



Do experts use idealised structural models? Insights from a deepwater fold–thrust belt

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ARTICLE INFO

Article history:

Received 24 June 2010

Received in revised form

27 September 2010

Accepted 11 October 2010

Available online 4 November 2010

Keywords:

Fold–thrust belt

Structural model

Kinematics

Interpretation

Seismic reflection

Deepwater

ABSTRACT

Theoretical models are often used to aid interpretation of geological data. For fold–thrust belts, structural and kinematic models have existed for over a century. While greatly contributing to our understanding of thrust systems, the usage of models can result in oversimplification and false kinematic interpretations. This paper investigates how and if experts use structural models in the interpretation of a seismic image from a deepwater fold–thrust belt. The results show that in the majority of cases experts produced interpretations that were compliant with key features in existing structural models. Those interpretations that were less compliant to existing models, better accounted for features present in natural and experimental analogues. This has implications for the general applicability of structural models in interpretation.

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1. Introduction

Understanding the evolution of fold–thrust structures involves significant interpretation of geological data. Theoretical models have existed for over a century to aid in this (e.g. Willis, 1893; Suppe, 1983; Jamison, 1987; Suppe and Medwedeff, 1990; Erlsev, 1991), but the models define a simplified, mathematically constructible solution for a process that is not, in reality, simply explained. Theoretical models in geology create idealised analogues that can be further used in the interpretation of similar geological systems. This is, in general terms, a very useful approach but may also cause oversimplification of interpretations, especially as the geological system deviates from that for which the model was originally created. The models often fail to explain features observed in many natural fold–thrust structures, such as strain localisation, fault propagation and fault linkage.

We present the results of an expert elicitation exercise, in which we have used experts to gather their collective geological interpretation knowledge (in the sense of ‘*the Wisdom of Crowds*’; Surowiecki, 2004). Explicit expert elicitation techniques (e.g. Meyer and Booker, 1991; Cooke, 1991) have been used in science, notably within the nuclear waste disposal sector to evaluate

interpretational uncertainty and risk (Aspinall, 2010). In our example, rather than asking experts to risk assess their own or others’ interpretations, we use the collective interpretations of experts to investigate how theoretical fold–thrust models influence the interpretation of seismic data. We use the results to discuss the general usability of established theoretical models in the interpretation of fold–thrust structures. This case study uses high quality seismic reflection data from the toe–thrust sector of a gravity-driven deepwater fold and thrust belt, but the conclusions are more generally applicable to the application of models in data interpretation.

2. Data and experiment

2.1. The expert group

The exercise was performed at the American Association of Petroleum Geologists Hedberg Research Conference ‘*DeepWater Fold and Thrust Belts*’ in October 2009. Hedberg Research Conferences are scientific meetings designed to gather scientists from both industry and academia with the aim of discussing state-of-the-art concepts, methodologies, case histories, and future directions relating to the conference subject (<http://www.aapg.org/education/hedberg>). Participation is selective and individuals apply, or are invited, to attend ensuring a diversity of key experts in

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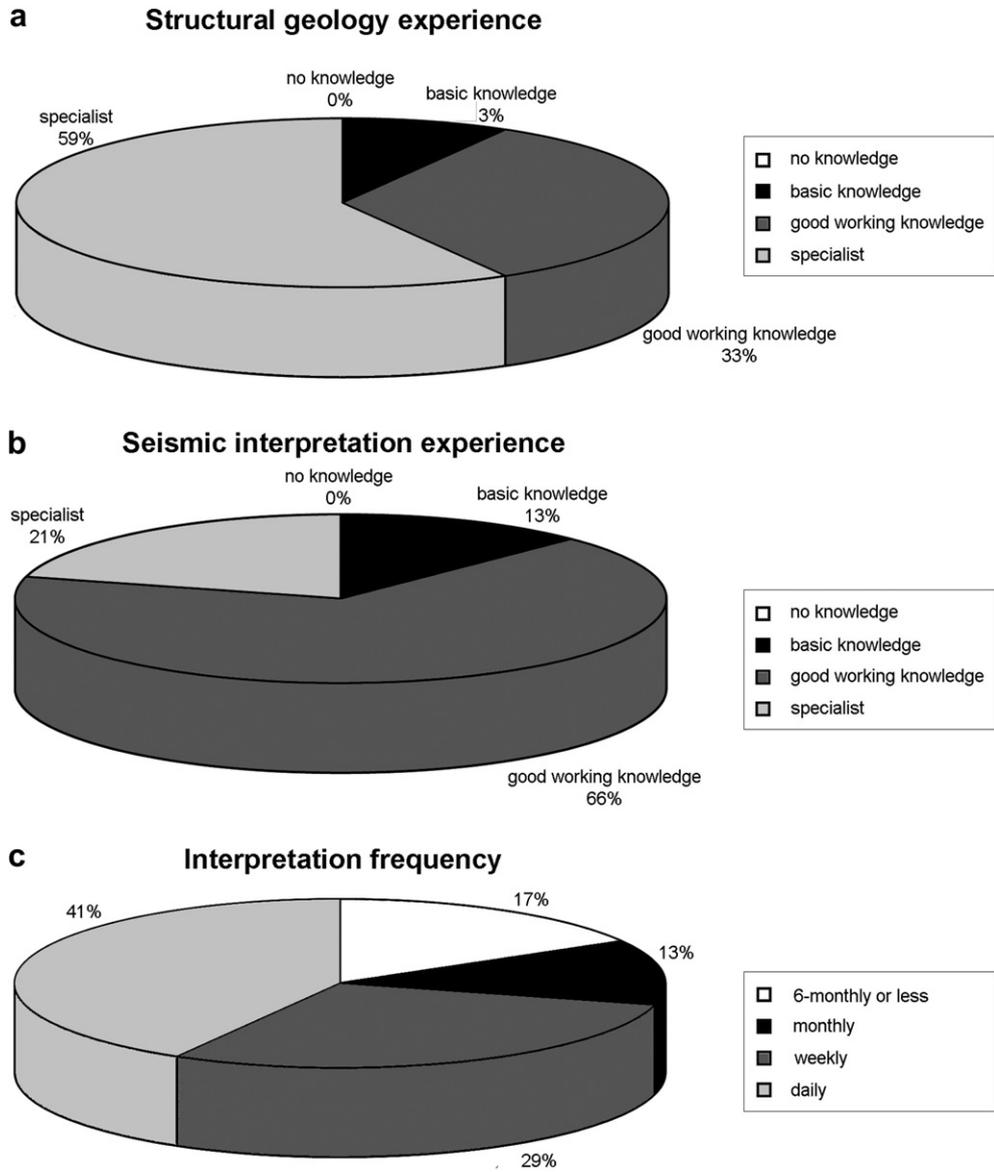


Fig. 1. Pie charts illustrating the level of self-assessed experience of the expert group in a) structural geology, b) interpretation of seismic data, and c) how often they interpret seismic images.

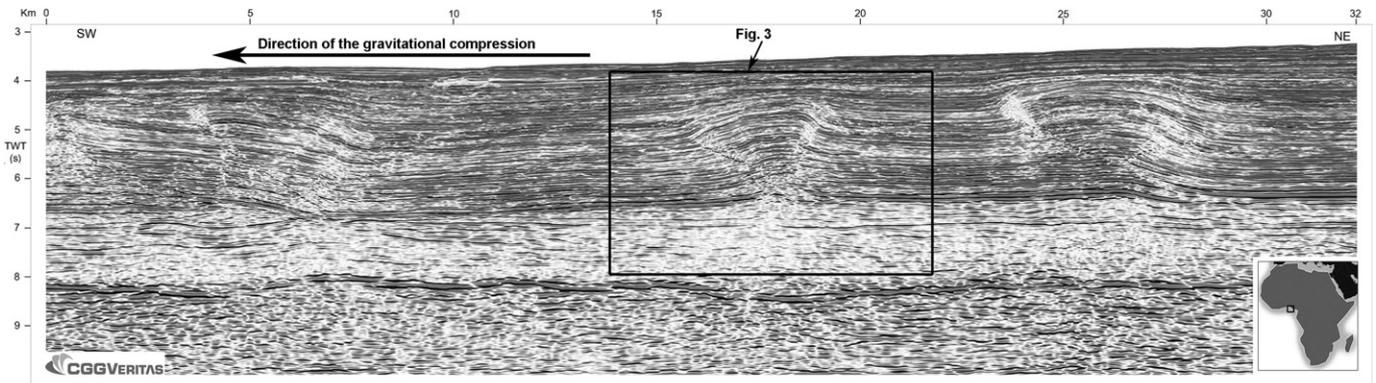


Fig. 2. The uninterpreted seismic section used in the exercise. The black box indicates the central fold used in the analysis (Fig. 3). The inset shows the location of the seismic 3D volume from which the profile was extracted (Niger Delta).

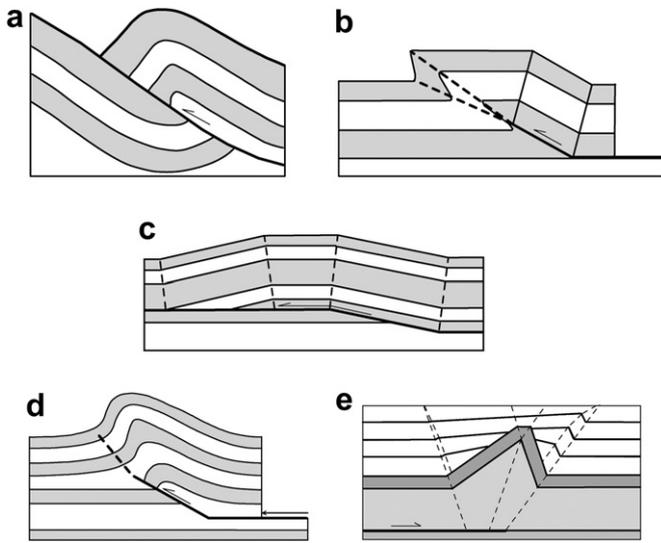


Fig. 3. The theoretical models that were compared with the collected interpretations. a) The break–thrust fold model (Willis, 1893); b) The trishear fault propagation fold model (Erlsev, 1991); c) The fault–bend fold model (Suppe, 1983); d) The ‘simple’ fault propagation fold model (Suppe and Medwedeff, 1990); e) The detachment fold model (Jamison, 1987). The break–thrust fold redrawn from Willis (1893), the other models redrawn from Shaw et al. (2004).

the subject area required to achieve the Hedberg Research Conference aims. In this case, experts in fold–thrust belts, possessing a range of knowledge in the associated geological systems and processes (representing a range of disciplines including structural geology, geophysics and seismic interpretation) attended the conference.

Our expert group included scientists with extensive experience in structural interpretation of fold–thrust belts, with authors of heavily cited papers on the topic (h-factors of up to 21; source Scopus, May 2010). The participants were asked to fill out a questionnaire attached to the seismic image, in order to map their background and expertise. 67% of the 24 people who returned an interpretation had more than 5 years of experience after their degree, the average experience of all participants being 12.6 years. 92% and 87% indicated that they were specialists or had a good working knowledge in structural geology and/or seismic interpretation, respectively (Fig. 1a,b). 83% of the group interprets seismic images at least on a monthly basis (Fig. 1c).

2.2. The dataset

The experiment used a high-resolution 3D seismic dataset, from which a single vertical 2D profile was chosen. The quality of the

seismic data used in the exercise is excellent, thus minimising the impact of seismic artefacts and noise on the interpretations. The dataset comes from the contractional zone of the gravity-driven Niger Delta deepwater fold–thrust belt where a shaly, poorly reflective package lies between the oceanic basement below and a reflective, sand-dominated sediment package with a thickness in the order of several km’s on top (Fig. 2; Avbovbo, 1978). The shales represent the pro-delta marine phase of the depositional history (the Akata formation; e.g. Avbovbo, 1978), followed and overlain by the units deposited in the distal part of the delta (the Agbada formation; e.g. Avbovbo, 1978; Deptuck et al., 2003). The still active fold–thrust belt formed within the Agbada formation, driven by a gravitational collapse of the delta along major detachments within the overpressurised shale unit (Morley and Guerin, 1996; Briggs et al., 2006).

2.3. The experiment

The participants were asked to complete a paper interpretation of the 2D line using colouring pens and to provide some information about their professional background. No further instructions or information about the location or the stratigraphy were given. The aim of the exercise, unknown to the participants, was to collect a range of interpretations of the seismic image, largely following the principles for capturing the widest possible range of interpretations presented in Bond et al. (2008), and to compare them to the existing theoretical models to see whether the interpreters were influenced, consciously or subconsciously, by the models. The ultimate goal was to see whether the experts produced model-driven interpretations or image-/observation-driven interpretations, to compare the interpretations with natural and experimental examples, and to discuss the implications of both interpretational styles in the light of the comparison. A total of 24 interpretations were collected. All interpretations, along with the original seismic image, can be viewed at and downloaded from the Virtual Seismic Atlas VSA (www.seismicatlas.org).

2.4. The theoretical model set

The suite of structural (kinematic) models used here to define the theoretical model set, against which we have compared the experts interpretations, are: the break–thrust fold model by Willis (1893), the fault–bend fold model by Suppe (1983), the detachment fold model by Jamison (1987), the ‘simple’ fault propagation fold model by Suppe and Medwedeff (1990), and the trishear fault propagation model of Erlsev (1991). The resultant fold–thrust geometries for each of the models are shown in Fig. 3. The five models have been characterised by key features which the authors would expect to see in an interpretation if the interpretation is compliant with a specific theoretical model (Table 1). It is worth noting that most of the theoretical models, bar the detachment fold

Table 1
The key features of the five structural end-member models used in the analysis of the interpreted seismic images.

Model	Fault–detachment linkage	Kinematic style	Fold forelimb	Fold backlimb
Break–thrust fold	Soft- to hard-linked	Fold–first, then faulting	Faulted, major folding of FW ^c	Featureless
Trishear	Hard-linked	FP ^a from D ^b with folding	Faulted, tighter HW ^d folds toward D	Kink fold/minor faults
Fault–bend fold	Hard-linked	Ramped D	Above flat, kink folded	Kink fold
Fault propagation fold	Hard-linked	FP from D with folding	Faulted, no change in HW fold tightness	Featureless
Detachment fold	No faults above D	Folding above D	Kink fold	Kink fold

^a FP = forward-propagating fault.

^b D = Detachment.

^c FW = footwall.

^d HW = hanging wall.

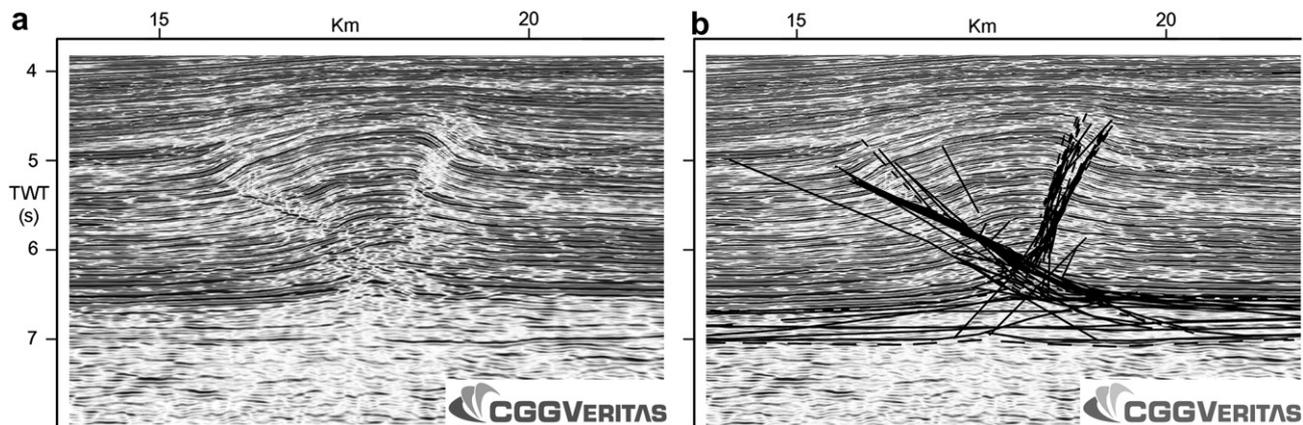


Fig. 4. Detail of the seismic section used in the exercise (black box in Fig. 1). a) Uninterpreted image; b) All 24 interpretations superimposed. The stratigraphic interpretations and annotations are removed for clarity.

model and the break–thrust fold model, predict a continuous fault propagating upwards from a detachment.

The terminology used in the classification is defined by the geological setting and the fault geometry. ‘Forethrust’ and ‘forelimb’ refer to down-slope i.e. oceanward direction, and ‘backthrust’ and ‘backlimb’, accordingly, to the up-slope, or landward, direction. Use of the term ‘hard-linked’ refers to a continuous fault within the fold structure reaching down to an inferred detachment. A ‘soft-linked/isolated fault’ refers to a single fault or an array of faults within the fold that are interpreted to be soft-linked to the inferred detachment (through distributed strain) or isolated from the detachment and/or other interpreted faults.

The chosen models have been widely used to explain the evolution of different fold–thrust belts. These models have also been extended and modified by a number of authors in order to describe more complex natural systems; for example, complex internal folding patterns can form (Medwedeff and Suppe, 1997); the fold and fault geometries can vary (e.g. Chester and Chester, 1990; Allmendinger, 1998; Mitra, 2003); the kinematic styles and fold hinge behaviour can differ (e.g. Morley, 1994; Wickham, 1995; Woodward, 1997; Tavani et al., 2005; Hardy and Finch, 2007); and/or fractures and backthrusts form (e.g. Maillot and Koyi, 2006; Lin et al., 2010). Nevertheless, the tacit assumptions of the original models used provide the fundamental basis for the geometric and kinematic descriptions of fold–thrust systems.

3. Results

Each interpretation of the faults and the deformation within the central fold (Fig. 2 black box; Fig. 4) was compared with the theoretical model set. The 24 interpretations obtained show a range of approaches that can be divided into four main groups on the basis of the *dominant* fault and deformation style (Column A in Table 2, Fig. 5): *Group 1*) continuous (hard-linked) forelimb fault(s) ($n = 15$; Fig. 5a, f), *Group 2*) soft-linked/isolated forelimb faults ($n = 5$; Fig. 5c, e), *Group 3*) continuous (hard-linked) backlimb fault (‘backthrust’; $n = 1$), and *Group 4*) distributed strain (mostly annotated as kink folding; $n = 3$; Fig. 5b, d). Note that stratigraphic interpretations are omitted in the figures for clarity. The stratigraphic interpretations, where present (in 14 interpretations out of 24), were used to constrain the overall deformation style. A detachment (a subhorizontal fault plane) was interpreted in 16 cases; of these, 6 people interpreted the detachment to terminate at the fold, i.e. not to exist down-slope, ahead the fold (e.g. Fig. 5a, d). Of the 8 people who did not interpret a discrete detachment plane, one annotated a wide ‘shear zone’ instead to be located within the

seismically unreflective package. After making these observations, each interpretation was compared with the theoretical model set and their key fault and deformation features as described in Table 1. On the basis of the comparison, the interpretations are categorised as 1) model-compliant ($n = 14$), 2) model-influenced ($n = 7$), or 3) model-independent ($n = 3$; Fig. 6).

The *model-compliant* category ($n = 14$) does not imply that the included interpretations exactly represent a particular model; the compliancy is here seen to indicate the presence of key features assigned for each model in Table 1. The influence of the structural models for fold–thrust belts on the interpretations is most evident in Group 1, where the presence of one dominant, hard-linked fault in the forelimb and a basal detachment can usually, but not always, be seen to correlate with one or more end-member models (Fig. 5a, b). The trishear model geometry clearly dominates the interpretations, although many show combinations of two or more end-member models (Figs. 5 and 6).

The *model-influenced* category ($n = 7$) includes the interpretations that can be seen to follow a general fold-fault geometry predicted in the theoretical models, but where the deformation is interpreted to consist of soft-linked/isolated faults rather than one continuous fault. The linkage between the soft-linked/isolated faults and the detachment (and between faults themselves) is

Table 2

Distribution of the main deformation mechanisms in the interpretations. HL = hard-linked, SL = soft-linked, DS = distributed strain, n.i. = not indicated. The number (no.) gives the number of interpretations allocated into each group in column A (an interpreted fault or zone of distributed deformation in the fold forelimb). Column B (Backlimb) further shows the division of the interpreted deformation mechanism in the backlimb. Column C (no detachment) lists the interpretations where no distinct detachment plane was indicated. Percentages of the total number of the interpretations give the distribution of the deformation mechanisms.

Main deformation mechanism	A. Forelimb	B. Backlimb	C. No detachment
Group 1: HL no.	15 62.5%	HL = 4 SL = 5 DS = 4 n.i. = 2	4
Group 2: SL no.	5 20.8%	SL = 3 DS = 1 n.i. = 1	3
Group 3: Back-thrust (HL) no.	1 4.2%	HL = 1 (in forelimb)	
Group 4: Distributed strain no.	3 12.5%	DS = 3	1

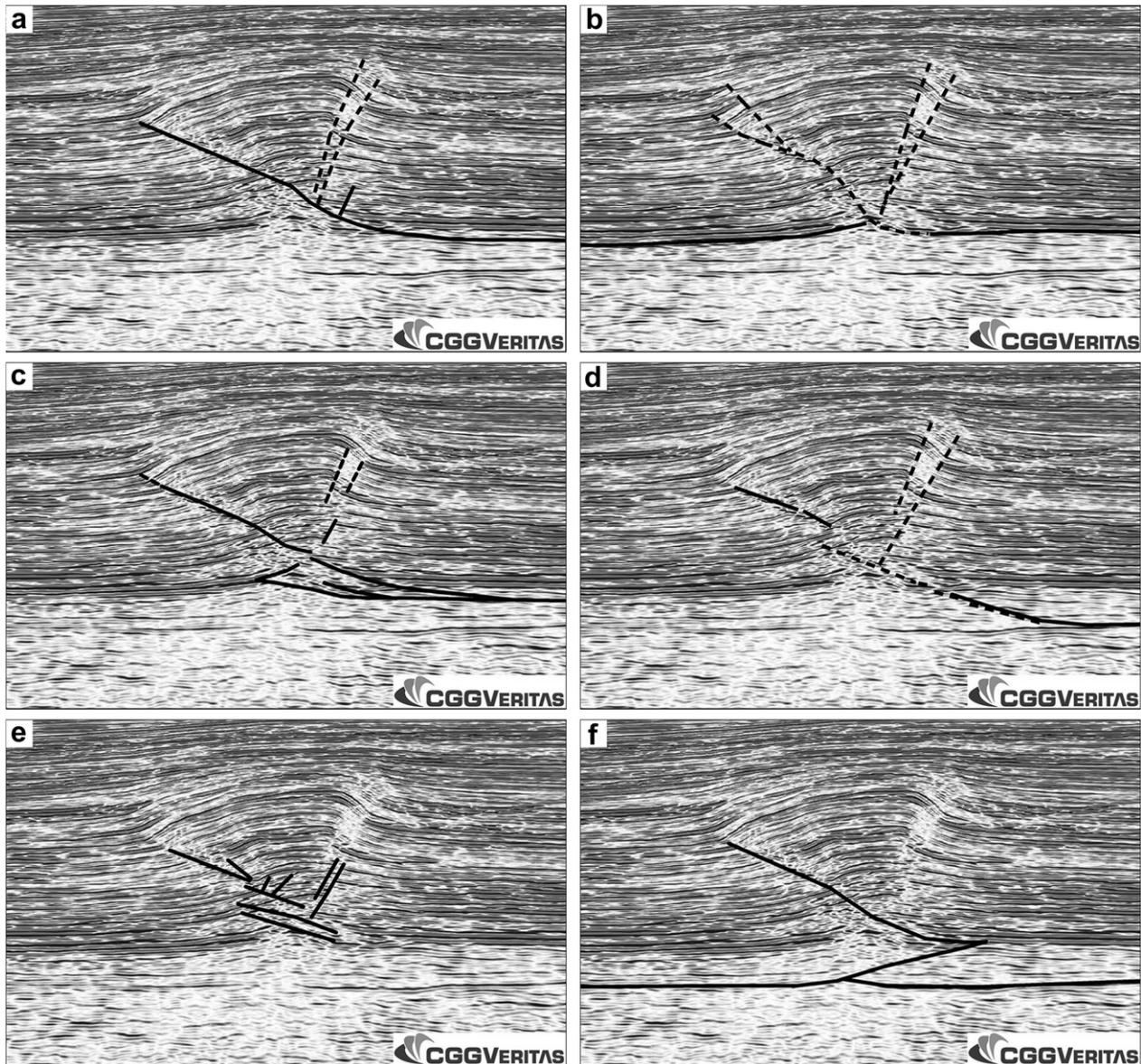


Fig. 5. Examples of the interpretations, divided on the basis of their correlation with structural models (see also Table 1 and Figs. 2 and 5). The stratigraphic interpretations and annotations are removed for clarity. a) and b) Examples of the *model-compliant* group. a) shows features similar to the trishear model (a hard-linked fault and kink folding in the backlimb), while b) is correlated with the detachment fold model. c) and d) Examples of the *model-influenced* group. These interpretations resemble the kinematic models geometrically but imply a different kinematic development (see text). Many interpretations, such as c), also include features not predicted by the models, such as backthrusting. e) and f) Examples of the *model-independent* group. These interpretations cannot be correlated with any of the chosen structural models (see text). The examples can also be grouped as described in the text: a) and f) belong to Group 1, b) and d) are attributed to Group 4, while c) and e) fall into Group 2. Group 3 is not illustrated here.

sometimes, but not always, indicated by the interpreter to consist of a zone of distributed strain. Many interpretations classified into Group 2 are model-influenced to various degrees. However, these interpretations do not fully follow the theoretical model set kinematically in that the models (except for the detachment fold and break–thrust fold models) predict a fault propagating from the detachment upwards, while the final geometries of the interpretations in this group imply that at least some of the faults initiate within the folded, sandy package above the detachment (Fig. 5c–e). In this respect, some of these interpretations are influenced by the break–thrust fold model (Morley, 1994, 2009; Fig. 5d), but they are not entirely compliant with the model as footwall folding is not indicated. Furthermore, many interpretations showing faulting within the fold show significant deformation in the backlimb which is not attributed to the break–thrust fold model. Many interpretations in this group also indicate some

backthrusting which is not predicted by the theoretical model set (e.g. Fig. 5c).

The rest of the interpretations fall into the category *model-independent* ($n = 3$) as their conformity with the chosen theoretical model set is loose to non-existent (Fig. 5e, f). For example, any interpretation with a significant backthrust element would be included in this category (Fig. 5f). Similarly, some interpretations in Group 2 cannot be associated with any of the models and are considered as model-independent; these include interpretations with two or more soft-linked/isolated, parallel or multi-level faults, displaying geometries that are not represented in the current theoretical models (Fig. 5e).

A spatial analysis of all interpretations with faults only (i.e. areas with interpreted distributed strain omitted) reveals the location where the majority of the participants interpreted a fault (Fig. 7a). The majority placed a relatively continuous fault in the upper and

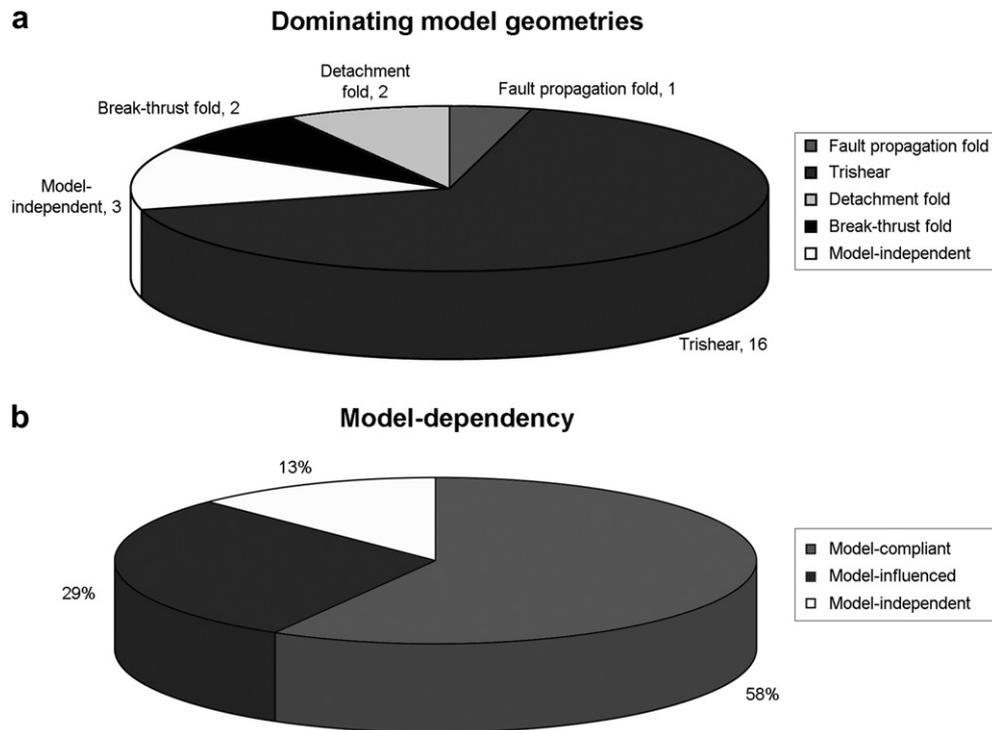


Fig. 6. a) Pie charts illustrating how the theoretical model geometries are represented in the interpretations. The trishear geometry is most dominant ($n = 16$), while none of the interpretations indicated a fault-bend fold geometry. b) Most interpretations are included in the group *model-compliant*. The models were allocated according to the dominant features defined in Table 1.

central parts of the fold forelimb, but there is significant disagreement on the location and continuity of the faults, especially in the backlimb of the fold, and on how the faults in the fore- and backlimbs link to each other and to the detachment. The interpreted location of the detachment also varies significantly. A similar trend is observable in the spatial analysis of the areas with interpreted distributed strain (Fig. 7b), although the number of interpretations with distributed strain is much smaller. Most of the distributed strain was interpreted to be located in the fold backlimb (usually associated with interpreted kink folding above the thrust ramp, as in the trishear model).

4. Discussion

Having made observations of the range and style of interpretations and assessed the use of theoretical models in interpretation

by the experts, we consider 1) what geometries are present in natural and experimental analogues for thrust belts, with specific reference to deepwater fold–thrust belts, and following this, 2) the applicability of the theoretical model set in this context and 3) the problems that may arise from using the popularity of an interpretation to get the ‘right’ answer.

Many of the collected interpretations show clear signs of having been influenced by the existing structural models for fold–thrust systems, but many also diverge significantly from the attributes of the theoretical model set. Most of the theoretical models, bar the detachment fold model and the break–thrust fold model, are characterised by propagation of a single-strand, hard-linked thrust fault from the detachment plane upwards. The majority of the returned interpretations show aspects of the trishear model, but a significant number of participants interpreted discontinuous fault geometries. The discontinuous faults are more compatible with the

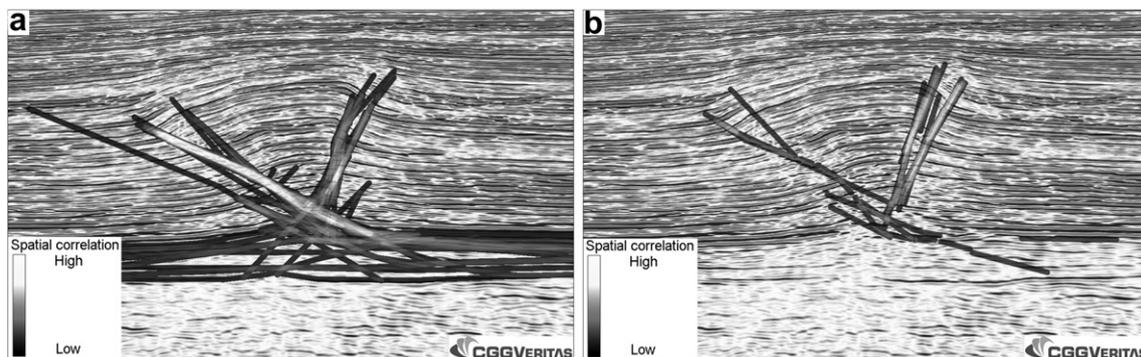


Fig. 7. A composite spatial analysis of all interpretations, a) faults only (i.e. areas of interpreted distributed strain omitted; $n = 21$), and b) distributed strain only ($n = 9$). In a), the majority placed a relatively continuous fault in the upper and central parts of the fold forelimb, but there is significant disagreement on the location, continuity and linkage of the faults, especially in the backlimb of the fold. The interpreted location of the detachment is also highly variable. In b), most of the distributed strain was interpreted to be located in the fold backlimb (usually associated with trishear-style geometry). See text for further discussion.

break–thrust model (the interpretations were not deemed model-compliant as they did not fulfil all the characteristics allocated for the model in Table 1). Discontinuous fault geometries are observed at various scales, in crystalline and sedimentary rocks, as well as in unconsolidated sediments, including outcrop analogues for deep-water fold–thrust belts, (e.g. Vannucchi, 1999; Nicol et al., 2002; Butler and McCaffrey, 2004; Kristensen et al., 2008). Natural examples also show that thrust systems can develop a network of multiple faults and backthrusts, which are not necessarily hard-linked, so that complex changes in fold/fault vergences and backthrust-dominated fold systems, even backthrust belts, are not only possible but quite common (e.g. Morley, 1994, 2009; McQuarrie and DeCelles, 2001; Nicol et al., 2002; Higgins et al., 2009). These types of structures are not within the scope of the theoretical models. Distinct fault planes may not develop at all in some cases, shortening being instead accommodated mostly by distributed strain or by soft-linked segmented faults; Kostenko et al. (2008) note that poorly imaged seismic zones in deepwater fold–thrust belts, such as present in the dataset used in our exercise, are commonly interpreted as faults in published seismic interpretations. However, their results from a Niger Delta fold–thrust belt anticline show that overturned forelimbs, i.e. essentially large kink-folds, are the more likely candidate for the accommodation of the deformation in the poorly imaged fold forelimbs, and that faults may be much less common in deepwater fold–thrust belts in general than previously thought. The rheology of deepwater sedimentary systems with unconsolidated sand and shale seems to inhibit brittle faulting, promoting distributed deformation instead accommodated by lateral compaction and/or internal shortening (e.g. Butler and Paton, 2010; de Vera et al., 2010).

The development of multiple faults, backthrusts and changes in fault vergences has also been modelled with analogue and numerical experiments (e.g. Cobbold et al., 2001; Luján et al., 2003; Maillot and Koyi, 2006). Experiments specifically with strain analysis at early stages of the thrust system development, i.e. with isolated and/or soft-linked faults that don't necessarily initiate at and propagate from a detachment plane, are less common (examples from modelling thrust systems include Ellis et al., 2004; Adam et al., 2005; Andersen et al., 2005). Modern techniques in numerical and analogue modelling with unconsolidated sediments and other granular materials have allowed small-scale, increasingly detailed, quantitative studies of the development of individual faults and strain distribution during the evolution of the modelled structures (e.g. Adam et al., 2005; Schmatz et al., 2010). The experiments show that, in contrast to the existing kinematic models, fault zones often initiate and develop in a non-linear manner as segmented, soft-linked systems, especially if the lithology consists of layers with differing rheologies. In such non-linear systems, the pre-failure deformation is distributed and shear zones localise at all levels (e.g. Adam et al., 2005).

Theoretical models can be applicable in many settings, and at best they explain the primary elements of fold–thrust systems very well. However, given the above discussion, the application of theoretical structural models (constructed on the basis of observations made from continental, lithified and/or crystalline rocks) to the interpretation of seismic data from deepwater fold–thrust belts may not be appropriate. This is especially true for the models that predict a development of a single, forward-propagating fault plane. Most geoscientists are likely to be conscious of the shortcomings of the structural models, but the analysis of the collected interpretations demonstrates that many are still potentially affected by them when interpreting data. This leads to oversimplification of and, in the worst case, errors in interpretations. This is not to say that kinematic models do not have a place or a use when assessing the deformation mechanisms and the strain distribution at play. For

example, Butler and Paton (2010) were able to show, through the application of a 'classic' kinematic model for restoration, that the model in question was not applicable in their study area as it failed to account for the entire shortening. This allowed them to hypothesise other options for the strain distribution.

It is recognised that, given proper tools and sufficient time, many geoscientists would use multiple techniques (e.g. seismic attribute analysis as well as 'unfiltered' amplitude images, backstripping and restoration techniques, and more detailed growth strata analysis) to interpret seismic reflection data, and that they would also attempt to gather other data before making their final interpretation. Availability of the full 3D dataset (serial 2D sections and/or time slices) would also have provided further constraining information to aid interpretation of the dataset. Nevertheless, the initial approach to the interpretational problem, i.e. usage or non-usage of models, is critical to the end result as it has been shown that people are not likely to change the main features of their initial interpretation, even when provided with additional information (e.g. Rankey and Mitchell, 2003). We infer that the experts that produced model-compliant solutions showing a single, continuous fault plane extrapolated observations from the seismic image to fit an existing model, i.e. they assumed a presence of sub-seismic structures that link together into a continuous fault plane. To conclude, the existing theoretical models may be inapplicable in natural settings and they should, therefore, be used with caution, particularly for systems that diverge significantly from the original model environment. Application of models should not constitute the initial approach when interpreting data, but rather be used to help constrain the problem, or as one possible solution after a careful, detailed analysis of the data.

As a final observation, it is tempting to use the composite spatial correlation of the experts' interpretations to deduce the 'right answer'. On the basis of the results, there are some problems with this approach. Most importantly, the dominant *backlimb* deformation mechanism was attributed to kink folding (distributed strain) nearly as often as to hard- or soft-linked/isolated faulting (8 vs. 13, respectively; Table 2), with the faulting further almost equally divided between soft-linked/isolated and hard-linked systems (8 vs. 5, respectively), so that choosing the most representative interpretation becomes impossible. Similarly, the number of interpretations defining a soft-linked/isolated system or distributed strain (no faulting) in the *forelimb* constitute 33% of all interpretations (as opposed to an interpreted hard-linked fault; Table 2), not an equal split but a significant percentage nevertheless. Therefore, the 'popularity' of one answer is not easily defined, and even where a dominant interpretation can be found, in this case faulting in the *forelimb*, it may not be correct, or at least as common in natural examples as previously thought (e.g. Kostenko et al., 2008). Future analysis of the interpretations in conjunction with the background information collected from the participants may provide further clues as to why the experts made their interpretational choices.

5. Conclusions

The evidence from analogue and numerical models of thrust systems and, perhaps more importantly, natural examples show that the traditional kinematic and geometrical models for fold–thrust belts fail to account for crucial features present in natural systems. This is especially true for deepwater fold–thrust belts where the geological environment and the rheological properties of the involved material promote distributed deformation, as opposed to the distinct, forward-propagating, continuous fault planes predicted by most of the commonly used structural models. Our study has shown that:

- many experts showed model-compliance when initially interpreting a seismic data set from a fold–thrust belt,
- the interpretations produced that were not model-compliant appear more consistent with both natural and experimental analogues, and therefore
- existing models are not necessarily applicable to all fold–thrust belt systems.

Acknowledgements

CGGVeritas is thanked for providing the seismic image used in the exercise. Constructive comments by Rob Butler greatly helped to improve this paper. This study forms a part of a wider exercise by PhD NERC CASE candidate Euan Macrae (NE/F013728/1) to understand the influence of prior knowledge in seismic interpretation. Case partner Midland Valley Exploration Ltd. is acknowledged and thanked for funding CEB to attend the AAPG Hedberg. TT is supported by the Virtual Seismic Atlas project. Reviewers Chris Morley and Carlos Rivero are gratefully acknowledged for their constructive comments.

The colour seismic image and the full range of the interpretations collected in this study can be viewed at and downloaded from the Virtual Seismic Atlas VSA (www.seismicatlas.org).

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