Fault-Related Folding: A Review of Kinematic Models and their Application

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Abstract

Folding that is directly related to fault activity is an important deformation feature that occurs all over the world in mountain belts, accretionary wedges, fold-and-thrust belts, and intra-plate settings in either strike-slip, compressional, or extensional regimes. Due to their widespread occurrence, knowledge about the development of these structures is important to a broad spectrum of geoscience sub-disciplines, such as structural geology, seismology, geomorphology, petroleum geology, and Quaternary geology. Fault-related folding has been analysed intensively over the last 140 years. For the sake of this review, we divide the folds up according to the way the faults and the folds form; that is into detachment, fault-bend, and fault-propagation folds.

All fault-related folds are caused by changes in fault parameters. The simplest method to produce folds is to transport material along faults that have stepped, flat-ramp-flat geometries (fault-bend fold). Alternatively the slip can decrease along the length of the fault, and depending on whether the fault remains within a detachment layer or steps up through mechanical stratigraphy, either a
Detachment fold or a fault-propagation fold is formed, respectively.

Detachment folding was first investigated in the early 20th Century, whereas the full significance of fault-propagation folds was recognized quite late in the 1980s. Seminal work on fault-related folding was carried out in the 1930s, but quantitative kinematic models have only been available in the last 30 years. These models are extremely valuable, because they allow a comprehensive understanding of the evolution of fault-related folds and lead to more accurate predictions of the sub-surface structure. From the mid-1990s onwards, numerical simulations have been used to identify how fault parameters (such as dip and fault-bend angle, propagation-to-slip ratio, and shape of the trishear zone) influence the geometry of the related folding. This is directly applicable to the analysis of the shape of anticlines produced. However, this does not mean that fold geometry is uniquely related to fault geometry; on the contrary, different kinematic approaches can lead to a similar fold shape.

**Keywords:** kinematic model, fault-related folding, fault-propagation fold, fault-bend fold, detachment fold, trishear

### 1. Introduction

Numerous outcrops and seismic reflection lines show the intimate association of faults and folds; this is termed fault-related folding (Fig. 1). In this work we discuss the geometrical relationship of the two structural elements and show the various kinematic models that have been produced to explain them. Folds that are related to faults were recognized early on in the history of geological science (Buxtorf, 1916; Rich, 1934; Rettger, 1935) and quantitative kinematic models have been available since the mid-80s onwards (e.g. Suppe, 1983; Suppe & Medwedeff, 1990; Epard & Groshong, 1995; Poblet & McClay, 1996, Mitra, 2003).
The number of different fault-related fold types depends on how strictly the group is defined. Since folds have to evolve, not only geometrically, but also temporally linked to fault movement (as summarized by Suppe & Medwedeff, 1990), then three kinds of fault-related folds can be defined: *detachment folds, fault-bend folds,* and *fault-propagation folds* (Jamison 1987). Hybrid structures are also possible (Marrett & Bentham, 1997). *Drag folding* can be added to this list because it is also temporally and geometrically-related to faulting.

Fault-related folds are, in general, due to the changes in fault parameters. Thus the simplest method to produce folds is to transport material along faults that have stepped, flat-ramp-flat geometries (fault-bend fold model; Fig. 2C). Alternatively the slip can decrease along the fault’s length, which is either compensated by folding at the fault tip point, if the fault cuts through stratigraphy (fault-propagation fold model; Fig. 2D), or if instead the fault does not ramp up, a detachment fold may form (Fig. 2B).

Secondary faults that form as the result of strain discontinuities during folding are named fold-accommodation faults (Mitra, 2002a). They usually show distinctly smaller amounts of slip than the fold-forming faults. Fold-accommodation faults form as a consequence of increased curvature of folds, shear of forelimbs, or as back-thrusts that accommodate hanging-wall strain during fault-related folding (Mitra, 2002). In general, fault-related folds can form on a kilometre- (Apotria & Wilkerson, 2002; Korsch, 2004) to metre-scale (McConnell et al., 1997).

**Aims and scope of this work**

Over the last 30 years, fault-related folding has been treated in a kinematic context. The aim of this paper is to summarize and review these models. We will focus on the kinematic evolution and the resulting geometry of fold structures. The intention is to stress the role of fault-related folding as
one of the most important deformation mechanisms that globally occurs in various tectonic settings, to review different kinematic models, and to show the relevance of fault-related folding in several geosciences subdisciplines. This review aims to synthesize the state of the art by presenting the first comprehensive review of the full range of fault-related folding kinematics. Previous reviews only have focused on individual kinematic approaches. We refer to the simplest kinematic solutions of the models because this makes it easier to understand. However this also reduces the degrees of freedom and therefore the necessary variables. In addition, we treat both contractional and extensional structures, where applicable. Finally we identify the limitations of the current models and give an outlook on future fault-related folding research.

Why is fault-related folding important?

Fault-related folding is a significant deformation mechanism that occurs in mountain belts and foothills (e.g., Boyer, 1986; Vann et al., 1986; Ford et al., 1997; Erslev & Mayborn, 1997; Homza & Wallace, 1997; Delcaillau et al., 1998; Burbank et al., 1999; Tozer et al., 2002; McClay, 2011; Calamita et al., 2012) (Fig. 1A, B), deepwater fold-and-thrust belts (Corredor et al., 2005; Morley et al., 2011), accretionary wedges (Biju-Duval et al., 1982; Gulick et al., 2004), intraplate settings (Bump, 2003), and during basin inversion (Mitra, 1993; Okamura et al. 2007). The beauty of the concept of fault-related folding is that it can explain the evolution of folds in the upper crustal levels, where brittle processes are typically expected to exist (Suppe, 1983). Besides its dominance in compressional regimes, it is also an important deformation process in extensional settings (Howard & John, 1997; Sharp et al., 2000; Ferrill et al., 2012) (Fig. 1C, D), where it is often expressed either as roll-over anticlines on listric normal faults (Song & Cawood, 2000) (Fig. 1E), as extensional fault-propagation folds, or extensional forced folds.

In addition, fault-related folding can occur in strike-slip situations (e.g., Tindall & Davis, 1999). It
is also significant in the field of deepwater fold-and-thrust belts (Morley et al., 2011; Camerlo & Benson, 2006), soft-sediment deformation, gravity-driven slumps, and mass-transport complexes (Alsop & Marco, 2012), as well as in ice-sheet induced glaciotectonics (Thomas & Chiverrell, 2007; Burke et al., 2009; Brandes & Le Heron, 2010). It has been well known for a long time that anticlines represent traps for oil and gas (Hopkins, 1917; Rich, 1921). Therefore fault-related folding plays a great role in the formation of structural hydrocarbon reservoirs (Mitra, 1990; Kent & Dasgupta, 2004; Ingram et al., 2004). It also acts as an important co-seismic deformation process (e.g. Kao, 2000; Chen et al., 2001; Johnson & Segall, 2004; Lin et al., 2007; Guzofski et al., 2007). Consequently, fault-related folding is of great economic interest and represents a crucial parameter in the evaluation of earthquake hazards (Allmendinger & Shaw, 2000; DeVecchio et al., 2012).

Fault-related folding also influences the evolution of the Earth’s surface (Jackson et al., 1996; Mueller & Suppe, 1997; Delcaillau et al., 2006) by its impact on the evolution of the drainage pattern (Keller et al., 1998), and it would even seem that it affects the topography on other planets (Okubo & Schultz, 2004). This shows that fault-related folding is not only relevant to the field of pure structural geology; but it is also highly pertinent to a wide range of geoscience subdisciplines, such as seismology, geomorphology, petroleum geology and Quaternary geology. Kinematic models of fault-related folding can be utilized in all fields of applied geology, in which an understanding of the deformation in the subsurface is required (such as hydrocarbon/geothermal energy exploration and CO$_2$ sequestration). The limits in visualization deformation in the vicinity of faults on seismic surveys due to the so-called “fault-shadow” (Aikulola et al., 2010) can be overcome by kinematic models. Kinematic models allow to forward model the position of the faults, based on the geometry of the hanging-wall deformation. Another application for kinematic models of fault-related folding is in the field of petroleum geology for fracture prediction. In many cases, hydrocarbons are trapped in fractured reservoirs and fractures are important migration pathways (e.g. Aydin, 2000; Nelson, 2001), but in general, such fractures are below the resolution of standard geophysical methods and their orientation and extent is rather difficult to map in the
subsurface and can only be predicted by models. The geometry of an anticline has been put forward as a proxy for fracture distribution (Lisle 1994, Fisher & Wilkinson, 2000) but it has been also shown that these symmetric fracture-fold models can fail (Reches, 1976). Kinematic fault-related fold models can relate the anticline shape to the fault geometry and therefore serve as a tool for fracture prediction.

2. The history of fault-related folding

The early years

The fact that faults and folds could be linked was recognized early on in geological research (Fig. 3). Willis (1894) introduced the break-thrust concept, in which folding and faulting are directly related. He concluded that the rocks were initially folded, and, if the deformation continued, the shortening was compensated by faulting. This is not strictly fault-related folding because in Willis` model, faulting follows folding. Cadell (1889) presented analogue models where faulting and folding could be observed as closely-linked processes. Later Chamberlin (1910) introduced the first method to calculate the position of a basal detachment, based on the geometry of folds exposed at the Earth’s surface. Buxtorf (1916) showed an interpretation of the Swiss Jura Mountains, with several detachment folds, highlighting the regional importance of this type of deformation. Stille (1924) defined the so-called german-type paratectonics (= type of intraplate deformation in northern Germany), where faults and folds are the dominating structural elements. Benchmarking work on fault-related folding was presented by Rich (1934). He analysed folds in the Appalachians and concluded that anticlines in a fold belt were the result of thrust sheets moving over ramps. This model is still valid and the resulting structures are known today as fault-bend folds. Direct proof that faulting can cause folding was presented by Rettger (1935), based on analogue models. Cloos (1936) presented generic models to show that folding can be the consequence of faulting (Fig. 4).
He interpreted folding in the hanging walls and footwalls of large thrust faults to be related to drag. The term *Bruchfaltengebirge* (lit. - “brittly-folded mountain belt”) was explicitly used for areas in which folds are related to faults (Cloos, 1936).

*The period of application*

The 1960–80s were characterized by strong advances in the quantification of deformation processes. Several studies dealt with structural restoration techniques (Dahlstrom, 1969; Hossack, 1979; Elliott, 1983) and fault-related folds played a major role in quantifying shortening in fold-and-thrust belts (Cooper & Trayner, 1986; DePaor, 1988; Dahlstrom, 1990; Wu et al. 2005).

*Rise of the kinematic approach*

From the early 1980s onwards, fault-related folding began to be treated in a kinematic fashion (Fig. 3). Suppe (1983) introduced the first kinematic model of fault-bend folds, based on the concept of kink-band migration. Later in the 1990s, different kinematic models for detachment folds (Epard & Groshong, 1995; Homza & Wallace, 1995, Poblet & McClay, 1996) and fault-propagation folds (Suppe & Medwedeff, 1990; Mitra, 1990; Erslev, 1991; Mitra & Mount, 1998) were developed. These 2D models were then extended to pseudo 3D (Wilkerson et al., 1991). At the same time, contractional fault-related folds were successfully analysed using analogue sandbox models (McClay, 1995; Storti et al., 1997; Bernard et al., 2007). The use of numerical simulations since the late 1990s has greatly extended knowledge on fault-related folds (Hardy & Ford, 1997; Allmendinger, 1998; Tanner et al. 2003; Allmendinger et al., 2004; Cardozo & Aanonsen, 2009; Cardozo et al., 2011). Computer simulations led to a more quantitative understanding of these structures. Parameters such as the propagation-to-slip ratio of the fault were recognized as highly significant for the geometric evolution of the related fold (Hardy & Ford, 1997; Allmendinger,
The propagation-to-slip ratio was shown by Chapman & Williams (1984), using displacement-distance graphs, to be a key parameter of fault-propagation folds. Displacement-distance plots have been used also to compare fault-related folding processes that occur in natural structures observed at different scales (Tavanelli, 1997). Also in the late 1990s, fault-related folding in extensional regimes moved in the research focus (Howard & John, 1997; Hardy & McClay, 1999; Sharp et al., 2000) and attracted interest up to the mid-2000s (Khalil & McClay, 2002; Finch et al., 2004; Jin & Groshong, 2006). The work of Medwedeff (1989), Suppe et al. (1992, 1997) and Shaw & Suppe (1994, 1996) opened the door for the analysis of fault-related folds based on their growth strata. In the following years, growth strata studies increased (Hardy et al., 1996; Ford et al., 1997; Poblet et al., 1997; Storti & Poblet, 1997, Vergés et al., 2002; Brandes et al., 2007). Recent developments in this field are also the analysis of growth-strata distribution on the evolution of fault-related folds (Strayer et al., 2004).

4. The definition of geometrical, kinematic and dynamic models

Our model definition follows the criteria of Greenwood (1989), in that they 1) are based on a guiding conceptual model, 2) have a theoretically-based submodel, 3) have a predictive capability, and 4) have the ability to deliver testable predictions. Nevertheless it is entirely possible for different models to produce the same structure. If a model is unique, then only that model can explain an observation, whereas if a model is consistent, more than one model can explain the observation (Stüve, 2000).

Models that contain a primary dataset (2D or 3D) of stratigraphic units, faults, and other geological information, as e.g., shown in Culshaw (2005), can be termed geometrical. Depending on the quality and extent of a dataset, either a two- or three-dimensional geometrical model can be built. The accuracy of the dataset, for instance the resolution of the seismic data used to generate the
geometrical model determines the final resolution. Similarly, outcrop data can be included in the model, but they are increasingly limited in their ability to predict structure at greater depths.

Kinematic models determine the evolution of a geometrical structural model (e.g. Laubscher, 1985), so that the paths of material points in the model can be followed and examined. Kinematic indicators, i.e. information about the kinematic vectors involved in the structural development, are, for instance, slickensides on faults, axes of folds, curvature of faults, and stratigraphic contacts. Kinematic models can be compounded to include different geological events (i.e. unconformities) and various kinematic movements (i.e. basin inversion).

Dynamic models study the forces and stresses required to produce the structure. They require geometrical and kinematic models as input, as well as rheological information (e.g. density, thermal properties, Young’s Modulus, and Poisson’s ratio) about the rocks involved (e.g. Braun & Sambridge, 1994). Boundary conditions must include gravitational forces and the far-field stress vectors, including paleostress vectors when considering structural development over geological time.

5. Kinematic models of fault-related folding

5.1. Drag folds

5.1.1. Characteristics

Ramberg (1963) defined drag folds as quasi-monoclinic folds that often develop in thin competent rock layers bounded by more competent thick layers. In this model, drag folds form when a package of alternating competent and less competent layers bends as the result of horizontal shortening.
More commonly the term drag fold is used for a fold that developed as a consequence of friction along a fault (e.g. Cloos, 1936), although this is viewed skeptically by Grasemann et al. (2005), who propose that drag folds are in fact caused by the heterogeneous displacement field around a fault as it undergoes slip. Both reverse and normal drag can be distinguished (Fig. 5). Normal drag means that the deformed rock layers are convex in the direction of transport along the fault, whereas in the case of reverse drag they are concave in the transport direction (Hamblin, 1965; Grasemann et al., 2005).

5.1.2. Kinematic models

The sense of shear along the fault can be determined by the asymmetry of the drag fold. Furthermore, the slip vector can be estimated using Hansen’s Method (Hansen 1971, Twiss & Moores 1992). If the fold is conical, then the fold axis is the axis of rotation of the beds at the fault, which is perpendicular to the slip direction (Becker, 1995). Recently, numerical (finite element) models have been used to test drag folding geometries and processes (e.g. Reches & Eidelman, 1995; Resor & Pollard, 2012). These models prove that edge dislocation in an elastic half space is sufficient to produce the majority drag folds, and that friction on the fault is not important.

5.2. Detachment folds

Detachment folds are folds that evolve from the shortening of a rock mass above either a detachment or a décollement (e.g. Poblet & Hardy, 2005; Poblet et al., 1997; Rowan, 1997; Scharer et al., 2004) (Fig. 6A). A detachment is defined as a low-angle fault that may be nearly, but not exactly parallel to a horizon, whereas as a décollement is a bedding- or layer-parallel fault (Peacock et al., 2000). Detachment folds also develop above the tip of a bedding-parallel thrust (Poblet & McClay, 1996) in competent rocks and are often cored by less-competent rocks (Homza & Wallace,
Distinct detachment folds can only form if there is enough mobile material present in the detachment layer to fill the core of the growing anticline (Stewart, 1996). If there is not enough material to fill the amplifying fold, fold growth will stop and shortening may be compensated by faulting (Stewart, 1996).

5.2.1. Characteristics

The most important characteristic feature of detachment folds is the detachment horizon (i.e. décollement) (Fig. 6A) that is developed either above, below, or above and below the fold. Layer-parallel strain allows the fold to develop above a fixed stratigraphic detachment (Groshong & Epard, 1994). Detachment folds are often symmetric (Hardy & Finch, 2005) and their geometry ranges from concentric to chevron-type folds or even box folds (Rowan et al., 2004; Shaw et al., 2005). Internally, detachment folds are characterized by homogeneous strain, second-order folds, second-order conjugate faults, or duplex structures (Epard & Groshong, 1995).

Detachment folds can be subdivided into two main groups: a) disharmonic folds and b) lift-off folds (Mitra & Namson, 1989). Disharmonic folds are parallel or concentric folds with disharmonic folding in the core (Fig 6B). Lift-off folds are parallel folds, where the core of the anticline is characterized by isoclinal limbs (Fig. 6B). Early models of detachment folds were geometrical (Jamison, 1987) that focused on the shape of the folds. Different kinematic models were developed later. Based on an area-balanced cross-section it is possible to derive the depth of the detachment (Fig. 6C).

5.2.2. Kinematic models

Epard & Groshong (1995) introduced the limb rotation model, which describes the evolution of
detachment folds above a fixed layer-parallel detachment (see also Hardy & Poblet, 1994). The basic assumption of this model is that the deformation takes place between two pin lines and the displacement along the detachment is compensated by folding, which means that the model is locally line-balanced. Deformation occurs by amplification of the anticline. The model emphasizes symmetric folds (Epard & Groshong, 1995). The fold in the model has three axial planes, a vertical one in the centre (corresponding to the plane of symmetry) and two vertical or inclined ones that separate the fold from the undeformed area (Fig. 6D). Following Epard & Groshong (1995), the key parameters of the model are the width of the fold (W), the dip of the external axial planes (θ), the distance from the reference level to the detachment (H), and the displacement along the detachment (D). The fold grows by an increase of the area that is equal to Dh (Fig. 6D). Their model describes the evolution of a detachment fold with a fixed hinge, as well as the evolution of a fold with migrating hinge. In case of a fixed hinge, no material crosses the axial surfaces. The fold growth is the result of limb rotation and changes in bed length (Epard & Groshong, 1995; Hardy & Poblet 1994).

Homza & Wallace (1995) presented another geometrical and kinematic model for the evolution of detachment fold. Their model deals with two different scenarios: a) a detachment fold that develops above a detachment unit with constant thickness and b) a detachment fold that forms above a detachment unit with changing thickness during deformation. The model of Homza & Wallace (1995) assumes the conservation of bed length and area. The competent layer produces parallel folds by flexural-slip, therefore conserving bed length. The constant detachment depth model produces folds that are initially symmetric and grow with a fixed arc-length. The variable detachment fold model allows both fold growth with fixed and migrating hinges.

A third model for detachment folds was presented by Poblet & McClay (1996). These authors analysed three individual kinematic mechanisms for: a) constant limb dip, b) constant limb length
and c) variable limb dip and limb length (Fig. 6E). Constant limb dip means that the fold grows by lengthening of the limbs, whereas in the constant limb-length mechanism, fold growth is achieved by limb rotation. The variable limb length/limb dip mechanism produces a detachment fold that grows by limb lengthening and limb rotation. Poblet & McClay (1996) consider four different end-members (Fig. 6E): No. 1 assumes constant limb dip and variable limb length. In this case, the dip of the limb and the axial surfaces are fixed. The shortening is accommodated by an outward migration of the fold boundaries. No. 2 has a constant limb length and fold growth is caused by steepening of the limb dip (limb rotation). The stratigraphic thickness is maintained by the rotation of the axial surfaces. No. 3 and 4 are both characterized by variable limb dip and length. In these latter models, shortening is compensated by limb rotation and outward propagation of the axial surfaces. The fold grows by lengthening of the limbs and steepening of the limb dip. No. 4 is similar to No. 3, but in this case, the detachment depth is given by the intersection of the opposing axial surfaces. Poblet & Hardy (1995) showed that the key aspects of detachment folds, such as fold amplification and slip along the fault, can be derived from analysis of the growth-strata geometry that records the rotation of the anticline limbs.

Mitra (2002b, 2003) presented a kinematic model for detachment folds that explains why a large number of geometrically-different detachment folds can occur. Like all previous models, it assumes that the fold develops in a competent rock layer that is underlain by a less competent unit. The fold mainly deforms by flexural slip, with some additional faulting and fracturing. The wavelength of the fold is controlled by the thickness of the involved rock units. Continued deformation leads to increasing amplitude and wavelength of the fold. This is driven by the rotation of limb segments and hinge migration (Mitra, 2003). The initial limb rotation is a flexural-slip process. Ongoing shortening causes internal deformation between locked hinges. Variations in the structural style of detachment folds are controlled by the mechanical stratigraphy, the amount of shortening, the asymmetry, and the occurrence of faulting (Mitra, 2003).
Contreras (2010) considered detachment folding on the basis of the conservation of mass, and not on a specific folding mechanism. Therefore, in his model, fold limbs are not necessarily straight. The model can be extended to include erosion and sedimentation during the folding. From the resulting velocity models, Contreras (2010) has shown that detachment fold amplitude increases exponentially over time under constant shortening, which has been hypothesized from theoretical models (Biot, 1961), natural observation (e.g. Daëron et al., 2007), and retro-deformation of cross-sections (Tanner et al., 2011).

5.3. Fault-bend folds

Fault-bend folds occur when material is transported over a thrust footwall ramp (Berger & Johnson, 1980), i.e. a steepening of the fault plane that typically crosscuts stratigraphy rather than following the bedding plane (Suppe, 1983) (Fig. 2C). This concept was originally introduced by Rich (1934) based on his observations in the Appalachians. Wiltschko (1979) developed a mechanical model for a thrust sheet that moves over a ramp. Fault-bend faults have been recognized in fold-and-thrust belts all over the world and have been the focus of many studies (Suppe, 1983; Zoetemeijer et al., 1992; Medwedeff & Suppe, 1997; Savage & Cooke, 2003, Suppe et al., 2004).

A special type of fault-bend fold is a triangle zone or antiformal stack. Triangle zones are common structural elements that occur globally and are characteristic of the transition between fold-and-thrust belts and foreland basins. The term “triangle zone” has been given to different types of structures with a triangular shape in cross section (e.g., McClay, 1992). In most cases, it describes an antiformal duplex on the leading edge of a fold and thrust belt that internally consists of vertically-stacked horses. Different studies have focused on the mechanical and kinematic evolution of triangle zones (e.g., Erickson, 1995; Erickson & Jaminson, 1995; Jamison, 1996; Jones, 1996;
Stockmal et al., 2001; Tanner et al., 2010). Triangle zones begin as fault-bend folds. After a first fault-bend fold is formed by material that is transported over a footwall ramp, the ramp shifts slightly forward, which leads to the vertical stacking of overlapping fault-bend folds that form the core of the triangle zone (Jones, 1996). An antiformal stack forms when the displacement on each horse equals the ramp spacing (Doglioni & Carminati, 2008).

5.3.1. Characteristics

The basic requirements for the evolution of fault-bend folds are changes in the geometry of the fault plane, such as bends or ramps. A footwall ramp usually connects two horizontal detachments (flats) at different stratigraphic levels (Fig. 7). By moving from the first, deepest footwall flat to the shallowest, the hanging-wall material will be deformed into a syncline-anticline-syncline structure. Another requirement for fault-bend folding is that the fault blocks are in tight contact along the plane and the bend in the fault does not lead to the development of significant voids (Suppe, 1983). In the case of fault-bend folds, the propagation rate of the fault must be much higher than the slip, because the fold forms before the first increment of slip (McNaught & Mitra, 1993). Bending of the material during the transport over the ramp is accommodated by bedding-parallel simple shear and the magnitude of shear strains is related to the ramp angle (Sanderson, 1982). This causes beds to thin over a concave fault bend. To produce a fault-bend fault, enough energy must be available to overcome the friction on the fault, uplift the fold, and shear the fold material (Williams, 1987).

5.3.2. Kinematic models

Suppe (1983) introduced the first, and still one of the most comprehensive kinematic models for fault-bend folds, which is now often called the “kink-band migration model”. Folds evolve above bends in the fault plane (i.e. the bends between the flats and ramps). The basic assumption is that
the fault consists of straight segments, which are separated by an angular bend and only the hanging wall block deforms by flexural slip; the footwall block remains rigid (Suppe, 1983; Medwedeff & Suppe, 1997). As the movement begins along the fault, two kink bands evolve, one at the base of the ramp and one at the upper end (Suppe, 1983) (Fig. 7). The axial surfaces of the kink band at the upper ramp end are named A and A’. The axial surfaces of the kink band at the base of the ramp are named B and B’ (Fig. 7). The axial surface B bisects the angle between the flat and the ramp. The axial surfaces A and B end in the fault bends (points X and Y, respectively). Further movement causes one of each of the axial surfaces of these folds to migrate in the slip direction, so that the two folds increase in amplitude with continued slip. The axial surfaces A´ and B´ end in the points X´ and Y´, respectively.

Due to the formation of the upper kink band, the slip along the fault decreases on the forelimb side by about 60% (Suppe, 1983). The basic pre-assumption for this kinematic model is layer-parallel slip that produces parallel folds. This means that bed thickness and length are conserved. The great advantage of the model of Suppe (1983) is that it relates the geometry of the fold directly to the geometry of the fault. This allows predictions of the subsurface geometry of tectonic structures to be based only on a small set of observations. The model assumes the following: a) sharp bends in the fault plane up to 30°, b) conservation of area and c) constant layer thickness of the beds. This implies conservation of bed length (in the slip direction), layer-parallel slip and the formation of kink folds that have straight limbs and show infinite curvature (Suppe, 1983). In such a case, the axial surface of the fold bisects the angle between the fold limbs. The model then predicts the fault bend angle \( \phi \), the cut-off angle \( \theta \), and the opening angle of the fold, characterized by the angle \( \gamma \):

\[
\phi = \theta = \tan^{-1} \left[ \frac{\sin 2\gamma}{1 + 2\cos^2 \gamma} \right]
\]
The maximum ramp angle of 30° consequently limits the forelimb angle of the resultant fault-bend fault. The relationship of the fold shape to the fault-bend angle means that the fault geometry can be predicted from the form of the fold. This is a key method for reconstructing the subsurface geology based on outcrop data. It allows the construction of cross-sections that can be used for the exploration of structural hydrocarbon traps and the assessment to seismic risks by identifying, for instance, the position of a potentially-seismogenic blind thrust. Many earthquakes occur along thrusts that are blind, i.e. they lack a surface fault trace (Lettis et al., 1997). In these cases near-surface shortening is accommodated by folding (Dolan et al., 2003). There are several well-studied examples of seismogenic blind thrusts from the Los Angeles area (Shaw & Shearer, 1999). For instance, the 1994 Northridge earthquake in Southern California took place along a blind thrust (Yeats & Huftile, 1995) and the 1987 Whittier Narrows earthquake was related to a pronounced, fault-related hanging-wall anticline that developed above a blind ramp (Shaw et al., 2002). Namson & Davis (1988) showed that the Coalinga anticline and the Kettleman Hills are also fault-related folds that evolved above seismically-active faults. Analysing blind thrusts with standard geological methods, such as mapping, is difficult because the faults do not intersect with the surface (Roering et al., 1997), and therefore other approaches have to be used. For instance, balanced cross-sections make it possible to identify unknown faults. This was shown by Davis & Namson (1994), who constructed a cross-section based on the kink-band method that revealed the seismogenic fault that caused the 1994 Northridge earthquake.

A modification of the kink-band migration approach is the concept of shear fault-bend folds (Suppe et al., 2004), which considers that internal shear that commonly affects thrust sheets. This kinematic model explains the observation that backlimb angles dip less than the fault ramp does. This problem has been tackled with the concept of shear fault-bend folding, which is a combination of limb rotation and kink-band migration (Suppe et al., 2004). Two end-member models for shear fault-bend folding have been developed (Fig. 8) (Suppe et al., 2004; Shaw et al., 2005). In the simple-
shear case, the décollement layer experiences bedding-parallel shear (Fig. 8A) (Suppe et al., 2004; Shaw et al., 2005). In the pure-shear case, the décollement layer moves above a flat as in the non-shear fault-bend fold model, but also shortens and thickens above the ramp (Fig 8B) (Shaw et al., 2005). By unfolding the hanging wall, the resulting shearing of the back pin gives the shear profile. From such a shear profile it is possible to derive the amount and position of shear in the deformed package (Suppe et al., 2004).

A kinematic velocity field of the Suppe fold-bend model was presented by Johnson & Berger (1989) (Fig. 9) and Hardy (1995). In the Johnson & Berger (1989) model the thrust sheet is divided into three velocity domains, which are related to the flat-ramp-flat geometries of the fault. The velocity domains are separated by velocity discontinuities that correspond to the kink-bands A and B in the model of Suppe (1983). In domain 1 the velocity vectors are parallel to the lower flat, in domain 2 they are parallel to the ramp and in domain 3 the velocity vectors are parallel to the upper flat (Fig. 6). This model perfectly reproduces the structural style of simple fault-bend folds.

Medwedeff & Suppe (1997) presented solutions for fault-bend folds, in which more than one bend is developed. Whereas single bends produce folds that have kink-like shapes, multi-bend faults will lead to more curved fold hinges. (Medwedeff & Suppe, 1997). A modified model for fault-bend fold with rounded hinges was developed by Tavani et al. (2005) using circular hinge sectors, in which the hinge sectors are pinned to the fault plane and replace the straight axial surfaces of the kink-band migration model. This is a step towards rounded “natural” fold shapes.

Tavani and Storti (2006) pointed out that the standard kinematic model for fault-bend folding is limited because it requires the entire fault to have propagated before any hanging-wall deformation can begin. They propose that progressive fault propagation is more realistic. This means that fault-bend folding can be treated as a type of fault-propagation folding (Tavani & Storti, 2006). With the
concept of double-edge fault-propagation folding (Tavani et al., 2006) (for explanation see chapter fault-propagation folding) it is possible to create realistic fault-bend folds. With small slip-to-propagation ratios a fault-propagation fold is produced, which when transported forward along the upper flat, is geometrically similar to standard kink-band migration fault-bend folds (Tavani & Storti, 2006).

Another kinematic algorithm to simulate fault-bend folding, known as “fault-parallel flow”, was developed by Egan et al. (1997). This algorithm quite simply states that all material objects within the hanging wall move parallel to the fault surface, along virtual flow paths (Fig. 10) (Tanner et al., 2003; Ziesch et al., 2014). This is theoretically applicable to a large range of complex fault geometries, such as rounded fault bends and multiple-dipping fault domains. However, Ziesch et al. (2014) have shown that the algorithm gives unnaturally high strain in the hanging walls of extensional faults and is therefore only suitable for fault bend angles of less than 40°, i.e. typically compressional structures.

5.4. Fault-propagation folds

Fault-propagation folds may also form in the hanging walls of faults (Fig. 11). However these folds are different from fault-bend folds, because they form as a consequence of variations in the slip along the fault. The slip on a fault is assumed to decrease to zero at the tip. This decrease in slip is compensated by buckling of material above the fault (Williams & Chapman, 1983; Suppe & Medwedeff, 1990). In contrast to fault-bend folds, fault-propagation folds do not require transfer of volume out of the structure (Mitra, 1990).

5.4.1. Characteristics
The typical characteristics of fault-propagation folding were summarized by Suppe & Medwedeff (1990) and Shaw et al. (2005). Such folding is generally located in the hanging wall of a low-angle thrust fault. The fold tends to tighten towards the fault, which indicates that fold and fault are related. Often the fold has a distinct asymmetry with a steep or even overturned forelimb and a less steep backlimb (Fig. 11). The forelimb is narrow, whereas the backlimb is wide. As a consequence the vergence of the fold points towards the transport direction of the thrust. In general, the folds are associated with low-angle thrust faults, which have low displacements (McNaught & Mitra, 1993). Typically the thrust dies out in the core of the fold. During propagation of the fault, the fold grows and preserves its initial geometry (Shaw et al., 2005). The deformation in the fold is controlled by the fault angle and the form of the fold (McConnell, 1994). Ongoing deformation can lead to modifications of the fault-propagation fold geometry by breakthrough thrusting (Mercier et al., 1997).

5.4.2. Kinematic models

Kinematic models for fault-propagation folds have been developed by Suppe & Medwedeff (1990), Mitra (1990) and Mitra & Mount (1998). The classic kinematic approach is the parallel kink-fold model introduced by Suppe & Medwedeff (1990). This model is similar to the approach of Suppe (1983) for fault-bend folds.

The basic assumption is a bedding-plane-parallel detachment. The folding is caused when the fault steps up over a ramp. The evolution of anticlines is controlled by the formation of two kink bands. The right axial surface of the lower kink band in Fig. 11 (named B in Suppe & Medwedeff, 1990) terminates at the point where the fault steps up and the left axial surface of the upper kink band (named A’ in Suppe & Medwedeff, 1990) ends at the fault tip. Another important plane is the surface AB’, which represents the axial surface of the fold (Fig. 11). It starts from the centre of the
fault trace and terminates at the point where the A and B´ merge. The tip of the fault and the branch of the axial surface AB´ are in the same stratigraphic position. When the fault propagates, the beds roll from a flat position into the steep kink band A-A´ (Suppe & Medwedeff, 1990). Therefore fold growth is a self-similar process.

Jamison (1987) developed a model that extends the parallel fold approach. In this model fault-parallel shear is possible. This is appropriate to explain the tightening of fault-propagation folds that is observed in many natural examples. Another kinematic model for fault-propagation folds was presented by Mitra (1990). This model is based on area-balancing and is suitable to describe the evolution of the fold in the case where the fault continues to propagate through undeformed units and the initial fault-propagation fold is subsequently translated into a fault-bend fold as it passes over the footwall ramp (Mitra, 1990). Spang & McConnell (1997) showed a kinematic model for fault-propagation folds, where deformation occurs in both the hanging wall and footwall of the faults. This model can also produce a footwall syncline and thus it is a step towards more realistic kinematic models.

The kink-band migration model of fault-propagation folding produces folds, in which the backlimb dip is parallel to the dip of the ramp (Fig. 11). However, natural examples often show diverging dips of ramp and backlimb (Tavani et al., 2006). Furthermore, analogue models have shown that faults in fold-and-thrust belts can have a more complex propagation pattern, whereby a fault nucleates within the deforming material and propagates upward and downward, finally merging with the basal detachment to form a flat-ramp geometry (Storti et al., 1997). Tavani et al. (2006) presented a kinematic model called double-edge fault-propagation folding that implements these observations and is able to overcome the limitations of previous models. The double-edge fault-propagation approach assumes a basal detachment above which layer-parallel shortening is accommodated (Tavani & Storti, 2011). A reverse fault nucleates in the deforming material above
the basal detachment (Tavani et al., 2006). The key feature of this model is the reverse fault that propagates in two directions, upwards and downwards. Above this reverse fault hanging-wall deformation occurs. Ongoing shortening leads to continued ramp propagation and finally the connection of the downward propagating tip with the basal detachment (Tavani et al., 2006). The double-edge fault-propagation folding approach is also suitable to model extensional fault-related folds (Tavani et al., 2006) and the evolution of growth strata patterns (Tavani et al., 2007).

Storti & Salvini (1996) proposed another kinematic model for fault-propagation folding by called progressive roll-over fault-propagation folding. The aim of this approach is to compensate the problems of the standard fault-propagation to produce overturned to recumbent forelimbs, which are common in fold-and-thrust belts (Storti & Salvini, 1996). The model of Storti & Salvini (1996) extends the approach of Suppe & Medwedeff (1990) by the incorporating additional bending of the material in the hanging wall at the tip line. This requires more axial surfaces than in the model of Suppe & Medwedeff (1990) and splits the forelimb into a forward-dipping, a recumbent, and an overturned sector.

5.4.3. Velocity models

Waltham (1989) showed that tectonic deformation can be modeled using a velocity description and subsequently, Waltham & Hardy (1995) presented velocity solutions for simple shear, pure shear, flexure, isostasy, and compaction. The advantage of velocity descriptions are their applicability to many different deformation styles and the great flexibility of the method to model combined effects of e.g. tectonics and sedimentation (Waltham & Hardy, 1995). A velocity field provides the rate and movement direction of every point in the model at all times and therefore allows the position of any element in the model to be tracked. Because the velocity components of all the deformation mechanisms can be added together, this approach is highly flexible (Waltham & Hardy, 1995). The
relevance to this study is given by the work of Hardy and Poblet (1995), who applied velocity
descriptions to fault-bend folds and fault-propagation folds, and by the work of Waltham (1989),
who used a velocity approach to simulate the hanging-wall deformation above listric normal faults.
Hardy & Connors (2006) extended the velocity description to shear bend folding.

5.4.4. Trishear kinematics

As seen above, the kinematic model of Suppe & Medwedeff (1990) produces folds with straight
limbs and tight hinges that can be classified as kink or chevron folds. This kink-fold model is
limited to reproduce several characteristics of fault-propagation folds, such as the curved fold
shapes and the presence of footwall synclines, as well as systematic variations in the thickness and
dip of syn-tectonic strata deposited on the anticlinal forelimbs (Allmendinger et al., 2004). This
problem was solved by Erslev (1991) by the use of trishear kinematics to explain the development
of fault-propagation folds.

Trishear kinematics are consistent with the thinning of beds in the anticline hinge and thickening of
beds adjacent to the syncline hinge. Hardy & Ford (1997) showed that in contrast to kink-band
migration models, trishear kinematics produce folds with smooth profiles and rounded hinges. The
trishear concept is a numerical approach that assumes a triangular shear zone in front of the tip of a
propagating fault (Fig. 12) (Erslev, 1991). At the top of this zone the slip vectors are equal to that of
the hanging wall, whereas at the base the slip is zero. In the trishear zone the slip vectors vary
linearly in their magnitude and orientation from top to bottom (Allmendinger, 1998). In the
following years, the trishear concept has been extended to a velocity description (Hardy & Ford,
1997; Zehnder & Allmendinger, 2000; Hardy & Allmendinger, 2011). The velocity field is
calculated in a Cartesian coordinate system. The ζ-η coordinate systems is fixed to the initial tip of
fault, the X-Y coordinate system is attached to the tip of the fault and moves with the fault tip (Fig.
A basic boundary condition is that the hanging wall is a rigid block, in which all points move with the same velocity parallel to the fault (comparable to fault-parallel flow, see above). The footwall is fixed and the velocity vectors are zero (Fig. 12). In addition, area is conserved in the trishear zone (Zehnder & Allmendinger, 2000; Hardy & Allmendinger, 2011), however bed thickness is not preserved, which means layer-parallel shortening occurs. This must be considered when line-length balancing is carried out.

The geometry of a trishear fold is determined by the ramp angle, the slip along the fault, the position of the tip line (X/Y), the trishear angle and the propagation-to-slip ratio (Allmendinger et al., 2004). The propagation-to-slip ratio is one of the most important controlling factors for the geometry of fault-propagation folds (e.g. McNaught & Mitra, 1993, Hardy & Ford, 1997; Allmendinger, 1998). The value of the propagation-to-slip ratio is largely responsible for the shape of hanging-wall anticlines (Allmendinger & Shaw, 2000). The most obvious advantage of trishear is the great flexibility in the choice of different propagation-to-slip ratios (Allmendinger et al., 2004). Trishear allows the simulation of the strain distribution within fault-related folds. In cases where strain leads to fracturing, this can help to identify fractures reservoirs and predict strain paths (Allmendinger et al., 2004). With trishear kinematics it is also possible to predict the position of blind faults from the geometry of the hanging-wall anticline (Bump, 2003). The inverse grid search tool of Zehnder & Allmendinger (2000) makes it possible to calculate the best-fit model for the tip line position of the fault, based on the fold shape. In recent years the trishear approach has been widely applied to natural examples (Hardy & Ford, 1997; Cristallini & Allmendinger, 2001; Cardozo, 2005) and further computer programs that use trishear kinematics have been developed (Liu et al., 2012). The most recent advances are the realization of trishear in 3D (Cristallini et al., 2004; Cardozo, 2008) and the optimization of the inverse trishear approach (Cardozo & Aanonsen, 2009; Cardozo et al., 2011).
6. Folding mechanisms, distribution of deformation and growth-strata evolution

There are two major folding mechanisms that occur in the field of fault-related folding: folding by kink-band migration (also known as active-hinge folding), and folding by progressive limb rotation (also known as fix-hinge folding) (Shaw et al., 2005). These two folding mechanisms strongly influence the distribution of strain in the fold and the geometry of syn-tectonic sediments in the hanging wall of an evolving anticline. In case of kink-band migration, material moves across the axial surfaces and the anticlinal limbs widen, but maintain a constant dip (Suppe, 1992). This can be clearly seen in case of fault-bend folding (Fig. 13). The axial surfaces in the pre-growth strata are parallel. Migration of material across the axial surfaces allows a progressive extension of the rock volume. By the final stage of folding, deformation is distributed throughout the limb of the fault-bend fold (Salvini & Storti, 2004). Syn-tectonic sedimentation that exceeds the uplift of the growing anticline is characterized by a narrowing kink-band that has converging axial surfaces (Suppe, 1992; Shaw et al., 2005). In the case of limb rotation, the hinge is fixed and the limbs rotate, which means the limb dip progressively increases (Fig. 13; Poblet & McClay, 1996; Shaw et al., 2005). The same rock volume stays within the axial surfaces and undergoes progressive deformation. In case of fixed-hinge folding, the fold has a narrow, strongly deformed area in the axial surface sector, with highest strain at the pin of the axial surface, which decreases towards the limbs (Salvini & Storti, 2004). Fixed-hinge folding is an important mechanism in the case of detachment-folding, as shown by Poblet & McClay (1996). The growth strata evolution reflects the progressive limb rotation; therefore the limb dip shows a characteristic fanning. The syn-tectonic sediments thin towards the anticline. Due to the limb rotation, the axial surfaces change their dip and some material also moves across the axial surfaces (Shaw et al., 2005).

7. Fault-related folding in extensional domains
Fault-related folds have also been recognised in extensional regimes. They have been analysed in the field (Howard & John, 1997; Sharp et al., 2000; Corfield & Sharp, 2000), with analogue models (Withjack et al., 1990), and numerical simulations (Khalil & McClay, 2002; Jin & Groshong, 2006). Six different types of extensional fault-related folds were summarized by Khalil & McClay (2002): a) hanging-wall fault-bend folds formed due to variations in fault dip, b) “normal” drag folds developed as a consequence of frictional resistance on a normal fault, with hanging-wall strata dragged up and footwall strata dragged down the fault surface, c) “reverse” drag folds with hanging-wall strata that are bent down at the fault plane (roll-over anticline), d) transverse folds caused by along-strike changes in fault displacement, e) fault-propagation folds above the tip line of a normal fault and f) differential compaction over a pre-existing fault-scarp. Extensional forced folds can be also added to this list.

The recognition of fault-propagation folding in extensional regimes can explain the presence of monoclines and overturned beds (Sharp et al., 2000), as well as the occurrence of hanging-wall synclines (Khalil & McClay, 2002).

Kinematic models for extensional fault-propagation folds have been also developed based on the trishear approach (Hardy & McClay, 1999; Jin & Groshong, 2006). Figure 14 shows a comparison of contractional and extensional trishear folding. As in the compressional fault-propagation case (Fig. 14A), a triangular zone above the tip line of the (in this case) normal fault is assumed that is characterized by a velocity field that decreases from the hanging-wall to the footwall (Jin & Groshong, 2006). This velocity field determines the strain rate in the trishear zone. As a consequence of fault-propagation, a monocline evolves above the tip line of the normal fault (Fig. 14B). The geometry of the fold and the strain distribution is strongly controlled by the propagation-to-slip ratio of the fault (Jin & Groshong, 2006). This is comparable to the compressional fault-propagation folds. High P/S ratios produce narrow folds that are less deformed. The trishear angle is
an important controlling factor for the geometry of the hanging-wall syncline. Large trishear angles cause only small amounts of footwall deformation and wide hanging-wall synclines, whereas small trishear angles produce the opposite (Hardy & McClay, 1999; Khalil & McClay, 2002). The trishear approach allows the simulation of asymmetric extensional fault-propagation folds, which resemble the geometry of field examples (Khalil & McClay, 2002; Jin & Groshong, 2006).

8. Fault-related folding and the structure of deforming wedges

Fault-related folds are dominating elements of fold-and-thrust belts (e.g. Boyer, 1986; Vann et al., 1986) and accretionary wedges (e.g. Biju-Duval et al., 1982; Gulick et al., 2004). In general, the overall geometry of such deforming wedges can be described by the critical-taper wedge theory (Davis et al., 1983; Dahlen, 1984; Dahlen et al., 1984), in which fault-related folds are largely responsible for the internal structure.

Trains of fault-bend folds in contractional regimes, such as delta toe areas and accretionary wedges, are often dominated by ramps that sole out into a single décollement layer (Corredor et al., 2005; Zoetenmeijer & Sassi, 1992). The position of the initial décollement is controlled by pore fluid pressure, the strength of the rocks, and the accretion mode of the deforming wedge (Bigi et al., 2003). The position of the initial décollement defines the area of the deforming wedge. However, the depth of the basal décollement can vary along strike (Bigi et al., 2003). The décollement dip has a strong impact on the geometry of fault-related folds in the hanging wall. Mariotti & Doglioni (2000) showed that the distance between the ramps increases with increasing dip of the basal décollement. On the other hand, the distance between the ramps is a controlling factor for the geometry and kinematics of piggy-back basins on top of the wedge (Doglioni et al., 1999a). The décollement dip can be also a function of the orientation of the related subduction zone. Doglioni et al. (1999b) showed that in westward-directed subduction zones, the décollement is warped down,
while in east to northeast-directed subduction zones, the related décollement ramps up to the surface. Variations in décollement dip also control whether the fault-related folds will be exhumed and eroded (flat décollement) or buried under syntectonic sediments (steep hinterland-dipping décollement) (Mariotti & Doglioni, 2000). In addition, there is also interplay of fold uplift, regional subsidence, and sedimentation rate (Doglioni & Prosser, 1997). The total fold uplift is the fold uplift rate minus the regional subsidence. When the uplift rate of the fold is higher than the subsidence rate, the fold will be eroded and the onlap of the syn-tectonic strata will move away from the anticlinal crest. If the total fold uplift is negative and the sedimentation rate is high enough, the syn-tectonic strata will move towards the anticlinal crest (Doglioni & Prosser, 1997). A comparable interplay can be observed along normal faults. In such cases, the total subsidence is the sum of fault-controlled subsidence and the regional subsidence; it can be positive or negative. In addition, the subsidence rate can be higher or lower than the sedimentation rate. The interplay of fault slip, regional subsidence, sedimentation rate, and sea-level fluctuations determine the architecture of growth-strata along normal faults (Doglioni et al., 1998). This concept is applicable to the sedimentation above roll-over anticlines along normal faults.

9. Fault-related folding and inversion structures

Inversion is defined as the reactivation of a normal fault in a reverse sense. Thus inversion structures are characterized by a two or more-phase fault evolution. In general, initial normal movement is followed by reverse movement along the same fault. The resulting hanging wall is an antiformal feature that is called a “positive inversion structure” (Williams et al., 1989), “harpoon”, or “arrow head” structure (McClay, 1992; McClay & Buchanan, 1992; McClay, 1995). Inversion structures have been described by various authors from different locations (Roberts, 1989; Letouzey et al., 1990; Lowell, 1995), and they are characteristic of complex intracontinental basins (Kockel, 2003; Mazur et al., 2005). Inversion structures can occur on a kilometre- (Letouzey et al., 1990) to
metre-scale (Brandes et al., 2012). A comprehensive review of inversion structures is given by Turner & Williams (2004).

Inversion structures are further examples of fault-related folding. Their antiformal geometry resembles the shape of fault-propagation folds with a typically steep forelimb and a gently-dipping backlimb. Anticlines can be formed in two ways along an inversion structure. Initial normal faulting may cause the formation of anticlinal roll-overs (Yamada & McClay, 2004). The subsequent reverse movements produce a hanging-wall inversion anticline. Yamada & McClay (2004) showed that the shape of these anticlines is controlled by the geometry of the fault plane (concave-up/convex-up). Convex-up listric faults produce less asymmetrical hanging-wall anticlines than the concave-up listric faults.

10. Discussion

Kinematic models of fault-related folding evolved from the early 1980s onward. The ignition was the development of the kink-band migration models (Suppe, 1983; Suppe & Medwedeff, 1990), which then were followed by numerical descriptions (e.g. Waltham, 1989; Erslev, 1991; Hardy & Poblet, 1995). All kinematic models of fault-related folding should fulfil the general criteria for models in Earth Sciences as defined by Greenwood (1989). Models can be validated by testing their predictions, although it must be kept in mind that models are often not unique and different models may produce the same geometry (e.g. Thorbjornsen & Dunne, 1997).

Since their development the advantages of these kinematic models have become apparent. They give insight into deformation processes on different scales (Lohr et al. 2008, Yielding et al. 1996) and they allow the prediction of parameters, such as the fault geometry, which are not usually exposed (Davis & Namson, 1994; Allmendinger & Shaw, 2000). Their simplistic approach can
isolate important controlling factors e.g. the propagation-to-slip ratio, as demonstrated by Hardy & Ford (1997) and Allmendinger (1998). Numerical kinematic models are also able to describe different deformation styles (Waltham & Hardy, 1995) and allow a great flexibility in the choice of the input parameters (Allmendinger et al., 2004). Using kinematic models of fault-related folding can significantly reduce the uncertainties in the reflection seismics workflow by predicting fault trace from fold geometry and tip line location from the propagation-to-slip ratio.

Besides these advantages, there are also limitations of the kinematic models. First of all, they mostly lack a mechanical foundation (Allmendinger et al., 2004). The mechanical stratigraphy of a succession has a distinct impact on the deformation style (e.g. Fischer & Jackson, 1999). Hardy (2011) pointed out that velocity models like trishear can only describe large-scale structures and the bulk strain, whereas the distinct element method is able to reproduce small-scale features and allow a more detailed strain analysis. In addition, the lack of rheology in the model means that aspects of temporal evolution are not considered. In case of multi-layer folds, several parameters such as the material properties of the individual layers, the interlayer cohesion, contrasts in the layer properties, and the bulk moduli of the whole layer package control the behavior during deformation (Woodward, 1997). Johnson & Johnson (2002) have shown that the shape of the forelimb of forced folds is strongly controlled by the rheology of the cover but only weakly controlled by the geometry of the fault.

With true geomechanical models it should be possible, for instance, to simulate parallel and similar fold morphologies, or predict the pathways of new faults. Due to the need to maintain a physical continuum, the velocity field of kinematic models cannot incorporate effects such as strain partitioning. Finite element modelling and finite difference modelling studies that implement, e.g. the mechanical stratigraphy, can close this gap and allow the analysis of the related effects on fault and fold evolution (e.g. Strayer & Hudleston, 1997; Doglioni et al., 2011; Albertz & Lingrey, 2012;
Albertz & Sanz, 2012; Smart et al., 2012). Discrete element modelling is also an appropriate tool to analyse the impact of material properties like the mechanical stratigraphy on the deformation style (Hardy & Finch, 2007). Finch et al. (2003) demonstrated the effects of the cover strength on the geometry of fault-propagation folds. In this context a weak cover causes wide zones of deformation with limited fault propagation, while a cover with a high strength results in narrow zones of deformation and pronounced fault propagation (Finch et al. 2003).

It is immanent that the physical process of generating a kinematic model requires fixing the model geometry, i.e. the geometry of fault, stratigraphic units, and other markers. The modelling itself then will add further constraints to predict the (future or extended) fault geometry.

Kinematic models of fault-propagation folding, fault-bend folding, and detachment folding tend to oversimplify the natural deformation processes (Storti et al., 1997). With scaled sand-box models, Storti et al. (1997) were able to show that during the formation of a thrust-related anticline, the kinematic regime changes from layer-parallel shortening, through detachment-folding and fault-propagation folding, to fault-bend folding. This shows that the mechanism of fault-related folding may change over time (Storti et al., 1997) and this should be considered in the setup of kinematic models (see below “the future of fault-related folding kinematic models”).

Furthermore, all faults and folds have three dimensional terminations and therefore 3D kinematic models are required to cope with natural variations in fault slip and fold geometry. At present, only the trishear method (Cristallini et al., 2004, Cardozo, 2008) can fulfill this criterion. Other methods use parallel 2D sections to achieve a kinematically-unraveled 3D geometrical model. For instance fault-parallel flow in 3D can only maintain bed length in the transport direction, but not in any other section that is oblique to the transport direction (Tanner et al., 2003, Ziesch et al., 2013).
Fold models are an important tool for predicting strain and thus the orientation and distribution of small-scale deformation features such as fractures (e.g. Fischer & Wilkinson, 2000; Salvini & Storti, 2004). They therefore have a predictive capability (Greenwood 1989). Nevertheless, the results strongly depend on which model is used. In case of fixed-hinge folding, the deformation is concentrated in the crest of the anticline, whereas for active hinge folding it is manifested on the limbs (Salvini & Storti, 2001). This stresses the demand for unified kinematic models of fault-related folding.

11. The future of fault-related folding kinematic models

Though much work was carried out on fault-related folding during the last century, there is still potential for further research. Future work should focus on integrating seismic-scale and outcrop-scale observations to predict the orientation of features like joint sets or deformation bands. This would require the development of coupled kinematic and geomechanical models.

Understanding small-scale structural elements like joints and deformations bands is crucial to develop more comprehensive models that consider the influence of structural elements on the subsurface fluid flow. Increasing energy demands makes it imperative to achieve better reservoir characterization in hydrocarbon geology and geothermal applications. Kinematic fault-related folding models are a strong tool to predict the orientation of small-scale tectonic fabrics as demonstrated by Lohr et al. (2008) and Brandenburg et al. (2012). Further research on fault-related folding should also focus on the evolution of soft sediment fault-related folds to generate holistic models for mass wasting along continental margins.

Fault geometry is more complicated than has been modelled up to now. Using natural fault geometries would boost the reliability of the results and lead to the development of new algorithms.
Steps into this direction were recently made by Brandenburg (2013) who extended the trishear algorithm to naturally-curved fault planes.

All kinematic models of fault-related folding in the present-day include similar simplifications and limitations, such as:

1. They enforce the same kinematic behaviour throughout the model. If they could be combined, for instance using 40% trishear and 60% fault-parallel flow, this would allow the chance to get closer to natural deformation (Fig. 15).

2. They are mostly two dimensional. Natural deformation is always three-dimensional. Two-dimensional models can only model plane strain, which is exceptional in nature. All present-day algorithms should attempt to make the huge leap to three dimensions. The result would be far more realistic, albeit at the cost of computing power.

There are a number of general ways that the algorithms could be improved or even new algorithms written. For instance:

1. Analogue models, using, for instance, plasticine or sand, could be used, maybe analyzed using, e.g. particle image velocimetry, to design new velocity models for fault movement. The results could then be converted to numerical algorithms for kinematic modeling.

2. Ground-truthing. The authors are of the opinion that far more emphasis should be placed on the analysis of natural structures (e.g. Tanner et al., 2010). Algorithms can then be discriminated as to their applicability to particular structures. An algorithm, however good, is, without ground-truthing, of much less value.
3. Extraction of material properties from geophysical methods, such as reflection seismics. Examples of this include Poisson's Ratio from the seismic reflection velocities, i.e. Vp/Vs (e.g. Gassaway & Richgels 1983; Beilecke et al., 2014). This will allow rheological parameters to be entered into models.

12. Conclusions

Fault-related folding is one of the most important deformation processes in structural geology at all scales and occurs in very different tectonic settings (compressional, extensional and strike-slip). Nevertheless, the evolution of the structures can be explained or be at least partly reconstructed by simple kinematic models. Basic prerequisites are the presence of layer-parallel strain and mechanical stratigraphy. Layer-parallel strain is important for the evolution of detachment folds and fault-bend faults, where fixed stratigraphic detachments are involved. The mechanical stratigraphy determines the position of detachments and the development of ramps, which are the key elements for fault-bend folds and fault-propagation folds. Mechanical stratigraphy is also significant for the development of detachment folds because they require a stack of less competent and competent rock units.

Kinematic models clearly enhanced the understanding of the deformation processes that control fault-related folds. However, this does not mean that fold geometry is uniquely related to fault geometry; different kinematic approaches can lead to the same fold shape.

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Figure captions

Fig. 1. Different types of fault-related folds. A) Fold in the hanging wall of a large thrust sheet, Alps, southern Germany. B) Seismic section showing a fault-propagation fold, Limón fold-and-thrust belt, offshore southeastern Costa Rica. Modified after Brandes et al. (2007a). C) and D) Extensional fault-propagation fold, northern foreland basin of the Alps, southern Germany. E) Syn-tectonic growth fault in Namurian siliclastic sediments exposed on the west coast of Ireland, Donegal Point, County Clare.

Fig. 2. The three main types of fault-related folds. A) Undeformed state. B) A detachment fold evolve from the shortening of a rock mass above a detachment. The space in the fold core is filled with mobile material. C) A fault-bend fold forms when material is transported over a bend in a fault. This forces the material into an antiformal geometry. D) Fault-propagation folds form as a consequence of variation in the slip along the fault. The slip on a fault is assumed to decrease to zero at the tip, which is compensated by buckling of material above the fault.

Fig. 3. History of research on fault-related folds and their basic kinematic models.

Fig. 4. Drawing by Cloos (1936) that illustrates the evolution of a fold associated with a fault. The picture shows that the fold grows with increasing slip. This early illustration of fault-related folding shows faulting and folding as a contemporaneous process.
Fig. 5. Drag folds develop along normal faults and reverse faults. They can be classified into drag folds with normal drag and drag folds with reverse drag. Normal drag means that the beds are convexly warped in the transport direction of the fault while reverse drag means the opposite.

Fig. 6. Detachment folds. A) General characteristics of detachment folds are a horizontal detachment and a core of less-competent rocks (redrawn after Poblet & McClay, 1996). B) Types of detachment folds: 1. fold core is characterized by disharmonic folds, 2. Lift-off folds, where the core is characterized by isoclinal limbs. C) Depth-to-detachment calculation of a detachment fold, using the excess-area-method (modified after Mitra & Namson, 1989), Epard & Groshong, (1993) and Wiltschko & Groshong (2012)). D) Kinematic model of Epard & Groshong (1995) for fixed and migrating hinges (see text for explanation). E) Kinematic model of Poblet & McClay (1996), see text for explanation.

Fig. 7. Kink-band migration model for a fault bend fold, based on Suppe (1983). Material is transported over a footwall ramp and deformed into an antiform, see text for explanation.

Fig. 8. Shear fault-bend folding. Two end-member models for shear fault-bend folding have been developed. In the simple-shear case, the décollement layer experiences bedding-parallel shear, in the pure-shear case, the décollement layer moves above a flat, as in the no-shear fault-bend fold model, but instead shortens and thickens above the ramp (modified after Suppe et al., 1992; Shaw et al., 2005).

Fig. 9. Velocity model for fault-bend folds. The model has three velocity domains. The velocity vectors are always parallel to the fault trace. Modified after Johnson & Berger (1989).
Fig. 10. Fault-Parallel Flow. Material nodes move, parallel to the fault, along flow paths. A material line ($l_0$) is transported by the length $z$ over a concave ramp (angle $2\eta$), which is bisected by a flow deflector (fd). The line ($l_1$) undergoes strain and the angle $\alpha$ is now $\alpha'$. The parallel line ($l_1'$) is moved over a similar, but convex ramp, again by the length $z$. The line is restored in length to $l_0$ and the angle $\alpha'$ is restored to $\alpha$. Modified after Ziesch et al. (2014).

Fig. 11. Geometry and kinematics of fault-propagation folds (based on Suppe & Medwedeff, 1990 and Hardy & Poblet, 1995). See text for explanation.

Fig. 12. Concept of the trishear approach. Trishear kinematics assumes a triangular shear zone in front of the tip of a propagating fault. At the top of this zone the slip vectors are equal to that of the hanging wall, whereas at the base the slip is zero. Across the trishear zone, the velocity decreases. Material is deformed within the trishear zone. Modified after (Allmendinger, 1998; Allmendinger & Zehnder, 2000 and Hardy & Allmendinger, 2011).

Fig. 13. Comparison of kink-band migration folding and fixed-hinge folding. In the kink-band migration model (A), the limbs widen; in case of a fixed hinge (B), the limbs rotate. This affects the related growth-strata. In kink-band migration folding, a growth triangle forms, whereas in the fixed-hinge case, the growth-strata beds also rotate. Based on Shaw et al. (2005) and Salvini & Storti (2004).

Fig. 14. Comparison of trishear in A) compressional and B) extensional regimes. The fault dip is $50^\circ$, trishear angle is $60^\circ$, and the P/S ratio is 2 in both cases. The slip increment is equal. Simulation was carried out using the software FaultFoldForward by R. Allmendinger.

Fig. 15. Fault-related folds produced by A) fault-parallel flow over a detachment and ramp of $30^\circ$,
B) trishear of a ramp propagating upwards from a detachment at 30°, P/S ratio 2. The slip increment is equal. The resulting hanging-wall folds are substantially different in their geometry, which is a function of the P/S ratio. Future algorithms could aim to combine these approaches to create a unified kinematic model.

Table 1. Glossary of specific expressions used in the text.
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Information Box

- **Kinematics**: The study of the motion of points within a body without consideration of the cause of the motion.

- **Velocity**: A vector that is defined by magnitude and direction. It represents the rate of change of the position of an object. Velocity is an important concept in kinematics.

- **Flexural-slip**: The concept of allowing differential movement to take place on a detachment or multiple detachments.

- **Detachment**: A discontinuity within a body, usually along planes of mechanical weakness, i.e. bedding, across which points move with different velocities.

- **In-plane motion**: All the motion that is caused by the deformation is within a two-dimensional plane. This notion is synonymous with bulk plane strain.

- **Line-length, area, and volume preservation**: This is an attempt to constrain a kinematic algorithm, and therefore make it more realistic, by maintaining line-length and/or area in two-dimensions or up to all three values in three-dimensions, between, for instance, pins.

- **Pins**: Virtual lines or planes that are used to divide and bind a model. Fixed pins are set at the boundaries between deformed and undeformed domains or along the axial planes of folds, while loose pins are allowed anywhere in the model and may move and possibly rotate with the deformation. Analysis of the pins allows the quantification of deformation as well as the possibility to judge, e.g. the amount of strain within the model. Subdividing a model with a number of pins allows incremental deformation to be determined.
Fig. 1
Fig. 2

A) undeformed state

B) detachment fold

C) fault-bend fold

D) fault-propagation fold
Fig. 3
Fig. 5

normal fault

reverse fault

normal drag

convex

concave

reverse drag

convex

concave
Fig. 6

A  general characteristics of detachment folds

competent rocks

general characteristics of detachment folds

less competent rocks

slip

fault tip

detachment

B  basic types of detachment folds

disharmonic detachment fold


detachment

C  balanced detachment fold

depth to detachment: \( z = \frac{A}{l_0 - l_1} \)

detachment

D  model of Epard & Groshong (1995)

fixed hinge

migrating hinge

E  model of Poblet & McClay (1996)

1) constant limb dip/variable limb length

2) variable limb dip/constant limb length

3) variable limb dip/variable limb length

4) variable limb dip/variable limb length
Fig. 7

A

B

C

$A_1 + A_2 = A_0$
Fig. 8

A  simple-shear fault-bend fold

B  pure-shear fault-bend fold
Fig. 9
Fig. 10

Hanging wall

Footwall

flowpath

fault

material line

node
Fig. 11
Fig. 12
Fig. 13

A  fault-bend fold (limb widening)

B  narrowing kink-band
   widening backlimb

C  moderate limb deformation

A  detachment fold (limb rotation)

B  growth strata

C  strong deformation in the hinge area
Fig. 14

A

contraction

trishear zone

B

extension

trishear zone
Fig. 15

A  fault-parallel flow

B  trishear

loose pin  d

fixed pin

loose pin  d

sheared fixed pin