Are outcrop studies the key to understanding the origins of polygonal fault systems?

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INTRODUCTION

Polygonal fault systems (PFSs) are extraordinary features of many sedimentary basins. They consist of vast numbers of small (<100 m throw) normal faults aggregated into complex three-dimensional (3-D) arrays with a characteristically polygonal map pattern, and fault lengths and spacing of the order of a kilometer. Polygonal faults are more than just a curiosity, or a beautiful pattern to be admired on some computer-generated map of the subsurface. Fundamentally, they challenge us to think hard about the processes operating in many sedimentary basins during shallow burial.

PFSs are best developed in depositional systems where the dominant lithologies are fine-grained, often with hemipelagic affinities . Globally, PFSs are hosted in lithofacies that range from almost pure smectitic claystones to almost pure chalks (Cartwright and Dewhurst, 1998). They are found in hundreds of basins, especially in divergent margin settings, and have been described in successions ranging from Late Jurassic to Recent. They are also found in intracratonic basins; type examples being in the Cenozoic slope and basin floor claystones of the North Sea Basin, Chinese onshore basins, and the smectite-rich claystones of the Cretaceous in the Eromanga Basin of eastern Australia, where the PFS extends for >2,000,000 km^2.

First recognised on the edge of the North Sea Basin using 2-D seismic data (Henriet et al., 1991), subsequent mapping of these faults using 3-D seismic data revealed their polygonal geometry, a critical feature that could not be recognized in 2-D data (Cartwright, 1994). PFSs are layer bound (i.e., restricted to particular stratigraphic intervals or "tiers"), which indicates a non-tectonic origin. The shallow burial depth of these tiers led to suggestions that PFSs formed during early burial, and resulted from an anomalous mode of compaction (Henriet et al., 1991; Cartwright, 1994). However, after hundreds of detailed seismically based descriptions of these structures in basins in all over the world, their origin is still highly contentious. A diverse range of postulated genetic mechanisms are currently "on the table" including shallow overpressure development, abnormal gravitational loading, differential compaction, diagenesis, and chemically driven volumetric contraction (syneresis) (see Goulty [2008] and Cartwright [2011] for recent reviews).

IMPORTANCE OF OUTCROP STUDIES

One of the factors contributing to the uncertainty in the origin of PFSs is the lack of field analogues, and the almost total reliance on seismic and well data for basic lithologic and structural information. 3-D seismic data in particular have been invaluable in allowing first-order structural geological observations (throws, dips, strikes, intersection relationships, connectivity) to be made in a systematic fashion over the large areas of the basinal extents of the PFSs (e.g., Lonergan et al., 1998; Gay et al., 2004). However good the imaging of the seismic data, the subtle details of fault geometry and kinematics will always be concealed beneath the limits of their spatial resolution. Similarly, borehole calibration is very useful to add lithological and biostratigraphic "flesh" to the bones provided by seismic interpretation, but suffers from its own resolution limitations, and the inadequacies of a sampling probe in one dimension for a peculiarly 3-D problem. Hence the need for outcrop studies to fill this resolution gap.

Unfortunately, there has been a dearth of outcrop-based studies to provide the necessary detail to resolve the current debate on the origin of PFSs, or even to provide much-needed constraints as to their timing, kinematics, and relationship with host stratigraphy. There have been several isolated attempts at identifying polygonal faults at outcrop (Hibsch et al. 2003), in quarries (Verschuren, 1992), or in underground excavations (Dehandschutter et al., 2005). These studies have provided important clues, particularly on the microstructural details of PFSs, but in each case, the limited exposure (typically tens to hundreds of meters in extent) meant that the critical evidence of a polygonal map pattern could not be demonstrated.

Tewksbury et al. (2014, p. 479 in this issue of *Geology*) provide the first concrete evidence of a polygonal fault system exposed anywhere on land. They combine field-based investigations of the outcrop with interpretation of satellite imagery to demonstrate the pervasive development of polygonal faults within chalks of the Khoman Formation (Cretaceous) in the western desert of Egypt. Their analysis of the field and satellite data provides new insights that could be critical in helping to resolve the question of fault genesis, and opens the way to a new field-based approach to the analysis of PFSs in general. They document a laterally extensive polygonal array of normal faults with dominantly dip-slip characteristics and modest throw values over an area of ~900 km^2. Their centimetric-resolution satellite imagery shows networks of nested fault planes, with far more intricate array geometries than those revealed by the resolution-limited 3-D seismic map images. Most critically, they document extensive development of polycyclic vein calcite associated with many of the fault planes, which they argue provides strong evidence linking fault development and fluid expulsion. Finally, they suggest that the steep dips of the fault planes (typically 80°) imply that failure occurred under the influence of a significant overpressure in the host formation, a potentially vital constraint for fault genesis. One other potentially potent dividend from their study area is their recognition of a set of circular to subcircular basin-like outcrop features that they interpret as resulting from focused fluid escape (pockmarks or fluid escape pipes up to 200 m in diameter). These occur stratigraphically directly above the layer containing the polygonal fault array, and Tewksbury et al. draw an analogy between these relationships in their study area and subsurface studies linking fluid escape phenomena to polygonal faults (Berndt et al. 2003; Gay et al., 2004).

PFS: CHARACTERISTICS AND WIDER SIGNIFICANCE

The enormous lateral extent of PFSs makes them unique as a deformational system: no other type of fault or fracture network is so uniformly developed on such a vast areal scale. This extraordinary areal extent stems from their intimate association with what are typically hemipelagic host successions, but the meaning of this strong lithological association is not currently understood. The edges of PFSs commonly occur either where the host layer or tier thins beneath some critical limit, or where there is a pronounced bulk facies change within the tier; e.g., from a dominantly clay-rich interval to a sand-rich interval. The combination of a depositional system, rather than specifically mineralogical control on their distribution, along with some lower limit of thickness leads to two important conclusions: (1) their origin is linked to the physical or chemical char-

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acteristics of the host sediment, and (2) they can develop during shallow burial conditions (Cartwright and Dewhurst, 1998).

The depth of origin of polygonal faults is also currently poorly constrained. PFSs have been observed in sediments that have never been buried more than 70 m below the seabed (Cartwright, 2011), so this provides a crude minimum burial depth for their formation, but is it conceivable that they form within the first few meters of burial? Importantly, the fact that they are layer-bound, and often underlain and overlain by sedimentary units with no comparable deformation, means that PFSs cannot be considered as tectonic structures. Their polygonal planform and characteristically near-isotropic horizontal strain are also strongly suggestive of a non-tectonic origin (Cartwright and Lonergan, 1996).

If polygonal faults are just simple normal faults, but do not form by a tectonic mechanism, then how do they form? What stress conditions govern their initiation and growth? What is the timing of the growth phase: short and sweet, episodic, or protracted and slow? These are fundamental questions for which we still have no answers. But these questions take us to the heart of why PFSs are so interesting! How can we explain the origins of a fault array consisting of millions of small normal faults developed over areas of thousands to millions of square kilometers? One thing is clearly understood: over these vast areas, the stress state in the host sediments during PFS development can be largely regarded as passive (Cartwright and Lonergan, 1996; Goulty, 2008). Almost a century of classical soil mechanics doctrine has led us to consider that passive burial and consolidation of soils (sediments) should in fact not lead to failure, but to simple "Terzaghian" 1-D consolidation. If the sediment is not subject to external loading (i.e., a "no lateral strain" or "K_0" boundary condition), then why should normal faulting on the scale and extent observed be the end product? Could the answers to these questions lie at the outcrop scale of investigation, as now initiated by Tewksbury et al.?

It is tempting to argue that the key to understanding polygonal fault genesis does lie at the outcrop, but perhaps a fairer assessment is that the greatest potential lies with integrating outcrop studies with research based on subsurface data and theoretical and experimental modeling. Outcrop studies of polygonal faults certainly have the potential to provide much evidence on the detailed microstructure of fault zones, broader systematics of network evolution, the mechanics and timing of fault propagation, and the coupling of fluid flow, deformation, and host lithology, all of which remain stubbornly inaccessible to purely subsurface approaches.

Undoubtedly, then, the outcrop will provide critical evidence, but the evidence will be interpreted in different ways. For example, the notion that polygonal faults can act as fluid flow conduits comes from studies by Berndt et al. (2003) and Gay et al. (2004), based on their apparent association with pockmarks or fluid escape pipes. However, there are many examples of PFSs without such an association, so caution is needed in the interpretation of these relationships. Tewksbury et al. argue that the combination of the common development of calcite veins and the association with the overlying "basin" features could be evidence for early dewatering along the polygonal fault planes. However, there is no strong geochemical evidence yet that these veins were synchronous with the initial stages of fault propagation and growth, as opposed to a later reactivation, under conditions of deeper burial or later uplift. Further geochemical work on the calcite veins of the Egyptian western desert PFS may help resolve these questions and place the fluid expulsion in a structural evolutionary context. Irrespective of the precise interpretation of the evidence presented by Tewksbury et al., at least now we do have a comprehensive set of field-scale observations on what is undoubtedly a *bona fide* PFS, and it seems likely that other outcrop examples will add further constraints to those already gleaned from this impressive type example.

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