Ultra-Slow Throw Rates of Polygonal Fault Systems

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Abstract

Polygonal Fault Systems (PFS) are an enigmatic class of small non-tectonic extensional faults. PFS are predominantly hosted in fine-grained sedimentary tiers and are prevalent along many continental margin basins. The genesis of PFS is widely debated and little is known about the timeframe for polygonal fault growth. We present the first measurements of throw rates for polygonal faults by measuring the vertical offset of seven age-calibrated horizons mapped using three-dimensional seismic reflection data from the Norwegian Sea. Individual polygonal faults exhibit a range of throw rate profiles through time, ranging from near linear to singly or multiply stepped. The stepped profiles have a range of short-term throw rates ranging from 0 to 18 m/Ma. Time-averaged throw rates of 180 polygonal faults over the entire 2.61-0 Ma interval are normally distributed and range between 1.4-10.9 m/Ma. We convert our PFS throw rates to displacement rates and compare these to published displacement rates for gravity driven and tectonic normal faults. We find that the displacement rates of polygonal faults mark the lower limit of a continuous spectrum of extensional fault displacement rates; they are up to two orders-of-magnitude slower than gravity-driven faults, and up to three orders-of-magnitude slower than the fastest growing tectonic faults. We attribute the ultra-slow kinematic behaviour to the non-tectonic nature of polygonal faults where throw accumulates primarily through dewatering of the largely fine-grained sediments comprising the host layers for the PFS, and differential volumetric strain between the fault footwalls and hangingwalls.

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1. Introduction

What are Polygonal Fault Systems (PFS)?

- Laterally extensive arrays of ***layer bound*** normal faults typically spanning ~10^5-10^7 km^2.
- Exclusively found in ***fine-grained sediments***.
- Form complex interlinking ***polygonal planform patterns.***
- Formation is ***non-tectonic***.

Where are PFS found?

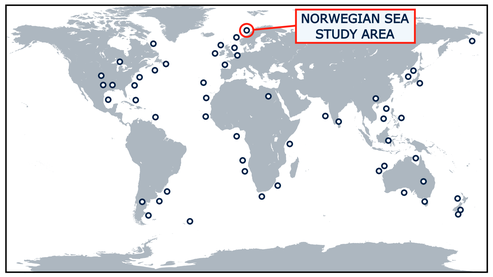

Figure 1: PFS are hosted in fine-grained sediments in basins around the world.

The Polygonal Fault System Enigma

- Despite ~30 yrs of research a universal PFS genetic mechanism remains elusive.
- Suggested mechanisms include '***Gravity Sliding***', '***Density Inversion***', '***Overpressure***', '***Gravitational Loading***', and '***Diagenetically-Induced Shear Failure***' (Goulty, 2008; *Cartwright, 2011*).
- To date, the rate at which polygonal faults grow has remained unconstrained.

Research Aims

- Derive the first measurements of ***PFS throw rates***.

2. Data & Methodology

Data

- Two-adjoining ***3D seismic surveys*** with bin spacings of 6.25 m and 25 m respectively, and vertical resolutions of ~6 m and ~10 m respectively.
- Seismic chrono- and lithostratigraphic calibration from ***ODP 644,*** 6604/2-1, and 6603/5-1 wells (Fig. 2).

Methods

- Dated horizons calibrated to seismic using a velocity of 1600 m/s, with uncertainty of +/-0.1 Ma and +/-0.2 Ma for horizons <1 Ma and >1 Ma respectively.
- Throw rate = ΔThrow / ΔTime
- Displacement rate = Throw rate / sin(fault dip)

3. Geological Setting

Study Area

- Located within the Vøring Basin, Norwegian Sea.
- PFS tier is ~1000 m thick across the study area.

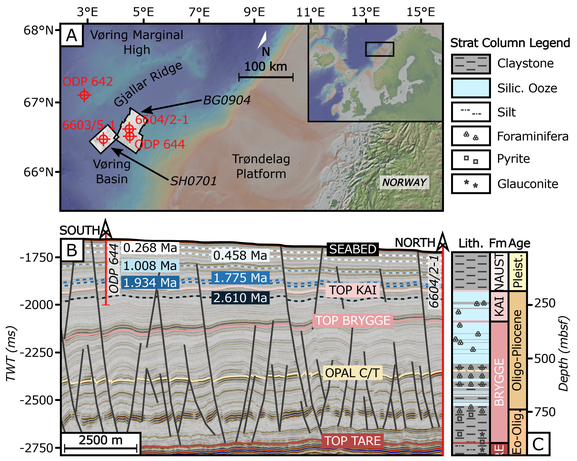

Figure 2: (A) Map of the study area located in the Vøring Basin. (B) Seismic profile through the PFS showing the mapped dated horizons and formation boundaries. (C) Stratigraphic column.

Stratigraphy

- Host strata comprise fine-grained siliceous mudstones, claystones, and oozes of the Naust, Kai, and Brygge Fm.
- Prominent Opal A/CT diagenetic phase boundary in lower third of tier.

4. Syn-sedimentary PFS

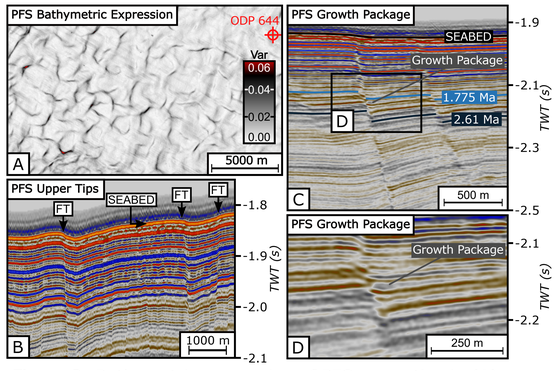

Figure 3: Bathymetric expression of PFS upper tips in (A) map view and (B) cross-section. (C, D) Syn-sedimentary growth package within age-calibrated stratigraphy.

5. Results

PFS Throw vs Horizon Age Plots

- Individual faults (n=52) exhibit a range of profiles of throw with time (Fig. 4), from almost linear to singly or multiply stepped.
- Of the 52 faults, around 60% of profiles are approx. linear or smoothly varying.
- Short-term throw rates range from 0 to 18 m/Ma.

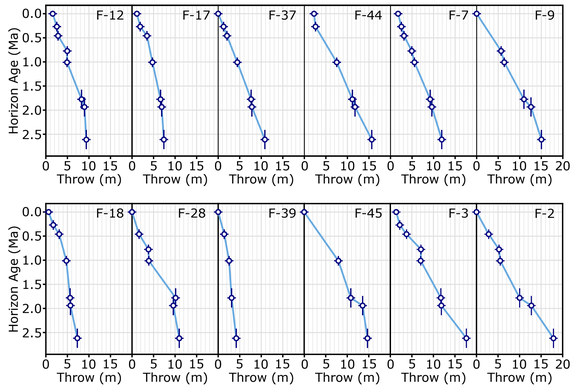

Figure 4: PFS throw versus horizon age for 12 upper tips.

PFS Time-Averaged Throw Rates

- Derived from the 2.61 Ma horizon.
- Range between ***1.4-10.9 m/Ma***, with a mean and median of 5.7 m/Ma and 5.6 m/Ma respectively.

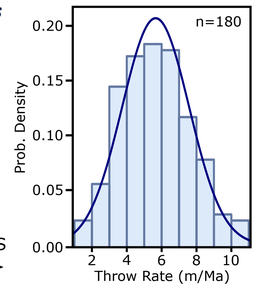

Figure 5: Probability density function of time-averaged PFS throw rates for 180 faults. →

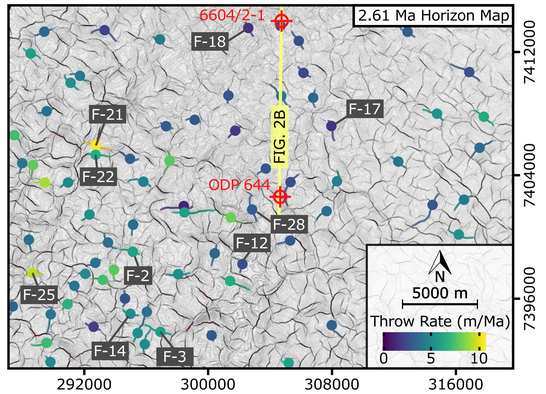

Figure 6: Map of the 2.61 Ma horizon showing the spatial distribution of measured PFS throw rates.

6. Discussion

Comparison to Tectonic & Gravity-Driven Faults

- Norwegian Sea PFS displacement rates mark the ***lower limit*** of a continuous spectrum of extensional fault displacement rates (Fig. 7).

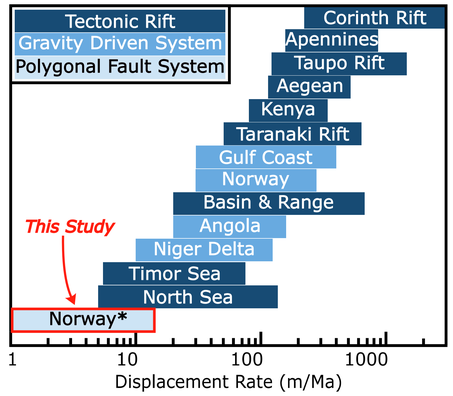

Figure 7: Log plot of displacement rates from extensional fault systems around the world. Sources; *Nicol et al., (1997); Pochat et al., (2009); Mouslopoulou et al., (2009); Dutton & Trudgill (2009); Jackson (2018).*

- Do polygonal faults ***creep*** with sedimentation (*cf. Goulty, 2008*) or do they exhibit ***stick-slip*** behaviour?
- ***Ultra-slow PFS throw rates*** are not surprising given the ***slow rates of geological processes*** governing volumetric reductions in ***shallowly buried fine-grained sediments***.

7. Conclusions

- ***First throw rates*** for a Polygonal Fault System.
- Time-averaged ***throw rates*** over the last 2.61 Myrs are ***normally distributed*** and range between ***1.4-10.9 m/Ma***.
- PFS displacement rates mark the lower limit of extensional fault displacement rates.
- Ultra-slow PFS throw rates are consistent with ***slow geological processes*** that drive ***differential volumetric reductions*** between footwalls and hangingwalls.
- Throw rates offer a temporal benchmark to model PFS growth.

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