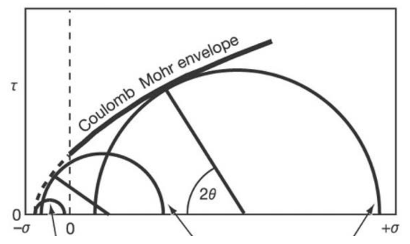
- Many of the features we see in the field in the Khoman lie below the resolution limit of seismic studies (right, seismic horizon map, contrasted with below right and bottom right).
- Fault networks in the Khoman reveal a complexity in both polygon boundaries and polygon cores that has not been apparent in seismic studies.



Evolution of structures during polygonal faulting

- Field relationships of faults show complex structural adjustment as the polygonal fault system evolved.
- Concentric normal fault segments, as well as outward-dipping, nested, conical normal faults, allowed polygon cores to continue to contract once polygons formed.





Role of pore fluid pressure in polygonal fault initiation

- Very steep fault dips (~80°) in the Khoman indicate that shear failure occurred under conditions where the Mohr circle intersected the failure envelope where σ_3 was negative (tensile), but had not reached the tensile strength of the rock.
- This condition was most likely achieved by driving a small Mohr circle (with maximum shear stress less than the rock cohesion) to the left by increasing pore fluid pressure.
- If steep initial dips under high Pf is characteristic of polygonal faults in general, shallower dips in buried systems would reflect flattening during burial.

Recognizing polygonal faults in the rock record

- Despite polygonal faults being very common in modern marine basins, our Farafra discovery represents the only well-exposed on-land example of a polygonal fault system.
- We suggest that polygonal faults *are* likely quite common in the rock record but are difficult to recognize because they occur in fine-grained, non-resistant lithologies and because the 3D polygonal geometry is difficult to establish where field exposures are limited.
- The extraordinary outcrop exposures in the Khoman should provide criteria for recognizing polygonal faults systems elsewhere in the rock record.

scan to connect to our June 2014 article in *Geology*

scan to connect to the Research Forum piece by Cartwright on our work in the June 2014 issue of *Geology*