Fold-Thrust Geometries - Is There a Right Model?*

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Abstract

Fold and thrust structures offer interpretational challenges, even when well-imaged in 3D seismic volumes. There are several end-member kinematic models for folding in compressional belts, including fault-bend, tip-line and detachment structures. On individual 2D profiles, the consequences of particular structural interpretations, either using ideal end-member behaviours or composite styles, can be explored using combinations of graphical restoration and forward models. It is well known that simple 2D restorations can serve to validate structural interpretations and thus begin to reduce interpretation uncertainty. Further tests can include the ability to model the patterns of growth strata. In three dimensions, serial section approaches can be used to test for lateral strain compatibility. Where strain paths and deformation mechanisms are appropriate, 3D forward models and restorations can be applied. While all these strategies can be applied to assess the options for stratal offsets and deformations of surfaces, where input data are restricted to seismic alone, the role of distributed strain on structures below seismic resolution commonly represents uncertainty that is difficult to evaluate.

In this presentation, the outcomes of different restoration and modelling strategies are compared for an individual structure imaged on 3D seismic data (from deep water Nigeria). While restoration and modelling can eliminate (or at least risk as being unlikely) geometrically unbalanced options, there remain a range of competing, viable structural interpretations. A key component of assessing this uncertainty lies in capturing a broad range of viable alternatives, best achieved through using different workflows and multiple interpreters with difference experience and backgrounds.
Fold-thrust geometries - is there a right model?

Rob Butler
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Douglas Paton

The Virtual Seismic Atlas
Cross-sections through the Chartreuse massif from published maps

Models - playing with outcrop

Subalpine thrust belt - good exposure - high relief...
1980s models
Kink-band vs buckles
IMPACTS?

What’s the point?
Regional structure - local (e.g. forelimb) - other..?
Analogues - view the range...

a time out.....
BIRPS NSDP-84: test-bed for continental extensional tectonics…..

Published interpretations

Contrasting available existing interpretations… may indicate uncertainty in any one model….

But how do you put the array together?

Known knowns, Known unknowns, or Unknown unknowns!

Project built by Mike Sizer
A new platform…. for analogues…

The Virtual Seismic Atlas

a brief introduction…..
This section is a deep profile from the Northern North Sea, originally collected by the BIRPS survey in 1994. Several interpretations of this section have been undertaken since 1996 that show an evolution in the thinking of geologists for the development and architecture of normal fault systems. These can be followed through the linked interpretations.

**Interpretation**

BIRPS North Sea Deep Profile - 1 overlain line drawing

This section is a deep profile from the Northern North Sea, originally collected by the BIRPS survey in 1994. Several interpretations of this section have been undertaken since 1996 that show an evolution in the thinking of geologists for the development and architecture of normal fault systems. The first part of the interpretation workflow traditionally is to hand-pick prominent, coherent reflections. Here is one model.

**Interpretation**

BIRPS North Sea Deep Profile - 1: line drawing alone

This section is a deep profile from the Northern North Sea, originally collected by the BIRPS survey in 1994. Several interpretations of this section have been undertaken since 1996 that show an evolution in the thinking of geologists for the development and architecture of normal fault systems. This is the interpretative line drawing of the seismic data - showing prominent reflectors.

**Interpretation**

Beach's 1996 interpretation of NSDP84-1

This section shows Beach's interpretation of part of NSDP84-1 that is based on the simple-shear model as proposed by Wernicke (1985). This interpretation is very simple and reflects Beach's broad interpretation of large rotated faulted blocks in a simple hanging-wall/footwall model. The shaded area represents a major extensional shear zone passing upwards from the mantle in the east to the middle crust in the west. Major eastward-dipping extensional faults, affecting the hanging-wall of the shear zone, are shown as dotted lines. The base of the crust is shown as a dashed line; the wavy line, drawn as a boundary to areas of different seismic character, reveals a large-scale crustal rollover in the hanging-wall. In the eastern portion of the profile the wavy line corresponds approximately to the base of the Devonian, and top of the metamorphic basement. See: BEACH, A. 1996. A Deep Seismic Reflection Profile across the Northern North Sea. Nature, 232, 55-55. (link to online article - see links section).

**Interpretation**

Brun & Tron's 1992 interpretation of NSDP84-1

Brun and Tron's interpretation of deep seismic reflection profile NSDP84-1 in the Northern North Sea provides a good example of the cumulative developments of the pure-shear model from before the early nineties. The normal faults are planar and only developed in the upper part of the crust.
This project acts as a hub for exploring the 3D structure of a fold-thrust structure in deep water, Western Niger Delta. In the "docs and links" there is a PDF with 40 serial sections through the fold. The associated scene projects consist of 7 triptychs, each of which contains a clean version of the seismic, an interpreted version and an annotated interpretation. These are a subset of the serial sections in the PDF.

**Scene: DW Niger delta fold - profile N10**
Author: Rob Butler Organization: N/A
Scenes: (0) Interpretations: (0)
Back-thrust structure - with associated fold that verges up regional slope.

**Scene: DW Niger delta fold - profile N118**
Author: Rob Butler Organization: N/A
Scenes: (0) Interpretations: (0)
Nearing the transfer zone along the anticline as the structure changes from a back-thrust (in NE) to a fore-thrust (in the SW). Both vergences are evident at depth - along the Agbada/Akata transition.

**Scene: DW Niger delta fold - profile N20**
Author: Rob Butler Organization: N/A
Scenes: (0) Interpretations: (0)
Triangle zone/pop-up structure in the deep water Western Niger Delta. Both thrusts pass upwards into thrust zones.

**Scene: DW Niger delta fold - profile N20**
Author: Rob Butler Organization: N/A
Scenes: (0) Interpretations: (0)
Fore-thrust structure from the deep water Western Niger Delta.

**Scene: DW Niger delta fold - profile N24**
Author: Rob Butler Organization: N/A
Scenes: (0) Interpretations: (0)
Fore-thrust structure in deep water Western Niger Delta.
The Virtual Seismic Atlas

2DMove
used for restoration

Scenario modeling
Predicting Fault shape and geometry

Using the top two beds and a small fault segment

Using all beds and a small fault segment

NB: Changing the algorithm has a minimal effect
Flexural Slip unfold – geometry testing

Straight pin

leaning pin
Flexural Slip unfold – geometry testing

All tests highlight unlikely thickening in middle package – reinterpretation…

Midland Valley

2DMove
Approach - forward models
Trishear

Variables:
Slip/ propagation rate
Trishear aperture
Forelimb not steep enough
Trishear apex 28.1
200m displacement, each step
prop/slip 3
trishear 50 degs
Stratigraphy does not fit - change depositional model
Adding beds earlier
Faster deposition rate (early) fits the forward model better to interpretation.
Best fit results:

Displacement 200m
Trishear angle 27.1
Propagation/slip 2.3
Trishear angle 110 deg
But - does this “best fit” knowledge reduce interpretation uncertainty on adjacent sections?
All that happened in 3.5 km...
What about in the other direction...?
Shape of shallow layers - only weakly relates to fault geometry at depth

Evolves in 5.5 km
Styles of thrust-fold structures - Niger fan

All scenes 9.5 km across, approx $v=h$
Layer-parallel shortening

Layers fail - Buckling instabilities - evolve to thrusts (but may be overtaken by adjacent buckling layers....)
There is no universal model (or strain path)... even for a single structure!

Coded models/workflows - large-scale structure consequences
structural history fault zone architecture/properties

PLAY THE FIELD - more models and analogues... BUT WHEN TO QUIT?