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Submarine thrust belts: combining marine seismic and field analogues to study the localization of contractional deformation in sedimentary successions

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Abstract: Modern 2D and 3D seismic data from gravity-driven thrust belts in deep submarine settings provide unparalleled images of fold-thrust structures. Cursory examination of these data suggests simple concentric deformation and a narrow range of structural styles. However, regional restorations combined with outcrop analogues suggest that distributed strain and large-scale volume loss (lateral compaction) during deformation are important. These deformations accommodate layer-parallel shortening that may serve to pre-condition thrusting. Evaluating the partitioning between localized thrusting, related folding and distributed strain is examined using examples from deepwater Niger delta, offshore Namibia and outcrop analogues from the French Alps and New Zealand.

Keywords: fold-thrust belts, section balancing, volume loss, deep water.

Thrust systems are widely recognised as being the principal way in which the upper crust accommodates convergence at destructive plate boundaries. These deformations are preserved at the outer parts of orogenic belts and by subduction-accretion complexes. They have been studied for over a century, exclusively based on field observations and surface mapping for the early work, enhanced for the past 20 years or so by increasingly refined well, geodetic, earthquake and geomorphological datasets. In continental systems, imaging from seismic reflection methods has been rather disappointing chiefly because of a combination of statics and velocity problems. Consequently, understanding of the 3D structure has been strongly driven by geometric models with interpretations tested using section balancing approaches. There remains a high level of geometric uncertainty in structural models (e.g. cross-sections) created in this way that is rarely addressed. The end-member deformations, especially those embedded within structural restoration and analysis software are rather restricted in scope. They include strict fault-bend folding, fault propagation folding, trishear and detachment folding. In all cases the tacit assumption is that progressive deformation leads to increasingly localized deformation, essentially slip on a few fault surfaces. The models do not entertain other localization behaviours. This restriction means that software applications are likely to promote in non-experts and inexperienced users unfoundedly high levels of confidence in their cross-sections together with the inappropriate elimination of apparently non-viable structural geometries. This is a problem because regional-scale thrust-belt cross-sections have been used to constrain kinematic models for entire orogens, predict the geometry and structural evolution of hydrocarbon traps and underpin potentially bogus mechanical models for continental deformation.

The central problem of continental thrust belts, the traditionally poor seismic imaging, is less of an issue in submarine settings, especially in modern data. The best data come from gravity-driven spreading and sliding systems at "passive" continental margins. However, these well-imaged systems have the compensating disadvantage of inaccessibility. The approach reported here uses a combination of marine seismic from deep-water fold-thrust belts and field data derived from outcropping analogues of submarine thrust systems. The examples chosen involve deformation of poorly consolidated siliciclastic successions –adjustment must be made if taking conclusions back into, say, continental fold-thrust belts formed in competent carbonate sequences.

Deep-water Nigeria – setting up the problem

3D seismic from deep-water Nigeria reveal spectacular thrust-fold complexes (e.g. Fig. 1) developed in sand-shale (turbidite: the Agbada Formation) multilayers above a regional over-pressured shale detachment (the Akarta Formation). Growth strata show thrust structures to be active in series. The vergence of thrusts switches between oceanward and landward (consistent with weak-detachment behaviour), in places over a few kilometers along individual folds. Thrust zones can be clearly imaged but more commonly, especially within the growth sequences, they are represented by zones of amplitude loss. In well-imaged structures fault zones generally have multiple, splaying strands.

Backthrust–forethrust systems have long been recognised in fold-thrust belts and are generally regarded a diverging from the regional detachment. In the Niger Delta the pattern is different. 3D seismic show that for many relaying systems the singularity between bivergent thrusts exists well within (ca. 750 ms) the overlying Agbada Formation. This suggests that parts of the Agbada are behaving as competent beams and that the loading conditions approximate to layer parallel shortening. This will promote buckling –a deduction that prompts examination of some outcrop analogues. The issues to be addressed are: evidence for complex thrust zones and buckling at individual fold-thrust complexes; and evidence for layer-parallel shortening within thrust wedges.

Outcrop analogues

The role of distributed strain and small-scale imbricate splays in fold-thrust forelimbs can be investigated using well-exposed field analogues: the western Champsaur Basin, SE France (Butler and McCaffrey, 2004). Alpine-age contractional structures, developed during local crustal shortening include thrusts that climb out of the Mesozoic substrate into Tertiary turbidite basins. Thrust ramp zones are complex and include panels of steeply-dipping sands between forelimb thrust splays. The thrusts are folded and cut – indicating a complex interaction between distributed folding and localized fault slip. Another outcrop analogue, from the Northern Apennines, shows thrust ramps to include significant trains of buckle folds. These behaviours have previously been recognised within multi-layers with very strong competence contrasts (e.g. the carbonate-dominant subalpine thrust belt; Butler, 1992; Butler and Bowler, 1995). Buckling is generally not considered within poorly

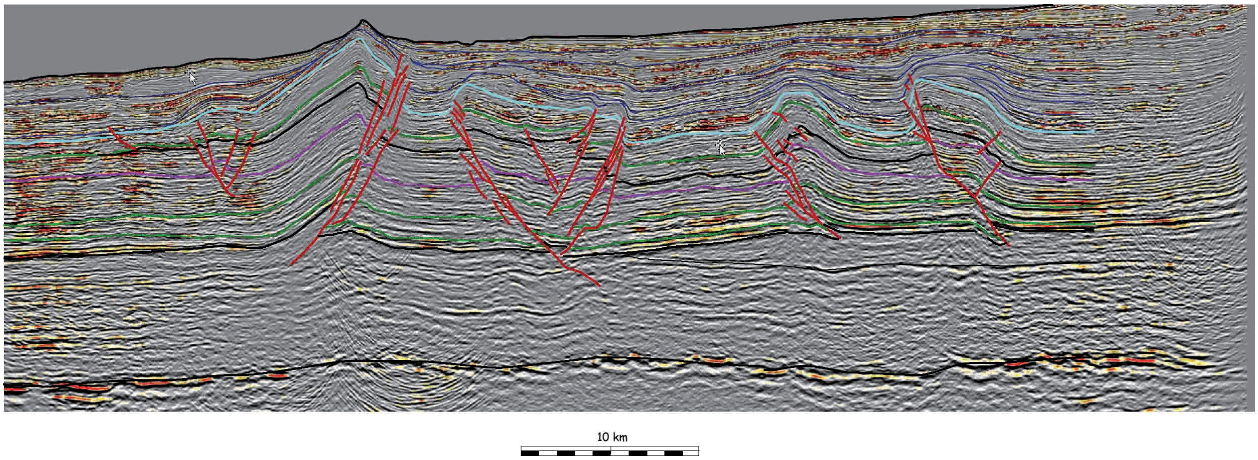

Figure1. Interpreted seismic profile (inline from 3D survey, courtesy of CGG Veritas) from the deepwater Niger Delta showing thrust zones developed in the Agbada turbidites above an inferred detachment (not shown) in the underlying overpressured Agbada Formation. Note vertical scale is seismic two-way time. Image available via the Virtual Seismic Atlas.

consolidated siliciclastic systems. Good examples exist however within the Waitemata of New Zealand. Excellent outcrops reveal entirely overturned dip panels and near-isoclinal folding within poorly lithified sandstones. Deformation is accommodated by numerous deformation bands and micro-faults. Evidence for loading conditions in thrust belts is hard to obtain. The frontal part of the Maghrebian thrust belt in Sicily is developed in dominantly shaley successions. Growth strata reveal slow, continuous deformation rates over several Ma at individual fold thrust structures (spaced at ±10 km). This suggests a continuous process of deformation within the overthrust wedge. Rather specially, the Messinian Salinity Crisis resulted in the deposition of a near-continuous layer, ca. 10-20 m thick of carbonate (the Calcare di Base) across the thrust belt. This deformed during late Messinian-Pliocene times into a series of short wavelength (ca. 1-2 km) buckle folds. Where the crests of antiforms have been eroded during deformation, subsequent fold amplification rates can be demonstrated to have greatly accelerated. These behaviours are best explained by boundary deformation conditions within the thrust wedge closely approximating layer-parallel shortening.

Volume loss – large-scale perspectives

A regional seismic line through the Orange Basin, offshore Namibia, reveals a classic paired gravity-driven deformation system with extension high on the submarine slope and contraction towards the toe of slope. The system is self-contained over a distance of ca. 200 km and should balance. Restoration of the seismically imaged contractional structures (thrusts and associated folds) is about 16 km (with a measurement uncertainty of <1 km and an estimated interpretation uncertainty of <2 km), while extension exceeds 63 km. Thus 40-45 km of shortening (66% of the total strain budget) is not accounted for in the seismically-imaged structures. If this missing strain (~40 km of shortening) is distributed through the contractional regime (82 km behind the leading thrust), it represents a strain of 32%. If distributed through the entire predeformational strata (both up-dip and ahead of the detachment: 120 km of section), the conservative estimate of strain is 25%. The "missing" stratal shortening in the Namibia section is common to many submarine gravity tectonic systems. Volume loss by tectonic compaction is the most plausible accommodation mechanism but should be both depth- and lithology-sensitive. Existing seismic data have yet to provide strain proxies (e.g. lateral variations of velocity). This deformation mechanism should be expected for other thrust systems developed in poorly consolidated sediment (e.g. accretionary prisms) and some do show lateral increases of seismic velocity across thrust fronts.

Conclusions

The preferred mechanism of deformation in poorly consolidated sediments is by distributed shortening, accommodated by both vertical stretching, buckling and inferred tectonic compaction (volume loss). Existing end-member kinematic models for fold-thrust complexes do not reflect this. They are likely to yield poor predictions of subseismic deformation and fault zone architecture: key risks in the exploitation of deep-water hydrocarbon reserves. While individual structures may conform to trishear geometries, localization is commonly complex leading to a variety of thrust zone architectures that can exhibit rapid along-strike variations.

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