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Subsurface structural interpretation by applying trishear algorithm: an example from the Lenghu5 fold-and-thrust belt, Qaidam Basin, Northern Tibetan Plateau

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Abstract

The application of trishear algorithm, in which deformation occurs in a triangle zone in front of a propagating fault tip, is often used to understand fault related folding. In comparison to kink-band methods, a key characteristic of trishear algorithm is that non-uniform deformation within the triangle zone allows the layer thickness and horizon length to change during deformation, which is commonly observed in natural structures. An example from the Lenghu5 fold-and-thrust belt (Qaidam Basin, northern Tibetan Plateau) is interpreted to help understand how to employ trishear forward modelling to improve the accuracy of seismic interpretation. High resolution fieldwork data, including high-angle dips, 'dragging structures', thinning hanging-wall and thickening footwall, are used to determined best-fit trishear model to explain the deformation happened to the Lenghu5 fold-and-thrust belt. We also consider the factors that increase the complexity of trishear models, including: (a) fault-dip changes and (b) pre-existing faults. We integrate fault dip change and pre-existing faults to predict subsurface structures that are apparently under seismic resolution.

The analogue analysis by trishear models indicates that the Lenghu5 fold-and-thrust belt is controlled by an upward-steepening reverse fault above a pre-existing opposite-thrusting fault in deeper subsurface. The validity of the trishear model is confirmed by the high accordance between the model and the high-resolution fieldwork. The validated trishear forward model provides geometric constraints to the faults and horizons in the seismic section, e.g., fault cutoffs and fault tip position, faults' intersecting relationship and horizon/fault cross-cutting relationship. The subsurface prediction using trishear algorithm can significantly increase the accuracy of seismic interpretation, particularly in seismic sections with low signal/noise ratio.

Keywords

trishear algorithm, high-resolution fieldwork, structural complexity, geometric constraints, subsurface prediction

Introduction

It has been extensively documented from outcrop and sub-surface studies that there is an intimate relationship between folding of sedimentary sequences and underlying faults, and a variety of different models are invoked, including fault-bend folding (Jamison, 1987; Medwedeff and Suppe, 1997; Suppe, 1983; Tavani et al., 2005), fault-propagation folding (Jamison, 1987; Mitra, 1990; Suppe and Medwedeff, 1990) and detachment folding (Dahlstrom, 1990; Jamison, 1987; Mitra, 2003; Poblet and McClay, 1996) to explain specific examples. Many of these models utilise a kink-band method (Fig. 1a, b) that maintains a constant layer thickness and line length, which results in uniform dips and homogeneous deformation of the fold limbs (Suppe, 1983; Suppe and Medwedeff, 1990).

However, there have been many examples that cannot be well illustrated by kink-band method, including both experimental analogue studies (e.g., Bose et al., 2009;

Ellis et al., 2004; McQuarrie, 2004; Miller and Mitra, 2011) and natural geological structures (e.g., Allmendinger, 1998; Cristallini and Allmendinger, 2001; Erslev, 1991; Erslev and Mayborn, 1997; Erslev and Rogers, 1993). For example, Fig. 2a shows a natural example of trishear algorithm, which is a simplified cross section of the Turner Valley anticline, Canadian Rocky Mountains (Allmendinger, 1998). The turner Valley anticline is controlled by the underlying reverse fault. Against the reverse fault, 'dragging structures' are developed, with an anticline in the hanging-wall and a syncline in the footwall, respectively. The trishear algorithm, maintaining section area during deformation, provides an alternative approach for those examples (Fig. 2b). Trishear mechanism was initially proposed by (Erslev, 1991), with a precondition that the section area is kept constant during deformation, allowing non-uniform dip and inhomogeneous strain occurs within the folds/faults. Within the trishear model, the deformation is concentrated within a triangle zone in front of the propagating fault tip. The trishear algorithm is determined by multiple parameters, e.g., trishear p/s ratio (the fault propagation/slip ratio), trishear apical angle, fault dip, etc.

Despite these studies on trishear algorithm, little attention has been paid on the integration of high-resolution field data, which limits the application of the trishear mechanism in subsurface structural prediction, particularly the structural features that are under seismic resolution. In this paper, we focus on prediction of subsurface structural geometry by employing trishear forward modelling. An example from the Lenghu5 fold-and-thrust belt in the Qaidam Basin (Northern Tibetan Plateau) is interpreted using the trishear algorithm, with validation by high-resolution field data, which provides an effective workflow of applying trishear algorithm to complex natural structures.

1. Geological Settings

The Cenozoic Qaidam Basin, with an average elevation of 2.8 km, is one of the largest sedimentary basins in the northern Tibetan Plateau (Fig. 3a). The Qaidam Basin presents a triangular shape in plain view (Fig. 3b), bounded by the QilianShan-NanShan Thrust Belt to the northeast, the Altyn Tagh Strike-slip Fault to the northwest and the QimenTagh-EasternKunlun Belt to the southwest (e.g. Burchfiel et al., 1989; Cowgill et al., 2000; Cowgill et al., 2003; e.g. Jolivet et al., 2003; Meyer et al., 1998; Tapponnier et al., 1990; Yin et al., 2007; Yin et al., 2008a; Yin and Harrison, 2000). The stratigraphy of Qaidam Basin is divided into three main packages, which are metamorphic basement, late Palaeozoic-Mesozoic package and Cenozoic package (e.g., Cui et al., 1995; Deng et al., 1995; Gao et al., 1995; Xia et al., 2001).

In Fig. 3c, a cross section, through the central portion of Qaidam Basin, is constructed based on the published studies (e.g., Liu et al., 2009; Yin et al., 2008b; Zhou et al., 2006). The NE-SW section (see position in Fig. 3b), ~180 km long, covers majority of the Qaidam Basin to present both the primary and regional structural geometry. In this section, the Qaidam Basin develops different orders of structures. The first-order structure is a large-scale synclinorium composed of a series of tight anticlines and open synclines, with a wavelength of ~380 km (length of Fig. 3c section is half wavelength) and amplitude of ~16 km. The Qaidam Basin develops huge thick Cenozoic strata up to 16 km and locally thin Mesozoic strata. The central thickening of Cenozoic stratigraphic units suggests that the development of Qaidam Basin is controlled by NE-SW compression, which is derived from the uplift of Tibetan Plateau (e.g., Cheng et al., 2015; Cheng et al., 2017; Mao et al., 2016; Molnar and Tapponnier, 1975; Wang and Burchfiel, 2004; Wei et al., 2016; Wu

et al., 2014; Yin et al., 2008a; Yin et al., 2008b; Yin and Harrison, 2000; Yu et al., 2014; Zhou et al., 2006; Zhu et al., 2006). The second-order structures are regional scale folds and faults. The inversed normal faults in Mesozoic strata and thrust faults in Jurassic-Eocene strata, forming fault-bend folds and fault-propagation folds, indicate a complicated structural deformation in the Qaidam Basin. The Lenghu5 fold-and-thrust belt, our study area, is located in the north Qaidam Basin (see position in Fig. 3c).

2. Structural Geometry of the Lenghu5 Fold-and-thrust Belt

In order to understand the structural geometry of the Lenghu5 fold-and-thrust belt, a depth-converted seismic section is constructed, with length of ~18 km and depth of ~9 km (Fig. 4). This section is well constrained by the 'Lengke1' well and the regional stratigraphy (Fig. 4a). An upward-steepening reverse fault (F_1) and an opposite-dipping thrust fault (F_2) are picked up in this seismic section (Fig. 4b). The stratigraphy is composed of basement, Mesozoic strata (J_r) and Cenozoic strata (E_{1+2}-N_{2-2}). The thicker unit J_r in the hanging-wall than the footwall, suggests that F_2 was initially a normal fault and is inversed in a later compression. The units of E_{1+2}-N_{2-1} keep constant thickness throughout the section, suggesting that these units are deposited before the later compression. The growth strata developed in unit N_{2-2} indicate that unit N_{2-2} is deposited simultaneously with the compression (Fig. 4c). Therefore, the Lenghu5 fold-and-thrust belt experience an inversion from the initial Mesozoic extension to the later Cenozoic compression. The fault F_2 was developed as a normal fault in the initial Mesozoic extension and transferred to be an inverted fault when it was subject to the later Cenozoic compression. However, the high angle F_2 was apparently too steep for the hanging-wall to move upward continuously upon the fault plane. Therefore, a low angle thrust fault F_1 was, therefore, developed in the

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upper E_3 unit to accommodate the compressional strain happened to the Lenghu5 fold-and-thrust belt. The interaction between F_1 and F_2 determines the resultant geometry of this structure.

However, the conventional structural restoration, using 'fault parallel flow' algorithm in 2DMove (Midland Valley), presents imbalance of the restored sections (Fig. 5). For example, the unit E_3 (the cyan layer) does not present constant thickness after the connection of the cutoffs A and A' by restoring the hanging-wall down the fault F_1 (*h_1*, *h_2* and *h_3* in Fig. 5b). Moreover, the intersecting relationship between the faults F_1 and F_2 is also unclear, because the tip of F_2 cannot be accurately determined based on the poor quality of seismic reflection. This hinders our understanding in the detailed deformation happened to the Lenghu5 fold-and-thrust belt. Given the detailed structural features (e.g., high-angle dip variation and small folds that are under seismic resolution) are usually not resolvable in seismic reflection, a high-resolution fieldwork is therefore necessary to understand fault architecture and structural deformation of the Lenghu5 fold-and-thrust belt.

3. High-resolution Fieldwork

In the Lenghu5 fold-and-thrust belt, the topography is relatively flat (see the QuickBird image in Fig. 6). Because of arid weather and strong winds, there are very limited plants and the rocks are well exposed in surface. In the high-resolution QuickBird image (with spatial resolution of 1 m, derived from DigitalGlobal), layering of stratigraphy is well imaged with different colours that are determined by lithology. In the QuickBird image, coarse sandstones or conglomerates present grey or light brown colour, medium to fine sandstones present brown colour, whereas siltstones and mudstones present reddish brown colour. Being constrained by the satellite image, the detailed stratigraphy is recorded in a high-resolution fieldwork, including a

column HW for the hanging-wall and a column FW for the footwall (see the horizontal columns in top of Fig. 6). These two stratigraphic columns HW and FW present thickness of ~1200 m and ~650 m, respectively. The stratigraphic columns are horizontally aligned with a high-resolution satellite image to assist the profile construction (see position of this section in Fig. 4). A SW-dipping thrust fault is interpreted in both the fieldwork and the satellite image. According to the stratigraphic correlation between the hanging-wall and footwall, the fault throw is inferred ~500 m. Therefore, the main thrust fault is a seismic-scale fault, corresponding to the fault F_1 in Fig. 4. Based on the stratigraphic columns, the lithology changes from coarse sandstone to clay-rich fine sandstone towards the central fault F_1, in either the hanging-wall or the footwall. By integrating field dip measurements and satellite image interpretation, a high-resolution profile is constructed by using Busk method in the fault zone and kink-band algorithm in the further hanging-wall and footwall, which can be used to constrain the seismic interpretation. This high-resolution profile allows us to observe detailed structural features that are under seismic resolution. For example, the hanging-wall strata present downward steepening dips towards the fault F_1, whereas the footwall strata against the fault zone are overturned. These structural features observed in field also suggest that the layer thickness is not universally constant in the profile. Therefore, the well-established kink-band method (Suppe, 1983; Suppe and Medwedeff, 1990) is no longer applicable for the structural interpretation of the Lenghu5 fold-and-thrust belt. An appropriate deformation mechanism, potentially trishear algorithm, is necessary to understand the structural deformation happened in the Lenghu5 fold-and-thrust belt.

4. Analogue Analysis by Trishear Models

The effects of trishear parameters on the geometry of trishear models have been evaluated by constructing a trishear parameter space (Pei et al., 2014). The trishear models in the parameter space focus on reverse faults with constant dip during deformation. The clusters of natural examples in the parameter space suggested p/s ratio of 2.0-2.5 and trishear apical angle of 50° for majority natural examples that have been investigated in previous studies (e.g., Allmendinger, 1998; Allmendinger et al., 2004; Cardozo, 2005; Cardozo and Aanonsen, 2009; Cardozo et al., 2005; Champion et al., 2001; Gold et al., 2006; Hardy and Ford, 1997; Lin et al., 2007). As the examples with different parameters in Fig. 7, monoclines are developed in front of the fault tip in the trishear models. Although these geometries are common to all examples, the specific resultant geometries vary significantly depending upon the specific parameters that are used. With a constant fault slip, the amplitude of the hanging wall uplift has a positive correlation with fault dip that is unaffected by p/s ratio or apical angle whereas the fault tip propagation is positively correlated with high p/s ratio and unaffected by apical angle or fault dip. Parameters of low fault dip, low p/s ratio and high apical angle result in a high magnitude of hanging wall thinning and footwall thickening, whereas parameters of low fault dip, low p/s ratio and high apical angle form a wide monocline. The monocline in front of the fault tip can be overturned with parameters of high fault dip, high p/s ratio and low apical angles. Moreover, the layers' thickness is not constant during deformation. For example, the hanging-wall strata are thinning and the footwall strata are thickening in all the trishear models. If the layers are cut by the propagating faults, 'dragging structures' are also observed in both hanging-wall and footwall adjacent to the faults. These features are also observed in the high-resolution fieldwork in the Lenghu5 fold-and-

thrust belt. The high accordance between the trishear models and the field observations indicate that trishear can be an appropriate approach to reveal the structural deformation happened to the Lenghu5 fold-and-thrust belt.

However, the simple trishear models cannot properly illustrate the geometry of hanging-wall and footwall in the Lenghu5 fold-and-thrust belt. For example, it is impossible to form an anticline in the hanging-wall with a constant-dipping reverse fault, and the minor folds presented in the footwall could not be formed with a single reverse fault in a structure (Fig. 6). The fault geometry is therefore more complex than the trishear models presented in Fig. 7. The factors that can increase the complexity of trishear models are, for example, fault-dip change and pre-existing faults (Allmendinger et al., 2004; Pei et al., 2014). Complex geometry is then formed by integrating these factors in trishear models. Here we consider trishear algorithm on curved reverse faults (i.e., fault-dip change) and multiple faults (i.e., pre-existing faults) for analogue analysis to predict the subsurface structures. In order to provide accurate geometric constraints on the structural deformation of the Lenghu5 fold-and-thrust belt, we investigate the structural geometry of the hanging-wall and footwall, individually.

We firstly apply trishear algorithm on curved reverse faults to test whether the Lenghu5 thrust fault is upward-steepening (p/s ratio of 2.0, apical angle of 50°, fault dip from 10° to 70°, Fig. 8b) or upward-shallowing (p/s ratio of 2.0, apical angle of 50°, fault dip from 70° to 20°, Fig. 8c) in subsurface. The upward-steepening and upward-shallowing reverse faults form very different hanging-wall geometries. The upward-steepening reverse fault forms an anticline in the hanging-wall, with a gentle backlimb and overturned forelimb (Fig. 8b), whereas the upward-shallowing reverse fault forms a monocline in the hanging-wall and the hanging-wall shows downward

steepening dips towards the triangle deformation zone (Fig. 8c). By comparing these two trishear models with the high-resolution surface data (e.g., dip distribution, Fig. 8a) in the Lenghu5 fold-and-thrust belt, the trishear model of upward-steepening reverse fault in Fig. 8b presents very similar hanging-wall geometry as observed in fieldwork. The upward-steepening trishear model can therefore provide good constraints on the hanging-wall geometry of the Lenghu5 fold-and-thrust belt.

We then apply trishear algorithm on reverse faults with lower pre-existing faults to explain the footwall geometry of the Lenghu5 fold-and-thrust belt. The pre-existing faults could have either same or opposite thrusting direction with the upper reverse fault. For example, Fig. 9b depicts a trishear model of an upward-steepening reverse fault (p/s ratio of 2.0, apical angle of 50°, fault dip from 70° to 80°) above two pre-existing faults (p/s ratio of 2.0, apical angle of 50°, fault dip from 50° to 60° and from 30° to 40°) with same thrusting direction, whereas Fig. 9c presents a trishear model of an upward-steepening reverse fault (p/s ratio of 2.0, apical angle of 50°, fault dip from 0° to 70°) above an opposite thrusting fault (p/s ratio of 2.0, apical angle of 50°, fault dip from 20° to 40°). A pair of tight syncline and open anticline is developed in the footwall of the upper reverse fault in the trishear model of Fig. 9c, which shows similar footwall geometry with the minor structures observed in the footwall of the Lenghu5 fold-and-thrust belt (Fig. 9a). The dip distribution in the footwall also presents high accordance between the trishear model in Fig. 9c and the field observations in the Lenghu5 fold-and-thrust belt. Therefore, it indicates that an opposite-thrusting fault is pre-existed in lower subsurface beneath the upper reverse fault, which controls the structural geometry of the Lenghu5 fold-and-thrust belt.

5. Constraints of Trishear Models on Structural Geometry

According to the above analogue analysis by the trishear models, the Lenghu5 fold-and-thrust belt is probably controlled by an upward-steepening reverse fault (i.e., SW-dipping fault F_1) above opposite-thrusting reverse faults in deeper subsurface (i.e., NE-dipping faults F_2 and F_3). In the seismic section (Fig. 4), the upward decreasing displacement of F_1 suggests a trishear algorithm is applicable in this structure. Moreover, the reverse faults F_1, F_2 and F_3 all present upward-steepening shapes, which is highly comparable with the complex trishear models (Fig. 8b, Fig. 9c). Therefore, we applied the trishear forward modelling to simulate the structural evolution of the Lenghu5 fold-and-thrust belt by allowing multiple curved faults in a single section. By employing the parameter space and strain quantification workflows (Pei et al., 2014), the parameters of the best-fit trishear model are determined, with an apical angle of 50° and p/s ratio of 2.0. The comparison between the fault slip (cutoffs B and B') and the fault tip propagation of F_2 also suggests a trishear p/s ratio of ~2.0. In order to simulate the upward-steepening reverse faults F_1 and F_2, we used the interpreted F_1 and F_2 as templates to define the stepwise values of upward-steepening fault dip angles (Fig. 10). The dip variation and slip along faults were measured to provide constraints on the forward trishear modelling to reveal the kinematic evolution of the Lenghu5 fold-and-thrust belt. For example, the fault F_1 presents upward-steepening dip from 5°, 12°, 20°, 32°, 45° to 60°, with fault slip of 4.9 km, 1.3 km, 1.2 km, 1.1 km, 2.3 km and 1.1 km, respectively; whereas the fault F_2 presents upward-steepening dip from 25°, 34°, 44° to 55°, with fault slip of 1.5 km, 0.8 km, 0.9 km and 0.8 km, respectively.

Fig. 11a-c depicts the progressive development of the Lenghu5 fold-and-thrust belt, based on the trishear forward modelling using 2DMove (Midland Valley). In Fig. 11a,

the normal fault F_2 was developed to form a half-graben in the J_r strata followed by

deposition of post-extension sequence from E_{1+2} to N_{2-1}; in Fig. 11b, the stress field

changed to be compressional which results in the inversion of F_2 and the

development of a small thrust fault F_3; in Fig. 11c, an opposite thrust fault F_1 was

developed within E_3 layer, forming the current hanging-wall anticline. After uplift and

erosion to present, Fig. 11c presents a good match to the geometry of the Lenghu5

fold-and-thrust belt, both in surface dip distribution and subsurface structural feature.

In order to make precise comparison between the trishear model and natural

observation, we integrated seismic interpretation, field data & satellite image and

trishear model to demonstrate the surface dip distribution and well logging (Fig. 12).

Because of limited resolution of seismic reflection, the seismic interpretation (Fig.

12a) can only present a very general pattern of surface dip distribution, with poor

reflection in vicinity of the thrust fault F_1. The detailed field dip measurements (Fig.

12b) compensate the limited resolution of seismic reflection, which allows precise

comparison of surface dip distribution between natural structure and the trishear

model. Although there is still geometric uncertainty between the trishear model and

natural observation, the trishear model (Fig. 12c) presents more detailed surface dip

distribution that is in good accordance with the seismic interpretation. The geometry

of trishear model also presents proper match with the stratigraphic logging in

Lengke1 well, i.e., repetition of N_1 and E_3 beneath the fault F_1.

The trishear forward models do no only reveal the detailed structural evolution of the

Lenghu5 fold-and-thrust belt, but also present smaller scale structures that are under

seismic resolution, which may help improve the understanding of detailed

deformation happened in both the hanging-wall and footwall adjacent to the faults.

For example, the dragging structures adjacent to F_1 and F_2 are not resolvable in

seismic section (Fig. 13a), and the minor syncline-anticline pair in the footwall are only observed in the trishear forward models (Fig. 13b). These detailed minor structures can constrain the fault and horizon interpretation in seismic section. For example, a) the detailed cross-cutting relationship between the horizons and faults could increase the accuracy of fault cutoffs interpretation in the seismic section, which is vital for determining fault displacement and propagation/slip ratio; b) the detailed intersecting relationship between the lower pre-existing fault F_2 and the upper reverse fault F_1 could also provide constraints on the fault tip interpretation in the seismic section. The trishear forward modelling, with the validation by high-resolution field data, can therefore be an effective technique for increasing the accuracy of seismic interpretation.

6. Discussion

6.1. Geometric constraints of trishear forward modelling

Balancing section restoration has been broadly employed to test the reliability of seismic interpretation. The conventional balancing restoration is working with a precondition that the layer thickness keeps constant during deformation or the horizon length keeps constant during deformation, for example, kink-band models. However, there are many structures in which the layer thickness and horizon length are changed during deformation, in both experimental analogue models (Bonini, 2007; Bose et al., 2009; Costa and Vendeville, 2002; Ellis et al., 2004; McQuarrie, 2004; Miller and Mitra, 2011) and natural geological structures (e.g., Allmendinger, 1998; Cristallini and Allmendinger, 2001; Cristallini et al., 2004; Erslev, 1991; Erslev and Mayborn, 1997; Erslev and Rogers, 1993; Pei et al., 2014; Pei et al., 2017). These structures present non-uniform dips in the same limb and inhomogeneous deformation adjacent to fault (zone). Consequently, as demonstrated by the Lenghu5

fold-and-thrust belt, the balancing section restoration following kink-band method is no longer applicable to verify the reliability of the seismic interpretation. In this situation, the trishear forward modelling could be taken into account to explain the complexity of the structural deformation, as the non-uniform deformation within the triangle zone in front of the fault tip allows the layer thickness and horizon length to change during deformation (Erslev, 1991; Hardy and Ford, 1997). By varying trishear parameters, a spectrum of trishear models with different geometries could be generated. The best-fit parameter combination can also be determined by employing the three-dimensional parameter space (Pei et al., 2014). The geometric spectrum and complexity of trishear models could also be increased by integrating fault-dip change, multiple faults and pre-existing faults in trishear forward modelling (Fig. 7). This allows the application of trishear algorithm to provide geometric constraints for the subsurface structural prediction. However, high complexity of the natural structures obviously increases the difficulty in finding an appropriate trishear solution. Therefore, some appropriate simplification of natural structures is necessary, as the first-order structures can provide initial geometric constraints to determine the best-fit trishear parameters. But this does not mean the small-scale structural features are completely neglected in the analogue analysis using trishear algorithm. The previously simplified structural complexity can be then reproduced in the trishear models to provide constraints for the structural interpretation in natural structures, e.g., the accurate prediction of fault cutoffs and fault tip (Fig. 13).

6.2. 'Ground truthing' by high-resolution field data

Trishear forward modelling could be possibly used to predict subsurface structures with very different geometries. The strata dip changes and minor structural features in trishear models could also be employed to assist the subsurface prediction that

are under seismic resolution. The successful application of trishear forward

modelling in the Lenghu5 fold-and-thrust belt has provided an effective workflow for

subsurface structural interpretation with the assistance of trishear forward modelling.

However, in the Lenghu5 fold-and-thrust belt, although there is good match of

surface dip distribution, there is still discrepancy between the trishear model and

natural observation. For example, the dip angle of N_1 and N_{2-1} in the hanging-wall is

higher than the field measurements in the hanging-wall; the N_1 unit in the footwall

presents significant thickening towards the fault F_1, which is not in strict accordance

with the seismic interpretation. This may be attributed to the parameter setting during

trishear forward modelling, particularly p/s ratio and apical angle (fault dip variation

was well-constrained by the geometry of interpreted faults in seismic section). In this

trishear forward modelling, the p/s ratio and apical angle were set with constant

value of 2.0 and 50°, respectively. Although published case studies mostly used

constant values for p/s ratio and apical angle for simplicity, geologists have realized

that the trishear parameters may vary during the propagation of a fault. Therefore,

high-resolution field data, such as stratigraphic logging and strata/fault dip

measurements, can help improve accuracy of trishear models. Moreover, as there is

a very wide spectrum of geometries in the trishear parameter space (Pei et al., 2014),

it is vital to use stratigraphic logging and dip measurements to test the validity of the

selected trishear models. Stratigraphic logging and dip measurement from multiple

wells, apparently effective for structural validation, however, are unrealistic for a

natural structure in many study areas. Therefore, high-resolution fieldwork, including

regional stratigraphic logging and detailed dip measurements, can be employed as

an effective 'ground truthing' tool to validate the trishear models. With the assistance

of trishear forward modelling validated by high-resolution field data, the accuracy of

seismic interpretation can be significantly improved, particularly the interpretation of second-order structural features in the hanging-wall and footwall adjacent to the faults where the quality of seismic reflection is usually poor.

6.3. Effects of mechanical stratigraphy on trishear forward modelling

This paper focuses on the geometric constraints of the trishear forward modelling on subsurface structural prediction, the trishear parameters p/s ratio and apical angle were therefore set as constant values (2.0 for p/s ratio and 50° for apical angle) without considering their variation during propagation of faults. However, we also realize that mechanical stratigraphy also plays an important control on geometry of resultant trishear models, because the trishear parameters can vary depending upon lithology and mechanical strength (e.g., Alonso and Teixell, 1992; Hardy and Finch, 2007; Hardy and Ford, 1997; Yang et al., 2014). In our study area, the hanging-wall and footwall of the Lenghu5 fold-and-thrust belt covers lithology ranging from conglomerates, coarse sandstones, medium sandstones, fine sandstones, siltstones and mudstones (see the stratigraphic columns in Fig. 6, Fig. 8a and Fig. 9a), which present fining direction towards the central fault zone of F_1. On the one hand, high competent rocks usually present higher p/s ratios and narrower apical angle than rocks with low competency (e.g., Allmendinger, 1998; Hardy and Ford, 1997; Pei et al., 2014; Welch et al., 2009a). Therefore, as demonstrated in the stratigraphic columns in our study area, the siltstone/mudstone-dominated stratigraphy adjacent to the fault F_1 may present lower p/s ratio and wider apical angle than the sandstone-dominated lithology in the further hanging-wall and footwall. On the other hand, when it comes to interbedded rocks with different lithology, such as interbedded layers of sandstone and mudstone, the resultant structure may present high degree of geometric complexity with increasing mechanical heterogeneity. By employing

discrete-element technique (Finch et al., 2003, 2004; Hardy and Finch, 2007; Yang et al., 2014), stratigraphy with low to high mechanical heterogeneity has been investigated to understand their different structural deformation in response to contractional stress. Welch et al. (2009a; 2009b) also employed a quadshear algorithm to study the complexity of folding deformation and fault architecture with different mechanical stratigraphy. Apparently, the Lenghu5 fold-and-thrust belt presents a certain level of stratigraphic heterogeneity in vertical direction, which may impact on the trishear forward models. However, it is still unrealistic to employ either discrete-element method or quadshear algorithm to precisely simulate geometry and kinematics of natural examples with same level of structural complexity in the Lenghu5 fold-and-thrust belt. Field observation is, therefore, necessary to validate the application of trishear forward modelling. Both the Lenghu5 fold-and-thrust belt and the published mechanical models demonstrate the important influence of stratigraphy and strength on structural deformation, however, stratigraphic heterogeneity is likely to determine minor structural features that are superimposed upon the primary structural geometry. Therefore, when employing trishear algorithm for analogue analysis, caution should be given on the effects of mechanical stratigraphy, particularly at a scale that is comparable with the mechanical stratigraphy.

7. Conclusion

This paper have presented a study using trishear forward modelling to constrain the structural deformation of natural structures. The following conclusions are drawn:

1) The best-fit trishear forward models for a natural structure could be identified by integrating high-resolution field data, e.g., stratigraphic logging, dip distribution and fault geometry. The best-fit trishear models could provide

geometric constraints on the subsurface faults and horizons picked in the seismic section with poor quality of reflection.

2) With the constraints provided by trishear forward models, the complexity of structural geometry that are under seismic resolution, e.g., high-angle dips, fault tip position, faults' intersecting relationship and horizon/fault cross-cutting relationship, can be reproduced to increase the accuracy of the seismic interpretation.

Trishear algorithm can be employed to improve the quality of seismic interpretation, particularly in seismic sections with poor reflection. However, the trishear models are not reliable until it has been properly validated by high-resolution field data.

Acknowledgements

Figure Captions

Figure 1. Fault-bend fold and fault-propagation fold based on kink band method (Suppe, 1983; Suppe and Medwedeff, 1990). (a) fault-bend fold; (b) fault-propagation fold. The kink-band models keep layer thickness consistent during structural deformation.

Figure 2. The conceptual trishear model and a natural example. (a) A natural trishear example presenting inconsistent layer thickness, from the Turner Valley anticline, foothills of the Canadian Rocky Mountains (modified from Allmendinger, 1998). (b) The conceptual model based on previous studies (e.g., Erslev, 1991; Hardy and Ford, 1997).

Figure 3. Structural geology of the Qaidam Basin. (a) Tectonic setting of the Qaidam Basin; (b) SRTM DEM overlaid by structural interpretation of the Qaidam Basin; (c) A basin-scale cross section constructed based on seismic reflection (modified from Yin et al., 2008b). Note: the south-verging detachment fault in deep subsurface in (c) was speculated and its existence is still under controversy.

Figure 4. The seismic section and structural interpretation present the primary structural geometry of the Lenghu5 fold-and-thrust belt. (a) Un-interpreted seismic section constrained by the Lengke1 well. (b) Structural interpretation. (c) Amplified seismic section depicting detailed reflection of growth strata in the N_{2-2} strata.

Figure 5. The structural restoration using 'fault parallel flow' algorithm in 2DMove, Midland Valley. (a) Central portion of the seismic section showing fault cutoff points and potential cross-cutting relationship. (b) A partially restored section by moving the hanging-wall down the fault F_1.

Figure 6. The high-resolution profile of the Lenghu5 fold-and-thrust belt, integrating satellite image interpretation (QuickBird image, spatial resolution of 1 m, from DigitalGlobal), stratigraphic logging data and field dip measurements. See the position of this profile in Fig. 4.

Figure 7. Geometry of trishear models of a single fault, with variable apical angle and fault dip. The fault dip does not change in individual section during deformation. Apparently, the simple trishear models with constant fault dip is not geometrically comparable with the Lenghu5 example.

Figure 8. Hanging-wall geometric constraints by trishear analogue models with changing fault dips in a section. (a) Hanging-wall portion of the Lenghu5 fold-and-thrust belt. Satellite image: QuickBird image, spatial resolution of 1 m, from DigitalGlobal. (b) An upward-steepening reverse fault. (c) An upward-shallowing reverse fault.

Figure 9. Footwall geometric constraints by trishear analogue models with pre-existing faults. (a) Hanging-wall portion of the Lenghu5 fold-and-thrust belt. Satellite image: QuickBird image, spatial resolution of 1 m, from DigitalGlobal. (b) A reverse fault above pre-existing faults. (c) A reverse fault above an opposite pre-existing fault.

Figure 10. Geometric constraints on forward trishear modelling, provided by the measurements (including fault dip and fault slip) of F_1, F_2 and F_3 interpreted in the seismic section in Fig. 4b.

Figure 11. Structural evolution of the Lenghu5 fold-and-thrust belt revealed by trishear forward modelling. (a) Normal faulting in Jurassic extension and deposition of post-extension sequence from E_{1+2} to N_{2-1}. (b) Development of reversed thrust faults and folds in the early compression. (c) Development of the upper reverse fault in the late compression.

Figure 12. Integration of seismic interpretation, field observation & satellite image (QuickBird image, spatial resolution of 1 m, from DigitalGlobal) and trishear forward model in the Lenghu5 fold-thrust-belt. The comparison between the three sets of data demonstrates general accordance, however, the discrepancy also suggests that there may be uncertainty in parameter setting during the trishear forward modelling.

Figure 13. The constraints of structural complexity reproduced in trishear models on subsurface structural geometry in seismic section. (a) Seismic interpretation. (b) Trishear model. The accuracy of seismic interpretation can be highly increased with the geometric constraints on faults and horizons.

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Figure 1

(a)

backlimb

forelimb (inactive)

(b)

growing backlimb

growing forelimb

Figure 2

(a)
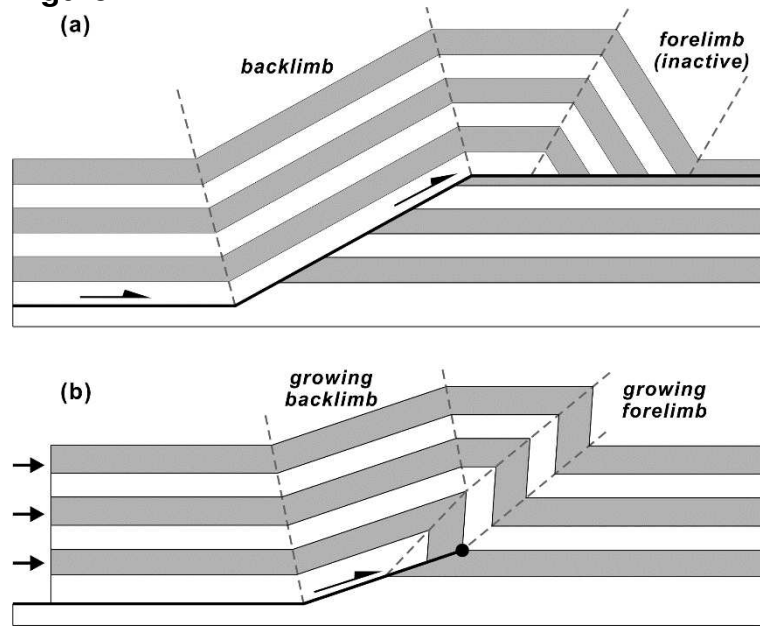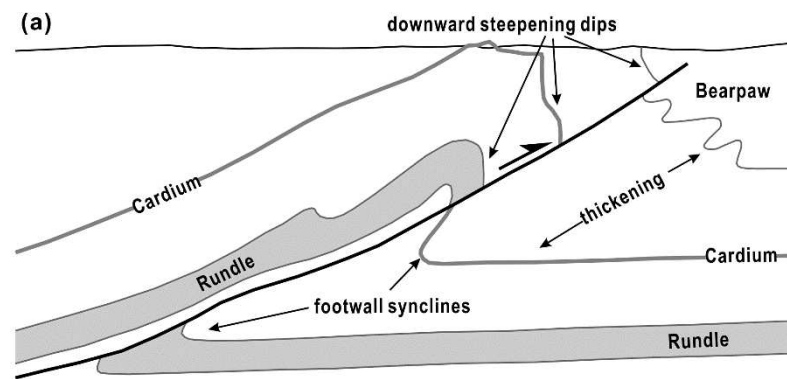
(b)
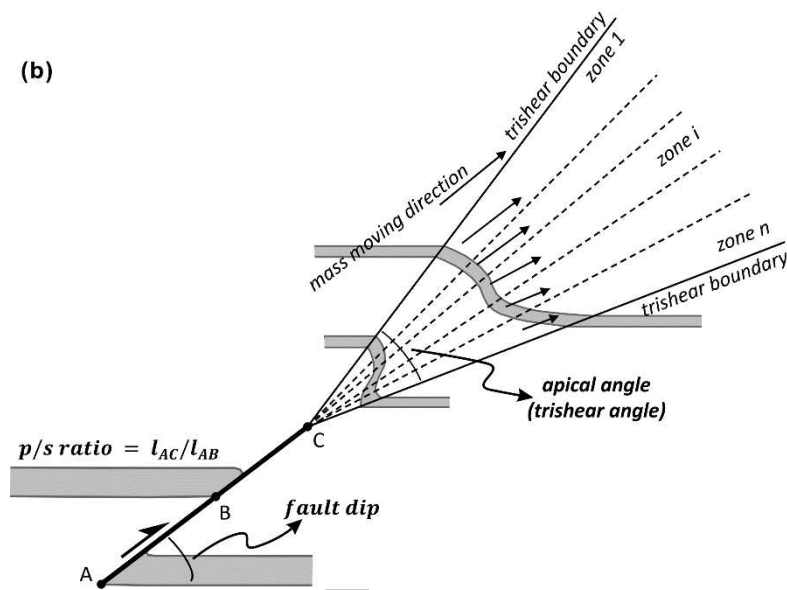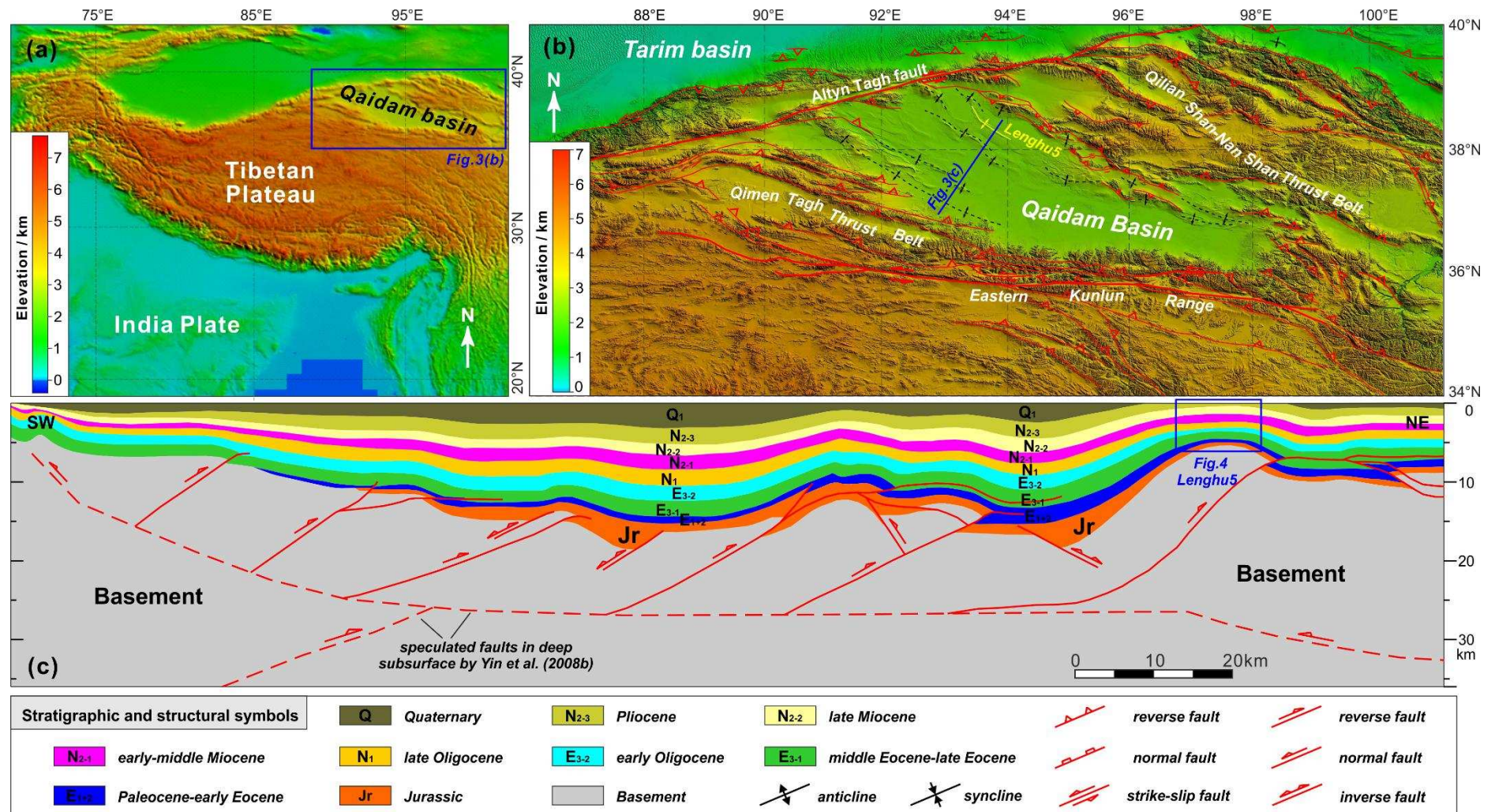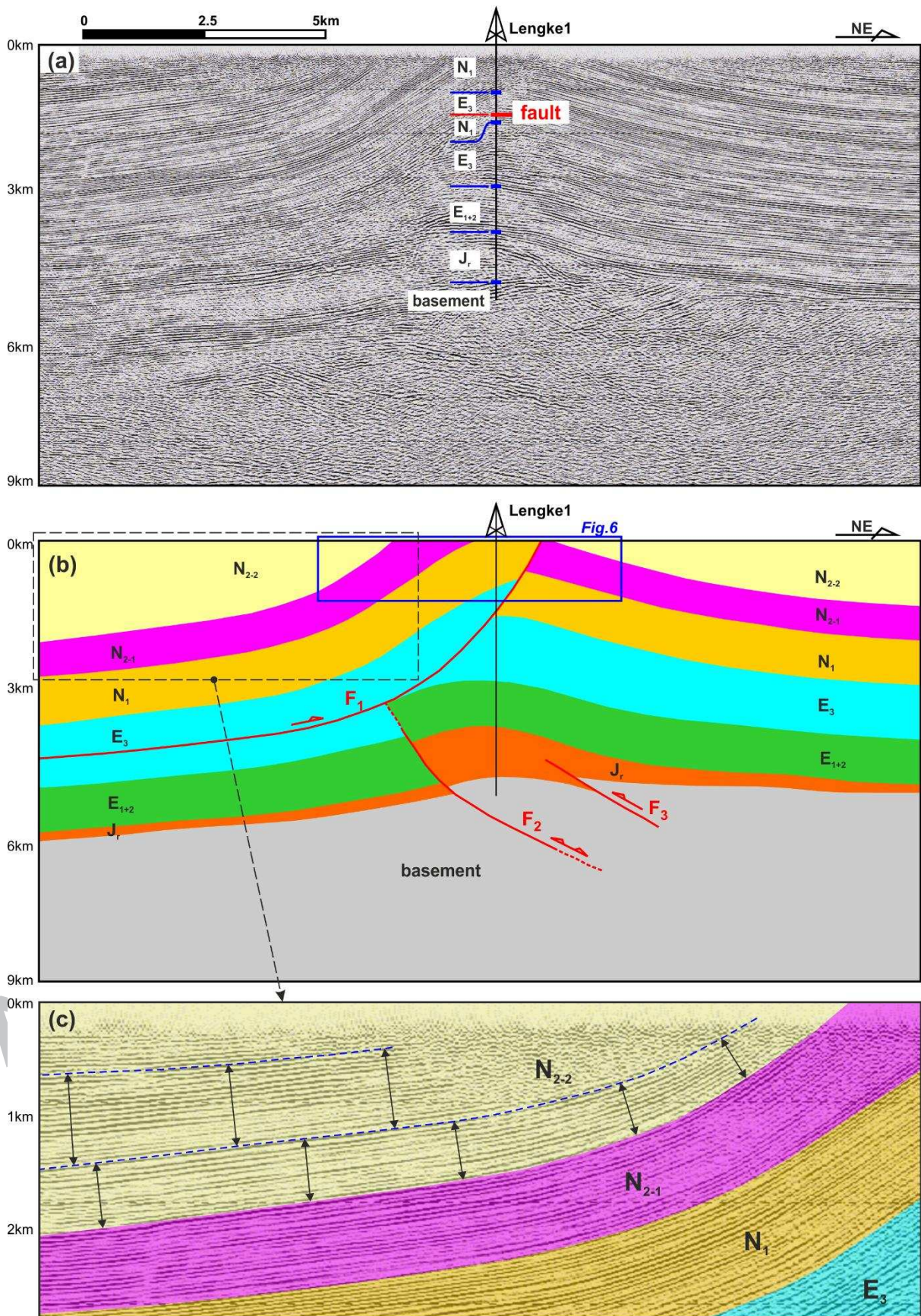
Figure 3

Figure 4

Figure 5
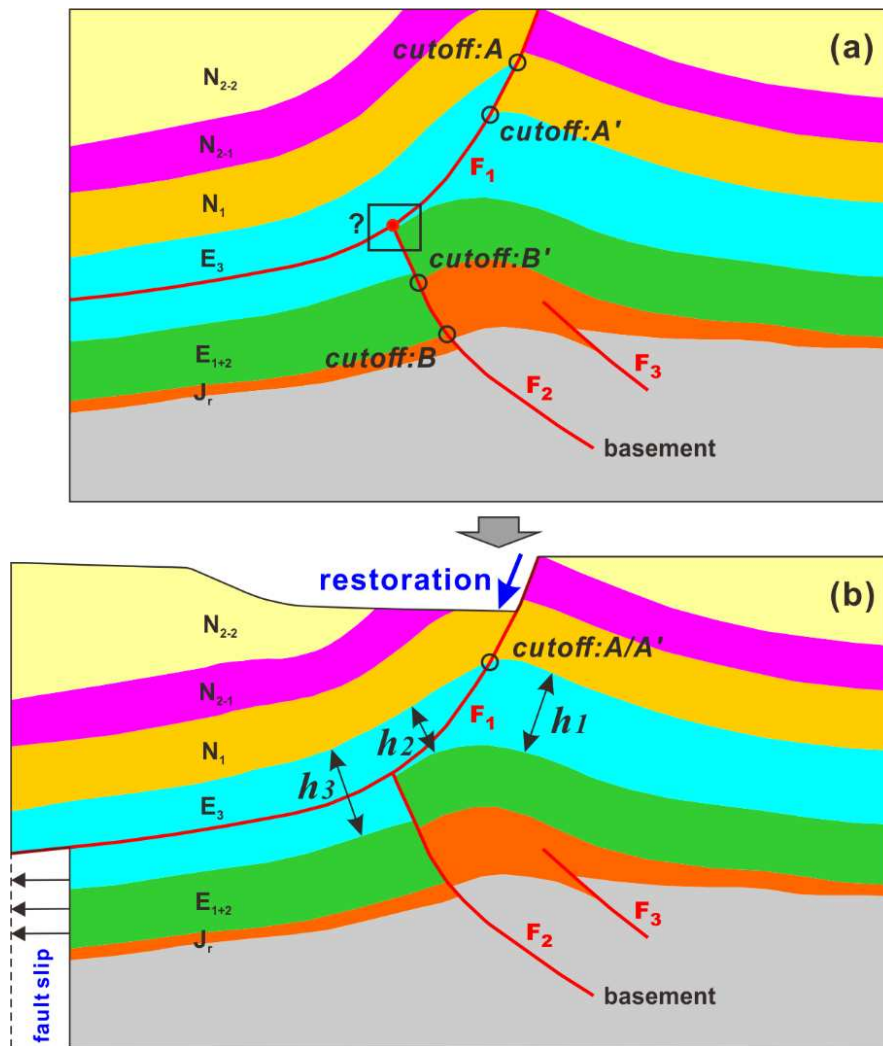
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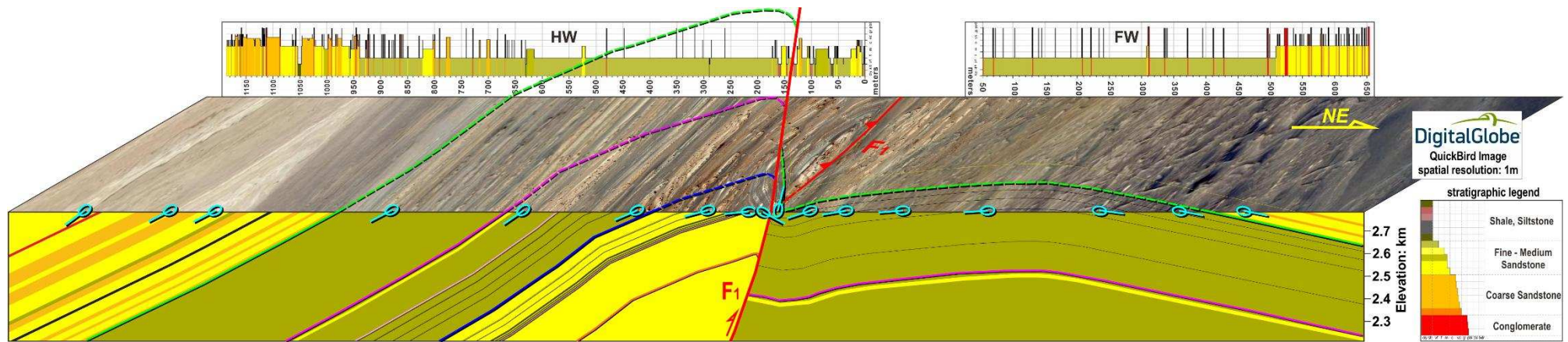
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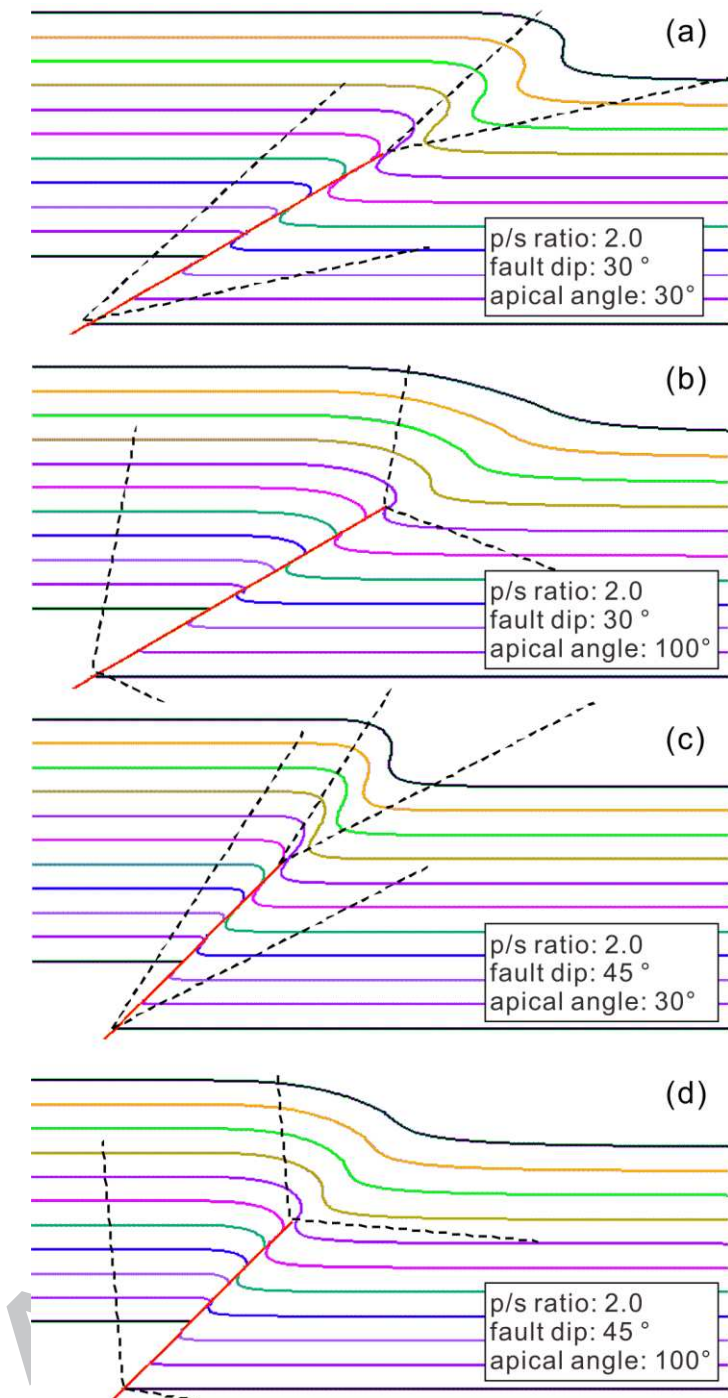
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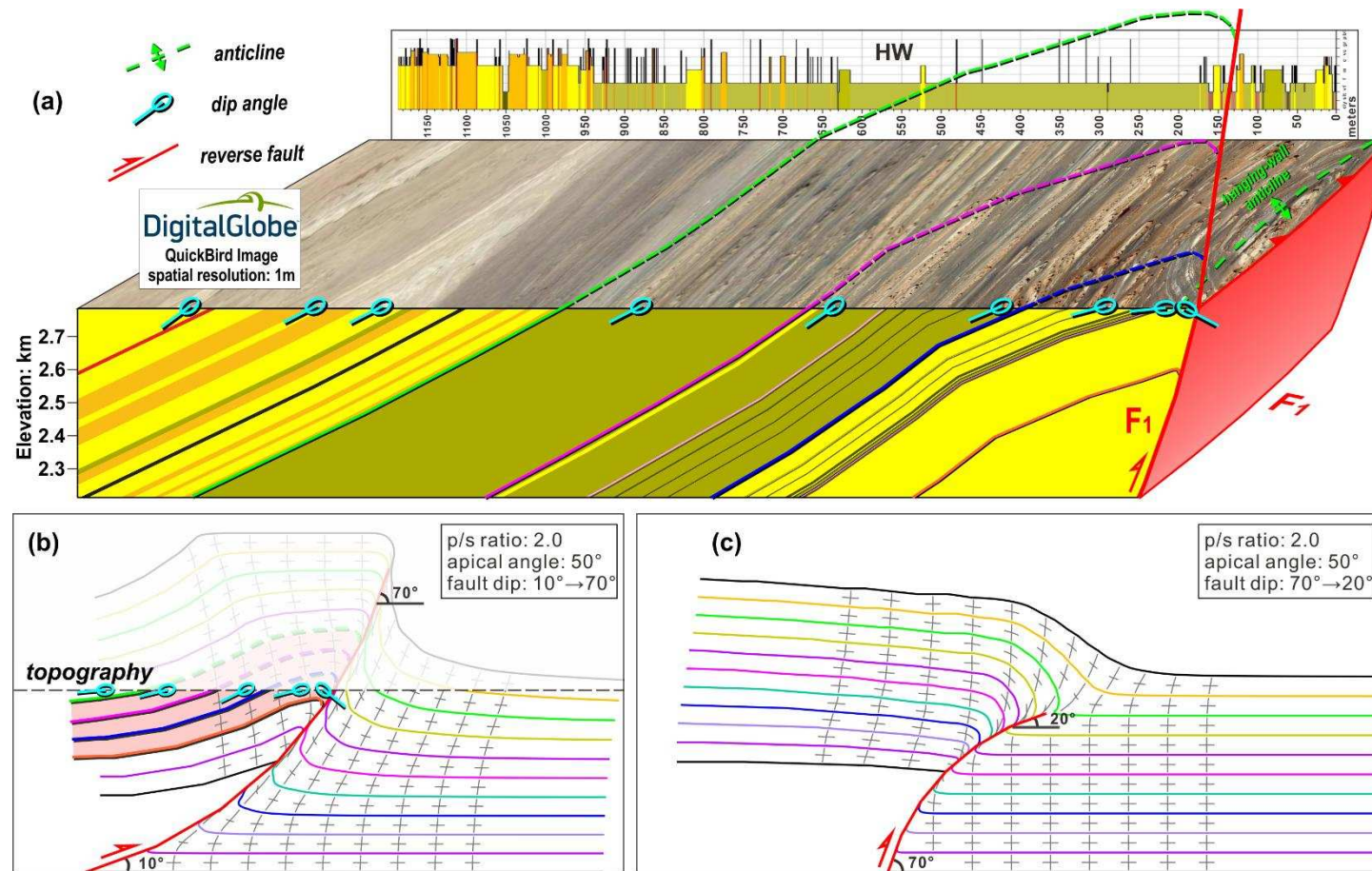
Figure 9

Figure 10

Figure 11

(a) normal faulting stopped and post-deposition — N_{2-1}, N_1, E_3, E_{1+2}, J_r, F_2, Basement

(b) early compression: reversed thrust and anticline formed — N_{2-2}, N_{2-1}, N_1, E_3, E_{1+2}, F_1, J_r, F_2, F_3, Basement

(c) late compression: intiation of the upper reverse fault — Lengke1, current topography, N_{2-2}, N_{2-1}, N_1, E_3, E_{1+2}, F_1, J_r, F_2, F_3, Basement

Figure 12

(a) seismic interpretation

(b) field data and satellite image

(c) trishear model

Figure 13

(a) seismic interpretation

(b) field data and satellite image

(c) trishear model
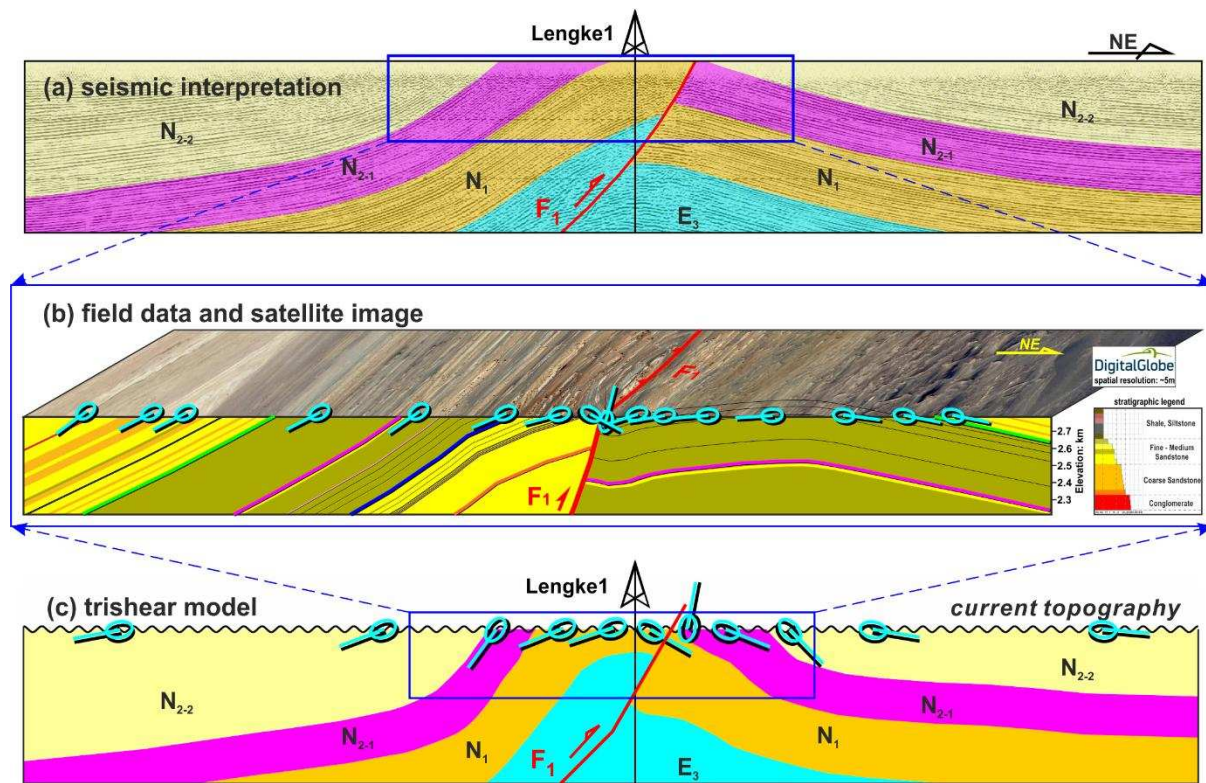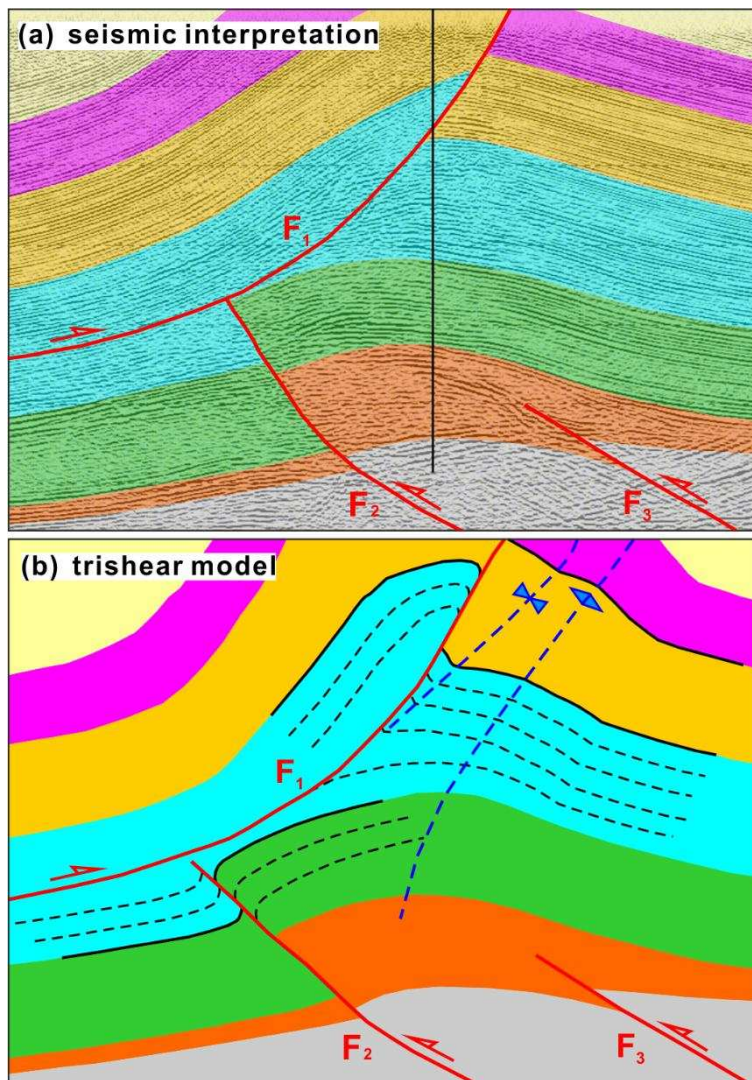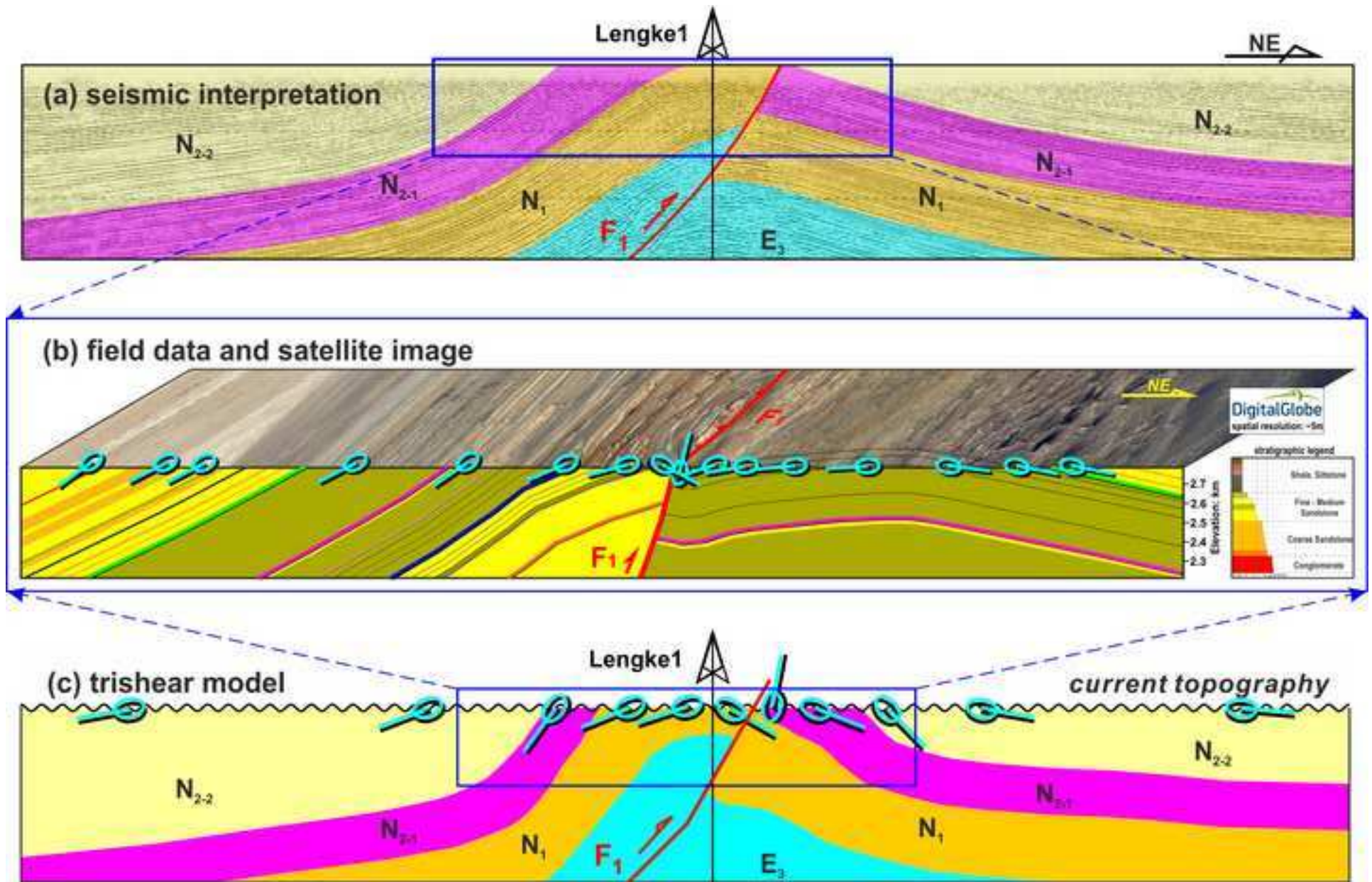
Highlights

- Trishear algorithm can generate a wide spectrum of structural geometry.

- High-resolution field data can help determine the best-fit model for natural example.

- Structures under seismic resolution can be built by trishear forward modelling.

- Trishear model provides geometric constraints to predict subsurface structures.