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Robert W.H. Butler, Clare E. Bond, Mark A. Cooper, Hannah Watkins

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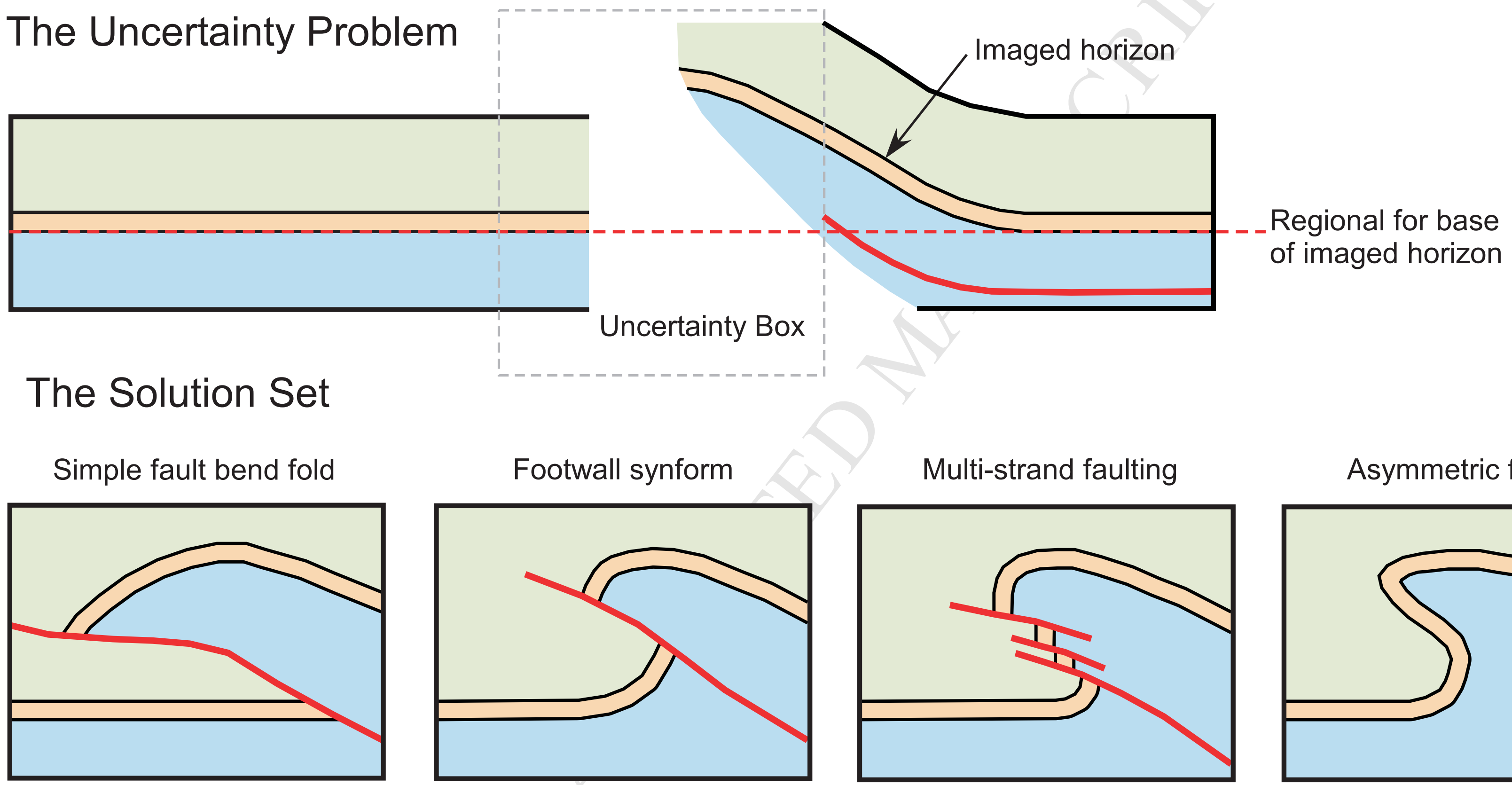

The Uncertainty Problem
Imaged horizon
Regional for base of imaged horizon
Uncertainty Box
The Solution Set
Simple fault bend fold
Footwall synform
Multi-strand faulting
Asymmetric fold pair

Interpreting structural geometry in fold-thrust belts: Why style matters.

Robert W.H. Butler[a]*, Clare E. Bond[a], Mark A. Cooper[a,b], Hannah Watkins[a]

[a]Geology and Petroleum Geology, School of Geosciences, University of Aberdeen, Aberdeen, AB24 3UE, United Kingdom.
[b]Sherwood Geoconsulting Inc, Suite 304, 1235 17th Ave SW, Calgary, Alberta, T2T 0C2, Canada.

*Corresponding author: rob.butler@abdn.ac.uk

ABSTRACT

Structural interpretation in fold-thrust belts has become reliant on a few idealized geometric models (i.e. fault-bend, fault-propagation and detachment folding) and their quantitative methods for section construction and validation. We couple historical review with selected outcrops to show that there is a substantially greater range of solutions available for interpreting the geometry and evolution of thrust belt structures than implied by these idealized models. Examples are documented, and lessons drawn, from comparing structural interpretations developed in the foothills of the Canadian Rockies with those in the Western Alps. Both show a range of structural geometries with regional variations that reflect variations in the pre-kinematic stratigraphic template. Locally, fold-thrust development can localize on pre-existing structures. Thus consideration of the precursor geology is essential for structural interpretation. Using a case study from the Papuan Fold Belt we show that even with seismic data, assessing the role of basement in structural development can be uncertain. The idealized models offer only a narrow range of possible geometries for constructing cross-sections and developing structural understanding in fold-thrust systems. Failure to consider alternatives, and the inherent interpretation uncertainty, has biased understanding of thrust systems leading in turn to over-optimistic risk assessment and repeated drilling surprises.

Key words: thrust belts, folding, interpretation uncertainty, fold thrust structures

1. Introduction

This paper takes a critical look at existing fold-thrust models and interpretation strategies in fold and thrust belts. Our premise is that the tendency to use a narrow range of idealised "structural styles" for the relationships between folds and thrusts is an important source of interpretational bias that can impede understanding of structural geometry. Our motivation comes from the repeated failure of many of these existing models to forecast the structural complexity encountered in the subsurface when hydrocarbon prospects are drilled. Perhaps unsurprisingly, these failures are rarely publicised – but there are a few.

In mid 2005, Shell Nigeria drilled well Alpha-1X into an anticline in the deep-water fold belt of the Niger Delta. The well was planned on the basis of idealised fold-thrust models, such as those presented by Shaw et al. (2005), including a single thrust fault across which a multilayer of sandstones and mudrocks had been displaced. This type of multilayer together with the significant inferred fault displacement implied that clay should have been smeared along the thrust (Yielding et al., 1997), hopefully supporting much of the oil column. As Kostenko et al. (2008) report, the Alpha-1X well passed through a tract of rock with a range of bedding dips indicative of structural complexity – overturned, folded and faulted beds (Fig. 1). The oil column in the anticline was significantly smaller than hoped. Kostenko et al. (2008) infer that this outcome is because oil migration pathways exist in the fold forelimb, through the folded sandstone-mudstone multilayer. Therefore, no single thrust surface with smeared clay could have acted as a lateral seal. The structural complexities encountered in well Alpha-1X exceed those predicted from the idealised fold-thrust models.

A fundamental problem with subsurface interpretation of fold-thrust structures is the inherent ambiguity in seismic imaging – especially in the steep forelimbs of folds and in the footwalls to thrusts. The data used to interpret the fold in deep-water Niger delta was industry-standard 3D seismic. However, in many onshore settings, especially young or active fold-thrust systems, these inherent imaging problems are exacerbated by the prohibitive cost and issues of acquisition of 3D seismic data and the consequent reliance on 2D profiles. Consider the Agogo structure in the outer fold belt of Papua New Guinea. Hill et al. (2010) interpreted this in terms of a stack of simple thrust ramps of relatively low displacement. The higher anticline, in the hangingwall of the Agogo Thrust, was penetrated by three wells. The 2D seismic imaging appears to be excellent – with good reflector continuity, even in the footwall to the Agogo Thrust. This footwall was targeted for further exploration drilling (Parish, 2015). Three sidetrack wells from an existing well (ADT2) were drilled. Rather than encounter sub-horizontal bedding and a simple reservoir structure, all three sidetrack wells crossed steeply dipping and faulted strata (Fig. 2). While this significantly increased the volumes of reservoir in the footwall to the Agogo Thrust, the structural complexity was entirely unexpected. Indeed it is entirely incompatible with the reflector geometries apparently imaged in the seismic data used to plan the wells. So even apparently good-quality 2D seismic imaging need not guarantee success in structural interpretation.

The two case studies described above, together with others (e.g. Cooper et al., 2004; Heidmann et al., 2017), indicate that the predominance of a rather narrow range of idealised geometries used in structural interpretations of thrust systems limits interpretation and causes anchoring bias (Bond, 2015). There are many reviews of these idealised models (e.g. Shaw et al., 2005; Groshong et al., 2012; Brandes and Tanner, 2014; and references therein) and it is not our intention to duplicate them here. Rather we note that in general the interpretation of fold-thrust structures is under-constrained and the use of a few simplified models of fold-thrust relationships to the exclusion of other, more complex patterns may lead to an under-estimate of structural risks associated with subsurface exploration. We concentrate on two key issues. The first is the geometry of individual fold-thrust structures such as those targeted in the deep-water Niger Delta and the Papuan fold belt. The second is the role of basement involvement in thrust systems, which in turn impacts not only on the assessment of tectonic detachments at depth but also on the geometry and mechanical properties of the stratigraphic template incorporated into the structures.

There is a vast literature on thrust systems and many case studies on the relationships between folds and thrusts. Rather than provide broad geographical coverage, we compare interpretative approaches adopted in the Canadian Rocky Mountain foothills with those in the Western Alps. These places are historically important for developing geometric understanding of fold-thrust belts, as reviewed briefly below. We also consider models for basement involvement in thrust belts that draw on examples from the Rockies and the Papuan thrust belt where the topic has significant importance for hydrocarbon exploration. The general issue for these applications is to identify not only where the hydrocarbons are located but also how they migrated there. The specific lessons learned from these case studies have broader impact for the general understanding of fold-thrust belts.

2. Thrust localisation and structural styles: historical perspectives

Understanding the development of ideas through the history of research can assist in identifying origins of community bias in interpretation. Many approaches to understanding fold-thrust relationships, especially through the development of geometrically quantitative methods, date back just a very few decades. But the geometry and kinematic evolution of fold-thrust systems, their impact on both structural style and the mechanics of thrust belts, have been investigated since the 1880s (e.g. Brandes and Tanner, 2014). One of the motivations for Cadell's (1888) "experiments in mountain building" was to challenge Heim's (1878) model from the Swiss Alps – that thrusts localised at a late stage in the folding process that created nappes (Fig. 3a). Cadell showed that thrusts can grow (propagate) without significant folding of strata (Fig 3b). These insights directly influenced the construction of cross-sections through the Moine Thrust Belt in the 1880s. The idealised structure, showing multiple imbricate stacks as used by Peach et al. (1907), is illustrated in Fig. 3c.

For most researchers (e.g. Brandes and Tanner, 2014), the first explicit attempt to relate thrust geometry to folding was that of Rich (1934) in his interpretation of the Powell Valley anticline and Cumberland fault block in the Appalachians of Virginia and Tennessee (Fig. 3d). For the following five decades the notion of what is now termed "fault-bend" folding together with large-scale detachment of "thin-skinned" structures rooting on a regional floor thrust above the basement (as shown by Cadell, 1888) held sway in the Appalachians (e.g. Rodgers, 1950, 1963; Boyer and Elliott, 1982). Through this period subsurface interpretations were largely controlled by borehole data (e.g. Perry, 1978). Confirmation of regional-scale detachment and thin-skinned tectonics had to wait for the acquisition of regional deep seismic reflection profiles (COCORP: e.g. Cook et al., 1979).

Contractional deformation detaching above basement was also recognised early, especially for the Jura mountains of SE France and Switzerland. Here too subsurface control was important, provided by boreholes together with railway tunnels (some over 8 km long). Pioneering work by Buxtorf (1916) generated regional cross-sections through the fold belt (Fig. 3e, f) and his profiles remain in use as examples for examining section-balancing methods (e.g. Mitra and Namson, 1989; Epard and Groshong, 1993) and fold-thrust mechanics (e.g. Jaquet et al., 2014). Most studies, at the time, focused on what are today termed "detachment folds" (e.g. Velleret and Graitery anticlines: Fig. 3e). However, other sections (e.g. Fig. 3f) show stacked imbricate thrusts with simple fault-bend folds (Fig. 3f). This variation rarely appears in discussions of Jura folding (c.f. Laubscher, 1977).

The relative timing between folding and thrusting has long been discussed in Alpine tectonics. Goguel (1952) documented locations where folds develop ahead of thrusting, as did Heim (1878) – presaging concepts such as fault-propagation folding. Goguel's interpretations of Buxtorf's Jura sections include the notion of temporal evolution: thrusts nucleated adjacent to developing anticlines and both structures continued to amplify together so that thrust surfaces became folded (see discussion in Frizon de Lamotte and Buil, 2002). Goguel (1952) also popularised the notion of "écailles intercutanées", a term coined by Fallot (1949) and a forerunner to the duplex model (see Graham, 1981 for discussion). This invoked ramp-flat geometries involving only part of the stratigraphic section to explain disharmonic, layer-controlled deformation.

Notwithstanding Goguel's (1952 and subsequent English translation) synthesis of structural styles, as Frizon de Lamotte and Buil (2002) note, research into fold-thrust relationships in North America and the western Alps developed largely independently through the twentieth century. This changed in the early 1980s, chiefly with the comparative study by Boyer and Elliott (1982) of the structures of the Appalachians and the western Alps. They sought to apply the building blocks of thrust belts, as encompassed by Dahlstom's (1969) so-called "foothills family" of structures to settings far removed from their origins in the Canadian Rockies. For the 35 years efforts have focused on applying and modifying fold-fault models to the Alps (discussed below). Many subsequent studies around the World have built upon quantitative relationships between stratal orientations and thrust geometry pioneered by Suppe (1983 and references therein), modified by paired faulting-strain models such as "trishear" (Erslev, 1991). Further application of these approaches has been facilitated by their incorporation, via algorithms, into structural modelling software (e.g. Guth, 1988; Contreras and Suter, 1990; and many others since; see Groshong et al., 2012; Brandes and Tanner, 2014; for recent reviews). Common adoption of these modelling tools has led to descriptions of structural styles in thrust systems that commonly rely on so-called "end-member" behaviours (Fig. 4), specifically fault-bend folding, fault-propagation folding and detachment folding (e.g. Jamison, 1987; Shaw et al., 2005). The models can be traced back to a few key publications in the 1980s and early 1990s (e.g. Suppe, 1983; Jamison, 1987; Erslev. 1991; reviewed by Shaw et al., 2005 and Brandes and Tanner, 2014). The widespread, generally uncritical, adoption of these structural models and their implicit quantitative relationships between folding and faulting, was presumably driven by a desire to "make better structural interpretations" (Shaw et al., 2005, p1). Yet a deleterious effect has been to narrow the range of solutions thereby introducing interpretation bias in cross-sections.

Many authors, while generally accepting the "end-member" behaviours (Fig. 4), note the limitations of utilizing purely kinematic approaches. The models are non-mechanical with no consideration of heterogeneous layer behaviour (see Brandes and Tanner 2014). Parallel approaches have investigated the role of layer-dependent heterogeneous strength through rock sequences, generally termed "mechanical stratigraphy", as reviewed by Ferrill et al. (2017). Generally the goal of these studies has been to predict subseismic faults and fracture patterns, especially in competent units. For example, Hughes et al. (2014) use discrete element models to examine how variable layer properties and loading conditions influence the propensity for fault-bend vs fault-propagation folding in the hangingwall to a defined thrust ramp. Smart et al. (2014) investigate the evolution of a fold-thrust complex in the Alps (the Bargy anticline – discussed later here), populating layers with material properties (e.g. Young's modulus, Poisson's ratio), then imposing deformation determined from kinematic structural restorations to model stress and strain histories within a layer of interest. These and most other examples are based on known or defined geometries on the scale of cross-sections and so are not designed to inform how entire fold-thrust complexes form, or to explore variations in the localisation of deformation through an entire multilayer. The stratigraphy used by Smart et al. (2014) was utilised by von Tscharner et al. (2016) to forward-model buckle-fold trains, using layer-variable viscosities. However, investigations of thrusting and folding as model outputs remain in their infancy.

Notwithstanding the absence of mechanical considerations, the descriptions of "end-member" kinematic models (Fig. 4) have further limitations. They build upon a layer-cake stratigraphic template and growth strata, where displayed, invariably assume simple aggradation across the structure. This assumption together with spatially-limited strain patterns allows fold axial surfaces to be extrapolated to depth, especially if folding is approximated to simple kink-bands (e.g. Fig 1). All of the models assume simple rules for deformation localisation, such as thrusts propagating upwards from a basal detachment. Therefore, within a stratigraphic succession, folding is more likely in shallower levels with thrusting more likely at depth. To better understand fold-thrust structures, we first consider outcrop-scale evidence.

3. Outcrop examples: embracing variety

Outcrops display a range of structural styles of fold-thrust structures that challenge the simplicity of the idealised models (Fig. 4) and their inherent assumptions. Some examples (Fig. 5a, b) show simple fault-bend fold geometries. In these the cut-off angles between beds and the thrust plane are less than 30 degrees, consistent with folding being a simple consequence of displacement along a shaped fault (Fig. 4a). However, in the experience of the authors and others (e.g. Ferrill, 1988), such relationships are very rare within thrust belts. More commonly, hangingwall anticlines display cut-off angles between bedding and thrust planes that exceed 30 degrees and anticline interlimb angles are tight (e.g. Fig. 5c). These geometries are consistent with those produced by fault-propagation folding (e.g. Jamison 1987; Fig. 4b) where a fold-pair forms ahead of the instantaneous tip-line to a growing thrust. As such the geometry derives from models of thrust growth proposed by Williams and Chapman (1983) and adapted by Wickham (1995). However, the idealized description of fault-propagation folding (e.g. Shaw et al., 2005) restricts the developing thrust to propagate strictly along the axial surface of the synform, leaving footwall strata as sub-planar creating a footwall ramp identical to that formed by fault-bend folding (Fig. 4b). We consider these geometries to be rare in nature. The preservation of footwall synforms (e.g. Fig. 5d) testifies to thrusts forming not along the synform axis but somewhere in the forelimb of the fold-pair above the synform axis. In many cases thrusts take more complex trajectories so that footwall synforms are only found in some stratigraphic horizons (e.g. Fig 5e). Greater complexity results from the forelimb containing multiple thrusts. These structures can develop linked geometries to isolate thrust-bound slices (e.g. Fig. 5e) or form as discrete segments (e.g. Fig. 5f). This latter geometry is important for understanding kinematic evolution of fold-thrust complexes because it implies that thrust segments need not grow simply by splaying from a deeper master detachment but form within a broader zone of distributed deformation (e.g. Fig. 5g).

The spectrum of natural examples (Fig. 5) offer a geologist a rich choice of geometrical solutions for interpreting fold-thrust structures in the subsurface where, data available for imaging the forelimb are commonly poor (Fig. 6). The under-constrained forelimb areas can be interpreted in different ways while still satisfying the well-imaged parts of the structure. Different interpretations of the forelimb carry different implications for how deformation has localised through a multilayer, strongly influencing not only the appraisal of resources in the subsurface but also understanding of the mechanical evolution of fold-thrust structures.

4. Alternative approaches to fold-thrust complexes

For a seismic interpretation experiment using a well-imaged fold-thrust structure (Torvela and Bond, 2010), a group of experts developed a wide range of solutions, very few of which conformed to the idealised geometries (Fig. 4). Here we examine "non-standard" treatments of fold-thrust structures, some of which reach back to much earlier descriptions of structural style (e.g. Goguel, 1952).

Well-exposed coastal sections together with analysis of historical, published cross-sections, led Williams and Chapman (1983) to link fault slip to deformation of wall-rocks. Their exemplar fold-thrust pair at Broadhaven, Pembrokeshire (SW Wales) is shown in Figure 5d. Williams and Chapman (1983) envisaged the propagation of the thrust as it accumulates slip, distributing deformation in the surrounding rocks, controlling the resultant fold geometries and kinematics (Fig 7a). Wickham (1995) takes this concept further, illustrating a wide range of kinematic histories for folding and displacement accumulation on thrusts. He coined the term "displacement-gradient folding" to embrace the resultant spectrum of structural geometries.

For displacement-gradient folding (Wickham, 1995), idealised fault-bend folds result from thrust propagation that is effectively instantaneous relative to the accumulation of slip. Thus the displacement gradient is zero. If thrust propagation rates are slower, relative to fault slip, then more complex folding develops, generally inferred to occur adjacent to the instantaneous fault tip. For fault-propagation folding, the inherently propagating thrust segment is the ramp. For detachment folds, the propagating thrust segment is the flat. But the approaches of Williams and Chapman (1983; also Wickham, 1995) allow a more complete geometric and kinematic analysis than using idealized geometries (Fig. 4).

Pfiffner (1985) developed the approach of Williams and Chapman (1983) to examine thrust faults that terminate both up and down dip, and are thus limited by both leading and trailing tip lines (Fig. 7b, Fig. 5g). This presages models for fault growth that underpin validation strategies in extensional tectonic domains (e.g., Walsh and Watterston, 1987). The notion that thrusts, rather than splay from branch lines, as formalised by Boyer and Elliott (1982), can occur in isolation from one another, embedded within an otherwise continuously deforming medium, was further developed by Eisenstadt and DePaor (1987; Fig. 7c). These authors considered that thrusting was an expression of failure of load bearing "competent beams" (layers) within a multilayer: hangingwall anticlines and footwall synclines may reflect the pattern of fault nucleation (see also Morley, 1994, 2009; Ferrill et al., 2016). In these models, faults initiate in the middle of a competent layer and grow radially outwards, both up and down dip eventually to form linked networks. These ideas were developed by Butler (1992) to examine the kinematic relationships between folding and faulting in thick multilayers in the external Alps. In his model (Fig. 7d), spatially isolated thrusts are kinematically linked via tracts (beads) of distributed strain. Thus, deformation styles reflect variations in the propensity of each layer to localise deformation and are essentially kinematic responses to mechanical stratigraphy.

The models outlined above are more complex than the commonly used models for fold-thrusts (Fig. 4), and this has implications for the understanding of fold forelimbs, and prediction of hydrocarbon reserves in exploration areas as exemplified by our introductory examples of the Alpha 1-X well (Fig. 1) and the Agogo structure (Fig. 2). We now contrast fold-forelimbs and thrust structures from the Canadian Rockies with those of the Western Alps to investigate the range of structures, both observed and interpreted.

5. Thrusts and Forelimbs in the Canadian Rockies Foothills – iterating seismic data with structural interpretation

The foothills of the Canadian Rocky Mountains (Fig. 8) have been extensively studied for over 70 years (Douglas, 1950, 1958; Fox, 1959; Bally et al., 1966; Dahlstrom, 1969, 1970; Price and Mountjoy, 1970; Thompson, 1979). For many, it is the type-example for "thin-skinned" (detachment-dominated) tectonics and research here has underpinned interpretations of thrust systems worldwide (e.g. Boyer and Elliott, 1982; McClay, 1992). Structural understanding has increased hand-in-hand with technological developments related to the exploitation of subsurface hydrocarbons. Here, we discuss the relationship between the history of drilling for hydrocarbons in the Canadian Rockies and the development of structural knowledge.

McMechan and Thompson (1989) provide a comprehensive review of the fold-and-thrust belt. The belt is broadly eastward-directed (Fig. 9) and evolved from the Late Jurassic until the Eocene to accommodate shortening consequent to the accretion of a series of exotic terranes onto the Pacific margin of North America (Monger et al., 1982). It is bounded by large thrust sheets of Paleozoic rocks to the west and the largely undeformed Western Canada Sedimentary Basin to the east. The eastern edge of the belt is commonly marked by a frontal monocline – or triangle zone (Jones, 1982; Fig. 9). The foothills contain significant volumes of hydrocarbons with some very large fields, including the West Jumping Pound and Waterton gas fields and the Turner Valley oil field (Figs 9d and 10d). A series of cross-sections through the foothills of Alberta and British Columbia show the variations in structural style from south to north (Fig 9). The same sections are in Figure 10 and are coloured by the dominant lithology instead of stratigraphic unit. In the Alberta Foothills (Fig 9c,d,e and Fig 10c,d,e), all three sections show a succession moving upwards of thick carbonates, a thin shale, thick interbedded sands and shales and finally a thick sequence of sands. All three sections show large displacement thrusts involving the carbonate dominated Paleozoic stratigraphy with a lower detachment within various units in the Lower Paleozoic that changes from South to North along the thrust belt, and generally steps down westwards to deeper stratigraphic levels (Fig. 9c,d,e). A major detachment in the thin shales of the Fernie Group (Jurassic) separates these large thrust sheets from the more closely spaced imbricate thrusts that deform the clastic dominated Mesozoic stratigraphic units above the Fernie Group detachment (Fig. 9c,d,e and Fig 10c,d,e). The detachment in the Fernie Group is therefore a major structural discontinuity throughout the Alberta foothills across which geometry changes as a result of the changes in the lithologies and hence, the mechanical stratigraphy of the units above and below the detachment. The variations in stratigraphic thickness and dominant lithologies are shown in a section parallel to the strike of the foothills on which the locations of the cross-sections are indicated (Fig 11). This figure illustrates that the thickness of the succession thickens gradually to the north within the Alberta Foothills and that the dominant lithofacies in any particular stratigraphic unit remain fairly consistent.

Many of the productive structures in the foothills of Alberta have traditionally been interpreted as fault-bend folds and duplexes (Fig. 9c,d,e): these interpretations have provided “type-example” analogues for subsurface interpretation around the world (e.g. Bally et al., 1966; Boyer and Elliott, 1982). However, as seismic imaging has improved and modern well logs have been acquired, steeply dipping forelimbs have been recognised as being more common than previously thought (Cooper et al., 2004; Rawnsley et al., 2007; Newson, 2015; Cooley et al., 2011). For example, the structure of the Turner Valley field (Fig. 9d) has been the subject of much debate over the years starting with Link (1934) and subsequent work (Link, 1949; Fox, 1959; Dahlstrom, 1970; Williams and Chapman, 1983), culminating with Mitra (1990) who interpreted Turner Valley as a fault propagation fold. Many of these interpretations infer the presence of an east-facing synclinal structure with overturned strata in the footwall of the main fault. Yet this interpretation is not supported by seismic data (Reimer, 1989; Fig. 12), which appears to image a simple panel of strata in the footwall. This constraint has been incorporated into more modern cross-sections through Turner Valley and other structures (Stockmal et al., 2001; Rottenfusser et al., 2002; Fig. 9c,d,e). Yet it is the early interpretations of the Turner Valley area that continue to provide analogues for global case studies.

In the Foothills of northeastern British Columbia (hereafter referred to as NEBC) between the Alberta border and Williston Lake, (Fig. 8), relatively few faults but numerous folds crop out at surface (Barss and Montandon, 1981; Fig. 9a,b and Fig. 10a,b). The amount of shortening is much less than is seen in the Alberta Foothills to the south, as is shown by comparing the sections in Figure 9a,b and Figure 10a,b with the sections in Figure 9c,d,e and Figure 10c,d,e. The stratigraphic thickness of the Triassic and Jurassic stratigraphic units increases significantly from south to north and the shale/sand ratio in the Mesozoic section also increases to create a multi-layered sequence of rapidly alternating lithologies (Fig. 11) and the dolomites of the Upper Triassic are underlain and overlain by thick shale dominant packages that compartmentalise the deformation. These changes result in simpler thrust sheets albeit with more modest displacements than those in Alberta in the Paleozoic carbonates.

The folds in the Upper Triassic dolomites are the primary target for gas exploration. These folds are large, with 1000 m amplitude, but are obscured by overlying alternations of sands and shales deformed into short-wavelength folds with minor thrusting, some of which show spectacular disharmony with the Upper Triassic folds (Figs. 9a,b, 10a,b). The seismic imaging of the exploration targets in the folded Upper Triassic dolomites is complicated by this structural disharmony. Exploration success in the area depends on locating, by integrating geological and geophysical data sets, the fractured fold hinges in the Triassic reservoirs. In areas of complex geology, like the NEBC area, uncertainties in the velocity structure, the refraction of seismic waves and seismic anisotropy all impact the quality of the seismic image. Initially unsuccessful wells are commonly sidetracked to hit targets. An excellent example of this is documented by Slawinski and Parkin (1996) and Cooper et al. (2004) where the crest of an east-vergent fold was targeted. However, the original wellbore was abandoned in Jurassic shales due to high formation stresses and the dip data showed that the well had penetrated the fold forelimb, not the hinge that lay 100m to the west (Fig. 13). The sidetrack well penetrated top reservoir 30m higher than this modelled prediction (Fig. 13).

Why is this outcome important? In the 20 years from 1978 – 1998, a total of 30 wells in the NEBC area (Fig. 8) were sidetracked to overcome original wellbore problems (Cooper et al., 2004). Of the original wells, 43% missed the target and were out in front of the forelimb, 23% got stuck in the tectonically stressed Jurassic shales, 23% had poor fracture densities, the final 10% were for unknown reasons. The results of subsequent sidetracks have been mixed. 50% resulted in high-deliverability commercial gas wells, 27% were failures and 23% were shut-in gas wells that may have subsequently become commercially viable. Since 1998, drilling horizontal sidetrack wells deliberately in forelimb and crestal locations has become a standard exploration and development tactic. Some were commercial successes, but others were commercial failures. The well results indicate that horizontal sidetracks whilst generally increasing flow rates will only increase the total drainage area of the well if a major fracture system that permits long-distance drainage of gas is intersected. The implications for commercial success are obvious but the key point here is in the inability to predict the forelimb geometry and structure that necessitates the sidetrack in the first instance.

The history of structural understanding in the Canadian foothills illustrates how new data and technology leads to modification and even abandonment of interpretations. Early interpretations were dominated by idealized fold-thrust models such as fault-bend folding, and still dominate conceptions of the structural style associated with the Canadian Rockies by researchers elsewhere. Thus, syntheses of "foothills" structural styles (e.g. Mitra, 1990) may still serve to anchor interpretations elsewhere (e.g. Zagros ranges; McQuarrie, 2004) even after the interpretations of examples such as Turner Valley used in these syntheses were significantly modified in the light of new data.

6. Thrusts and folds in the external Western Alps – the influence of inherited stratigraphic and structural heterogeneities

The Jura and Subalpine chains of SE France (Fig. 14) form a Miocene-aged fold-thrust system on the outer margin of the Western Alps (e.g. Doudoux et al., 1982; Bayer et al., 1986; Butler, 1991). Deformation involves a Mesozoic succession, overlain by Tertiary sediments chiefly constituting the ancestral foredeep basin fill. The Mesozoic strata show significant lateral variations in facies and thickness that are reflected in a diversity of structural styles (e.g. Ramsay, 1963; Charollais et al., 1996; Deville and Chauvière, 2000). Here we focus on the eastern Jura hills and adjacent Subalpine ranges of the Bauges and the Bornes-Aravis (Fig. 14). Surface relief of nearly 3km and an array of deeply incised valley transects, provide excellent map control for the structural geometries, with additional subsurface control provided by a regional deep seismic profile (ECORS-CROP; Bayer et al., 1986), further low-quality 2D seismic lines (e.g. Deville and Chauvière, 2000), various hydrocarbon exploration wells and an array of shallow hydrological boreholes.

The structure of the Bauges and Bornes-Aravis ranges and their relationships to the Jura have a number of interpretations (Butler, 1991; Charollais et al., 1996; Beck et al., 1998; Deville and Sassi, 2005: Fig. 15). Folds in the Jura are generally interpreted as being harmonic, involving stacked Jurassic to mid-Cretaceous platform carbonates, so that the structure of the youngest platform carbonates can serve as an interpretive guide construction of cross-sections into the subsurface. Interpretations also generally show these folds as detached just above the Palaeozoic basement (see also Deville and Chauvière, 2000).

Similar consensus exists on the general structure of the Subalpine chains, which lie to the east of the Jura fold belt (Fig. 15). The eastern part of the Subalps lies above a west-dipping monocline of a basement-cored fold - the so-called "external Belledonne massif" (Fig. 14). This massif is generally considered to form a hangingwall anticline to a master thrust (the Basal Belledonne thrust) at depth, although some authors show arrays of thrusts to imbricate basement at its leading edge (e.g. Fig. 15b, d, e). The Subalpine chains lie ahead of this basement-cored anticline and are dominated at outcrop by the cliff-forming Urgonian platform carbonates (Hauterivian-Barremian). Although general agreement exists about the structure defined by this formation through the Subalps, interpretations differ significantly about the structure at depth. The Mesozoic stratigraphic succession is expanded compared with that of the Jura, containing platform carbonate units of several hundred metres thickness separated by important shale-dominated intervals (Fig. 14b). Some authors (e.g. Guellec et al., 1990: Fig. 15b) have considered the succession to deform by thrusts that link up to form duplexes. Others show thrusts terminating into folds (e.g. Butler, 1991; Fig. 15c). Both of these interpretations infer disharmonic behaviour between the Urgonian and the underlying Tithonian limestone, which also represents a major competent layer. Thick lower Cretaceous shales are inferred to decouple the two competent limestone levels (e.g. Butler, 1992; Ferrill and Groshong, 1993). The versions shown in Fig. 15 (b,c) were both constructed before the availability of well-control in the Bornes area of the Subalpine chains. The Brizon well shows significant thickening of the Tithonian limestone (Fig. 16c) that Charollais et al. (1996) interpret by a combination of thrusting and folding (Fig. 15a).

Could the structural complexity encountered in the Brizon well (Fig. 16c) have been forecasted before drilling? Deformed Tithonian sections are found at the southern and northern extremities of the area (Fig. 14). In the Arve valley (Fig. 16a), the formation is deformed into a recumbent NW-facing fold pair, and further repeated in an overlying thrust slice. In contrast in the southern Bornes area (Fig. 16b), the Tithonian is repeated by imbricate thrusts. Thus, the outcrop offers competing structural styles that, while not providing definitive guides to the subsurface, at least illustrate that some significant recognition of uncertainty should be carried in the interpretations.

The various interpretations of structural style in the Bornes-Aravis area (Fig. 15ba-c) show differences in the harmony of deformation between the Tithonian and Urgonian limestones. Two sections through the Bornes-Aravis area illustrate the issue (Fig. 17). The Arve valley section (Fig. 17a) is largely informed by direct outcrop observation, exposed on valley-sides that exceed 2.5 km high. For much of the section, the Urgonian limestone forms a near-continuous beam, with significant thrust-related deformation limited to two locations (Balme and Flaine on Fig. 17a). Note the disharmonic deformation of the underlying Tithonian limestone layer under the Flaine segment (see also Fig. 16a). The displacements represented by the thrust and asymmetric fold pair in the Tithonian unit presumably relay into deformation in the Urgonian limestone via detachment and shearing within the intervening lower Cretaceous shales (Butler, 1992).

A complementary section (Fig. 17b) through the Subalps along the Bornes gorge (Fig. 14) again shows the geometry of the Urgonian limestone layer well-constrained by outcrop. The geometry of the Tithonian layer is less certain, but is constrained by outcrop in the ESE and by the Brizon well in the west. Top basement is as determined from the ECORS-CROP seismic reflection profile (Bayer et al., 1986), projected from c 15 km off section. This interpretation indicates that the multilayer deformed by combinations of folding and localized thrusting. Older Jurassic units are considered to have thickened at depth to balance broadly with shortening in the Cretaceous rocks above. The Brizon well shows that Jurassic rocks are stacked at depth without encountering Urgonian limestone. Therefore, the frontal thrust of the Bornes Subalps, that emerges into the Miocene basin, must have relatively little displacement. In this regard, many previous interpretations are invalidated (e.g. Fig. 15 b, c). Displacements emanating from the Basal Belledonne thrust must therefore pass forward along a regional detachment at the base of the Mesozoic cover out beneath the Jura.

The outcrop in the northern Subalpine chains presented here, and illustrated with cross-sections (Fig. 17), indicates that the Mesozoic succession deformed principally by buckle folding (e.g. Ramsay, 1989). The disharmony between the Urgonian and Tithonian limestones, together with the underlying Bathonian limestone (not considered here), was reported by Butler (1992). Ferrill and Groshong (1993) also recognise the importance of competency contrasts in creating a mechanical stratigraphy within the northern Subalpine chains. Smart et al. (2014) take this further, populating the Mesozoic stratigraphy with mechanical properties to model the stress and strain history of the Urgonian limestone. However, they developed this analysis from a kinematic restoration and were not concerned with structural variations with depth in the stratigraphic pile. The tendency for disharmonic folding presumably reflects the mechanical properties of the Mesozoic multilayer, with the thick shale units that separate the competent layers of Tithonian and Urgonian limestone permitting folds to amplify, at least initially, as single layers. Disharmonic buckle folding is investigated using finite element models by von Tscharner et al. (2016) for the equivalent structures and stratigraphy some 100 km along strike in the Swiss Alps.

The Urgonian limestone is cut by thrusts and these are not simply located in overturned forelimbs as might be expected for fault-propagation folding (c.f. Smart et al., 2012). Perhaps there are other controls on thrust localisation. The NW segment of the Arve valley section (Fig 17a) contains two thrusts that carry hangingwall anticlines of Urgonian limestone (Fig. 18a). Pre-dating the thrusts are normal faults (Fig. 18b; Welbon, 1988) that can be identified because of the differing stratigraphic thicknesses of upper Cretaceous strata preserved beneath a major (sub-Eocene) unconformity. The pre-thrusting relationship is apparent on restored sections through the thrusts (Fig. 18c). The co-occurrence of (post

Eocene) thrusts with (pre-Eocene) normal faults has been identified repeatedly through the region (Welbon and Butler, 1992).

We infer that thrusting within the Urgonian beam localises on pre-existing structures but that otherwise it tended to buckle during layer-contractional deformation. The structures of the NW Subalpine chains serve to illustrate the importance of "mechanical stratigraphy" and of pre-existing faults as influences on thrust localisation, and hence, the geometry of fold-thrust complexes. The implication is that the heterogeneities within the stratigraphic template within which thrusts develop are fundamentally important in the structural evolution.

7. Interactions between folding and thrusting – some lessons

Comparisons of structural styles between thrust belts in North America and those in Europe have been controversial (e.g. Ramsay and Huber, 1987). Nevertheless they share both similarities and differences. Our examples from the Canadian Rockies and the outer French Alps show detachment of the sedimentary cover from the underlying basement, as emphasised by Boyer and Elliott (1982). Thrusts splay upwards through the cover and link into folds. However, the forms of these folds are different. The well-layered Mississippian carbonates in the Alberta segment of the Rockies form characteristically kink-band fold shapes (Fig. 19f) that are widely interpreted to have developed by flexural slip. In contrast, the folds in the Cretaceous Urgonian limestones of the Alps are characterised by rounded fold hinges (Fig. 19a). Yet, these folding styles are not ubiquitous in either of our examples. The Cretaceous clastics in the Alberta foothills deform with short wavelength folding (Fig. 19e). Likewise the older Jurassic strata in the Alps form tight, short wavelength folds compared with those in the Urgonian (Fig. 19b). Thus in both settings, the structural style changes coincide with changes in the stratigraphic template (Fig. 19c, d), presumably reflecting lateral variations in mechanical properties.

In the case of the Canadian Rockies the stratigraphic sequence of the Mesozoic and Paleozoic becomes more shale-rich to the north and the mechanically stronger units correspondingly less dominant (Fig. 11).

Consequently, the structural style changes with these variations in stratigraphy, such that in the south the structure is dominated by large-displacement thrusts while in the north it is characterised by increased folding (Fig. 10).

These simple comparisons reveal that the idealized models of Figure 4 capture just a narrow range of fold-thrust relationships. Fold styles may relate to the mechanical properties of the stratigraphic multilayer that has been deformed - and this realisation has underpinned many attempts to develop mechanical approaches for fold-thrust systems rather than rely on purely kinematic descriptions as in Figure 4. Depth-constant layer-parallel shortening is a general kinematic boundary condition, required for section balancing, that can also underpin mechanical models (e.g. Buiter et al., 2006). In this way, there may be a continuum of deformation style, depending on layer rheologies, that spans a fully localised, discrete thrust through to vertically homogeneous distributed strain (e.g. Geiser, 1988; Butler, 1992). With the development of finite element methods and, critically, better meshing tools, mechanical models are now beginning to simulate the range of localisation behaviours seen in outcrop (e.g., Fig. 5) and interpreted in cross sections (e.g. Smart et al., 2012; Bauville and Schmalholz, 2015). Jacquet et al. (2014) show that in mechanical multilayers where stiffer stratigraphic formations are encased in thick, lower viscosity units, buckling has a strong tendency to occur, rather than simple thrust localisation. We develop this argument further elsewhere (Butler et al., in review). In competent-incompetent multi-layer sequences a significant range of distinct structural relationships can develop depending on the relative amplification of buckle folds and thrust growth. In essence these structures represent distributed ramps and can explain many otherwise enigmatic complexities in forelimb regions elsewhere (e.g. De Donatis and Mazzoli, 1994). The challenge then is to determine the organisation of the multilayer when attempting to understand the interplay of thrusts and folds during their development.

8. The role of basement – insights from Papua New Guinea

Interpretations of fold-thrust complexes are strongly dependent upon the choice of underlying detachment levels, and the role of basement (e.g. Coward, 1983; Butler and Mazzoli, 2006). The forelimbs of folds in foreland thrust belts that verge towards the foreland basin can be geometrically identical to frontal monoclines resulting from basement-involved faulting (Fig. 20). Thus, fold structures resulting from the contractional reactivation of pre-existing normal faults (tectonic inversion) can be difficult to distinguish from those simply due to folding above detachments (see Cooper and Warren, 2010, for numerous examples). Deep-rooting fault interpretations include range-bounding structures such as on the edge of the Wind River Uplift in Wyoming (Weil and Yonkee, 2012). The interpretation challenges of discriminating between detachment and deep-rooting thrusts are discussed by several review papers (e.g. Coward, 1994; Butler et al., 2006) and underpin considerations of large-scale orogenic structure (e.g. McQuarrie, 2004).

Where basement-rooting faults have relatively small contractional displacements, forelimb geometry can be used to derive several non-unique interpretations of the underlying fault geometry (Fig. 20). The thin-skinned model (Fig. 20b) maximizes shortening whilst the thick-skinned fault solution (Fig. 20c) minimizes shortening (see Coward, 1994; Tozer et al., 2002). The initial key to determining the most valid interpretation is whether the backlimb of the fold returns to regional as this constrains the possible combinations of the depth to detachment and the amount of shortening that created the fold structure. However, to identify a unique solution requires data about the stratigraphic section involved in the hangingwall of the structure. From a petroleum exploration perspective, the relevance of this is that the thin-skinned model could potentially not involve the reservoir section in the structure depending on the stratigraphic position of the upper detachment. The challenges involved in correctly locating the forelimb and crest of the structure are however similar in both models.

Exploration in the fold-thrust belt of central Papua New Guinea exemplifies how interpretations for the extent of basement involvement have evolved through time (Fig. 21). They are thoroughly documented by Hill et al. (2004, 2008, 2010). Exploration of the Papuan Fold Belt began in the 1950s by drilling of exposed anticlines based on surface geology alone, unconstrained by geophysical data (Hill et al., 2008). These blind drilling programmes led to early interpretations for the subsurface structure of the fold-thrust belt. The resultant structural model was one of gravity sliding along a shallow detachment, away from basement uplifts to the north-east of the fold belt (e.g. Smith, 1965; Findlay, 1974). The fault-bend fold model established in the Canadian Rockies was then applied to the southern Papuan Fold Belt (also known as the Aure Belt) by Hobson (1986), who developed a thin-skinned model where shortening in the fold belt was related to regional tectonic compression rather than gravity sliding (Fig. 21a).

As hydrocarbon exploration accelerated in the Papuan Fold Belt, a greater range of data was acquired that led to new structural models proposed for the fold-thrust belt. Regional cross sections by Hill (1991) show widely-spaced basement-normal faults reactivated as large-scale thrusts (Fig. 21b), below coupled thin-skinned deformation in the overlying Mesozoic sequence (Fig. 21b). Buchanan and Warburton (1996) proposed a much greater degree of basement-involvement, partially inferred using a combination of improved seismic imaging and wells encountering thrusts with much smaller displacements than would be expected from thin-skinned models. In their model, Buchanan and Warburton (1996) suggested that most of the shortening is accommodated by inverted basement-normal faults (Fig. 21c). Faults detach at a mid-crustal level and branch at shallower depths to form closely-spaced thrusts at the surface. The models of Hill (1991) and Buchanan and Warburton (1996) have very different implications for shortening across the fold belt. Hill's (1991) model infers low-angle thrusts, some of which accumulate more than 10 km of displacement (Fig. 21b), summing to tens of kilometres of shortening. In contrast, the model of Buchanan and Warburton (1996) suggests much higher angle faults with displacements of a few hundred metres to two kilometres in the Mesozoic sequence (Fig. 21c), totalling to much less shortening than Hill's (1991) cross section.

The two models (Fig. 21b, Hill, 1991; Fig. 21c, Buchanan and Warburton, 1996) also have very different implications for the petroleum system. The two models have different stratigraphic templates (see Fig. 21d for a stratigraphic column) and so potentially make different forecasts for the distribution of source rocks, reservoirs and seal risk. The two models also have different burial histories, so different timings for maturation, charge, and possibly the formation of key trapping structures. The regional detachment in the lower Mesozoic sequence of Hill's (1991) model could also represent a drilling risk, as compared to the deeper detachment in Buchanan and Warburton's (1996) model.

Although seismic imaging of the Papuan Fold Belt has improved greatly since exploration began in the 1950's, the geometries of folds and thrusts in the subsurface are not fully resolved. Seismic data quality is inhibited by heavily karstified Miocene limestones at the surface, resulting in variable seismic image quality and poor resolution of structures at depth. As a result, significant uncertainty exists for structural style, with on-going debate as to the extent of basement involvement in the Papuan Fold Belt. An example is the Gobe Anticline Fig. 22), which has been interpreted to have formed both from basement-fault inversion and thin-skinned deformation above a Lower Mesozoic detachment; seismic imaging is unable to distinguish between the two models. Although recent interpretations (e.g. Hill et al., 2008; 2010) generally imply basement inversion beneath the folded and imbricated strata above (e.g. Fig. 22c), it is not clearly imaged. It is difficult to acquire seismic reflection data across rugged terrain and image processing demands assumptions of subsurface structure and seismic velocities. These are general issues in continental fold-and thrust belts. Thus, inadequate sub-surface control, especially concerning the structure of the top of basement, is a general problem and a source of significant interpretation uncertainty

9. Discussion – embracing uncertainty in the interpretation of fold-thrust complexes

Structural geometry in fold-thrust systems has been assessed here using examples from the Canadian Rockies, the Western Alps and Papua New Guinea. These examples are necessarily limited in number but they are, in our experience, typical of systems elsewhere in the World. They highlight fold-thrust complexes developed in different stratigraphies with their contrasting mechanical properties together with the role of inherited structures. Collectively these examples increase the range of possible structural geometries that lie significantly outside those portrayed in idealised fold-thrust models. We have not considered other aspects, especially in the relationships between localised thrusts and widely distributed strain. This is likely to be important for deformation in highly porous strata, in muddy systems – as in the development of slate belts (e.g. Coward and Siddans, 1979) - or in crustal scale systems (e.g. Butler and Mazzoli, 2006). Nevertheless, a series of general points arise from our study.

The timeline of fold-thrust research prepared by Brandes and Tanner (2014) cites studies that are essentially theoretical: Researchers that use them cite only outcrop or well-constrained subsurface examples that conform rather than challenge aspects of the idealised models shown on Figure 4. The application of the models has become commonplace, arguably because they lent themselves to the creation of algorithms and software for balancing and forward modeling fold-thrust systems that have become widely adopted (e.g. Groshong et al., 2012). Consequently a body of highly cited literature has evolved that is far-removed from the complexity of natural systems. In an earlier review, Thorbjornsen and Dunne (1997) illustrate the necessity of challenging these models against real examples. Selective use of outcrop and subsurface examples has introduced significant bias in thrust system literature.

Historically, different fold-thrust belts were interpreted in isolation, as noted in section 2 here (see also Frizon de Lamotte and Buil, 2002). Consequently, the approaches and structural styles of the interpretations for different areas may be the consequence of the groups and individuals involved, their exposure to different models, ideas and differences in the types of data available (e.g. well bores in the Rockies). The widespread application of idealized structural geometries of recent years may suggest that many subsurface interpretations are as much a consequence of societal and environmental influences with their associated anchors and biases as they are products of the available data.

The idealized models of fault-propagation and trishear folding are necessarily simple when depicted in their idealized form (Fig. 4), and incorporated into modelling software. They show a single thrust ramping up from a deeper detachment so that thrust-related folds contain just a single fault segment in their forelimbs. However, as they become available, high-resolution 3D seismic data are revealing much more complex fold-thrust relationships with multiple fault strands cutting fold forelimbs (e.g. Totake et al., 2018). Our observations, particularly of deformation in stratigraphic multi-layers, suggest that multiple thrusts are common in forelimbs (see also Ferrill et al., 2016). Improved imaging does not necessarily reduce the number of competing interpretations of structural complexity in fold forelimbs (e.g. Torvela and Bond, 2010) but can identify sites of greater interpretation uncertainty. These uncertainties are obscured if interpretations are anchored by the idealized fold-thrust models, as commonly required when forward-modelling using existing software. Although improvements and refinements are being made to software algorithms (e.g. Cardozo and Oakley, in press), forcing interpretations to conform to idealized models may be misleading. While the forward models might be considered to validate structural interpretations, in practice they may engender false optimism in the reliability of an interpretation.

The use of single deterministic models for interpreting thrust-related folds where data only partially constrain geometry, which is typically the case, is indeed a high-risk strategy (Bond et al., 2008), as exemplified in our first case study for the Niger Delta (Kostenko et al., 2008). The use of multiple working models (e.g. Chamberlin, 1965) as developed and discussed by Bond et al. (2008) and Bond (2015) could allow faster generation of new models as multiple models are verified, or not, against newly acquired data. Mechanisms to determine optimal data acquisition, e.g. the position of a new borehole, to differentiate between possible 3D geological models are now also being proposed (e.g., Wellmann and Regenauer-Lieb, 2012) and could save significant time and money in the onshore exploration of fold-thrust belts. Embracing uncertainty, a range of possible models (structural styles), and mechanisms to manage model iterations in the light of new data seem essential for interpretation, and exploration, of sub-surface fold-thrust belts.

So, should we stop using idealised structural models? They do often prove useful in areas of poor or sparse subsurface information, for example, the interpretations of seismic imagery of the Rockies and the Papuan fold belt, provide a framework for building a working cross-section (e.g. Hill et al., 2008).

Characterised by Dahlstrom (1969) as the "foothills family of structures", idealised structural styles are useful for constructing regional cross-sections, which are necessary to understand large-scale tectonic processes (e.g. Butler, 2013, and references therein). The idealised models provide a geometric or kinematically consistent framework. They also obey the simple rules of mass balance and area or line-length conservation. They are possible, but the question is whether they are probable for a particular study and its presently-known geology.

When building interpretations of the subsurface it is clearly important to recognise the inherent uncertainties. Focussing solely on idealized structural geometries obscures uncertainties. In part, they can be assessed by addressing the quality and reliability of seismic images, both in onshore and offshore data, especially the seismic migration effects for the fold forelimbs. Interpreters can ask whether the mechanics of the deformation processes invoked are appropriate for the situation.

Analogues from field outcrops provide insight into the potential complexity and uncertainty in predictions of structural geometry. The term 'insight' is important because no single analogue can provide a robust deterministic solution. Uniqueness in both development of the structures and finally geometry must be acknowledged given the contributing factors such as: mechanical stratigraphy, stress orientation and magnitude, and the heterogeneity within sedimentary units from deposition and composition. For example, folds and thrusts in the western Alps seem to have localized at pre-existing heterogeneities (e.g., pre-existing normal faults) that acted as perturbations in ideal, layered materials. Using a range of relevant analogues to provide insight allows an appreciation of the likely possibilities and range in uncertainty for the structural interpretation and its implications.

Uncertainty is not simply an issue for structural geology. The seismic images used to resolve subsurface structure are themselves uncertain, where data processing requires decisions on seismic velocity structure, itself dependant on a geological model of the subsurface. Many thrust belts are only imaged in wide-spaced or solitary 2D profiles. But our opening example from deepwater Nigeria illustrates that 3D seismic volumes can also have these uncertainties.

Therefore structural interpretations should be used to update models of seismic velocity, the seismic data reprocessed and the structural interpretations updated accordingly. This iterative approach is of course the ideal. It is commonplace in some commercial settings but very rare in academe: Most published examples of subsurface structure in thrust belts arise from interpretations of seismic data that are made externally available from the organisations that own them. This decoupling of seismic data processing from the interpretation is clearly unhelpful for us as a community and inhibits appropriate testing of geometric models of fold-thrust complexes. And it engenders an over-optimistic assessment of the viability of specific interpretations and of idealised structures in general.

Producing only single deterministic geometries for fold-thrust structures (often based on "end-member" conceptual models) has been unfortunate, as these lead to over-reliance on a single solution that is often uncertain and hence high risk. We make the following recommendations for improving understanding of fold-thrust systems and for developing interpretations of subsurface structure:

1. Better documentation of workflows, specifically when things go wrong, would be a useful learning resource. There are too few examples in the literature of model failures; and no clear picture of how many sub-surface structures actually correspond to end member models, or if there is methodical documentation of the characteristics of those that don't.

2. Multiple interpretations and models are required, rather than the historical bias of single deterministic solutions. Of course the different solutions should be demonstrably restorable to show at least geometric viability. But the restoration approaches need to be flexible enough to deal with distributed heterogeneous strain.

3. The likelihood of competing interpretations being correct could be assessed by using example-specific information not used in section construction – such as predicted strain patterns, histories of growth rate, diagenesis and fracture.

4. If geometric uncertainty is high for a specific subsurface structure, drilling directly to target a reservoir may be high risk with the initial well being

unsuccessful. Well-designs should include sufficient flexibility to side-track so that subsurface interpretations can be refined by integrating successive well-data with structural models.

5. If the objective is to forecast small-scale (e.g. fracture) damage, a holistic view of the deformation (distributed strain, buckling together with localised faulting) is necessary.

6. As with most techniques for cross-section construction, the idealised thrusting models rely on a broad assumption of structural homogeneity. Disharmonic folding invalidates most construct techniques (e.g. Ramsay and Huber, 1987). So to assess risk we should assess the probability of disharmonic deformation in specific stratigraphic templates and in a range of tectonic settings.

10. Conclusions

Recent research on the structure of fold-thrust systems is strongly influenced by the adoption of a narrow range of idealized geometries and related kinematic models. These do not represent the geometric diversity of fold-thrust systems and the range in structural styles, whether observed in outcrop or proposed historically.

Natural outcrop examples, and subsurface interpretations tested by drilling, display a spectrum of structural geometries that reflect a range of relationships between folds and thrusts that do not conform to these idealized models.

Variations in the structure, both within individual fold-thrust belts and between different ones, can be related to variations in the pre-existing stratigraphic template and its mechanical behavior.

Determining the role of basement and the importance of detachment levels in the overlying sedimentary sequence is commonly problematic, even with seismic reflection data.

The propensity for disharmonic deformation, which greatly increases interpretation uncertainty for cross-section construction, is tentatively related to the nature of the stratigraphic multilayer involved in the structures. Widely spaced alternations of thick competent layers separated by incompetent units (e.g. Subalpine chains, Rockies of north-eastern British Columbia) appear more susceptible to structural disharmony compared to closely-layered successions (e.g., Alberta Rockies).

While the application of a narrow range of idealized structural styles can facilitate single realizations of cross-sections, a greater range of geometries are needed to describe fold-thrust systems and from these descriptions develop more representative mechanical understanding of these systems.

The failure to utilize an intellectual framework rooted in understanding the important role of uncertainty engenders an over-optimistic assessment of the interpretation of subsurface structure. This had led to many surprises during exploration drilling. Own the uncertainty – manage the risk.

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References

Bally, A. W., Gordy, P. L., Stewart, G. A., 1966. Structure, seismic data and orogenic evolution of southern Canadian Rocky Mountains. Bull. Can. Pet. Geol. 14, 337 – 381.

Barss, D. L., Montandon, F. A., 1981. Sukunka-Bullmoose gas fields: models for a developing trend in the southern Foothills of northeast British Columbia. Bull. Can. Petrol. Geol. 29, 293 – 333.

Bauville, A., Schmalholz, S.M., 2015. Transition from thin- to thick-skinned tectonics and consequences for nappe formation: Numerical simulations and applications to the Helvetic nappe system, Switzerland. Tectonophysics 665, 101-117.

Bayer, R., Cazea, M., Dal Piaz, G.V., Damotte, B., Elter, G., Gosso, G., Alfred, H., Lanza, R., Lombardo, B., Mugnier, J-L., Nicolas, A., Nicolich, R., Polino, R., Roure, F., Sacchi, R., Scarascia, S., Tobacco, I., Tapponnier, P., Tardy, M., Taylor, M., Thouvenot, F., Toreilles, G., Villien, A., 1987. Premiers résultats de la traversée des Alpes occidentales par sismique reflexion vertical (Programme ECORS-CROP). C. R. Acad. Sci. Paris 305, 1461-1470.

Beck C., Deville É., Blanc É., Philippe Y., Tardy M., 1998. Horizontal shortening control of Middle Miocene marine siliciclastic sedimentation in the southern terminaison of the Savoy Molasse Basin (northwestern Alps, southern Jura): combined surface and subsurface data. Geol. Soc. Lond. Spec. Publ. 134, 263–278.

Bond, C.E., 2015. Uncertainty in structural interpretation: Lessons to be learnt. J. Struct. Geol. 74, 185-200.

Bond, C.E., Shipton, Z.K., Gibbs, A.D., Jones, S., 2008. Structural models: optimizing risk analysis by understanding conceptual uncertainty. First Break 26(6), 65-71.

Boyer, S.E., Elliott, D., 1982. Thrust systems. Bull. Am. Assoc. Petrol. Geol. 66, 1196-1230.

Brandes, C., Tanner, D.C., 2014. Fault-related folding: A review of kinematic models and their application. Earth Sci. Rev. 138, 352-370.

Buchanan, P. G., Warburton, J., 1996. The Influence of Pre-existing Basin Architecture in the Development of the Papuan Fold and Thrust Belt: Implications for Petroleum Prospectivity. In: Buchanan, P. G. (Ed.), Petroleum Exploration, Development and Production in Papua New Guinea. Proceedings of the Third PNG Petroleum Convention, Port Moresby, 89-109.

Buiter, S.J.H., Babeyko, A.Y., Ellis, S., Gerya, T.V., Kaus, B.J.P., Kellner, A., Schreurs, G., Yamada, Y., 2006. The numerical sandbox: comparison of model results for a shortening and an extension experiment. Geol. Soc. Lond. Spec. Publ. 253, 29-64.

Butler, R.W.H., 1991. Hydrocarbon maturation, migration and thrust sheet loading in the Western Alpine foreland thrust belt. Geol. Soc. Lond. Spec. Publ. 59, 227-244.

Butler, R.W.H., 1992. Evolution of Alpine fold-thrust complexes: a linked kinematic approach. In: Mitra, S. & Fisher, G. (Eds.), Structural geology of fold and thrust belts. Johns Hopkins University Press, Baltimore, 29-44.

Butler, R.W.H., 2013. Area balancing as a test of models for the deep structure of mountain belts, with specific reference to the Alps. J. Struct. Geol. 52, 2-16.

Butler, R.W.H., Mazzoli, S. 2006. Styles of continental contraction: a review and introduction. Spec. Pap. Geol. Soc. Am. 414, 1-11.

Butler, R.W.H., Tavarnelli, E., Grasso, M., 2006. Structural inheritance in mountain belts: an Alpine-Apennine perspective. J. Struct. Geol. 28, 1893-1908.

Butler, R.W.H., Bond, C.E., Cooper, M.A., Watkins, H.M. (in review). Fold-thrust structures – where have all the buckles gone? Geol. Soc. Lond. Spec. Publ.

Buxtorf, A., 1916. Prognosen und Befunde beim Hauensteinbasis- und Grenchenbergtunnel und die Bedeutung der letzteren für die Geologie des Juragebirges. Verh. Naturforsch. Ges. Basel 27, 185-254.

Cadell, H. M., 1888. Experimental researches in mountain building. Trans. Roy. Soc. London 35, 337–357.

Cardozo, N., Oakley, D., in press. Inverse modeling for possible rather than unique solutions. J. Struct. Geol.

Chamberlin, T.C., 1965. The method of multiple working hypotheses. Science 148 (3671), 754-759.

Charollais, J., Davaud, E., Jamet, M., 1996. Evolution du bord oriental de la plate-forme jurassienne entre le Jurassique supérieur et l'Oligocène: modèle base sur trois forages pétroliers (Haute Savoie). Géologie de la France 1, 25-42.

Contreras, J., Suter, M., 1990. Kinematic modeling of cross-sectional deformation sequences by computer simulation. J. Geophys. Res. 95, 21913-21929.

Cook, F. A., Albaugh, D. S., Brown, L. D., Kaufman, S., Oliver, J. E. & Hatcher, R. D. JR 1979. Thin-skinned tectonics in the crystalline southern Appalachians: COCORP seismic reflection profiling of the Blue Ridge and Piedmont. Geology 7, 563–567.

Cooley, M.A, Price, R.A, Dixon, J.M., Kyser T.K., 2011. Along-strike variations and internal details of chevron-style, flexural-slip thrust-propagation folds within the southern Livingstone Range anticlinorium, a paleohydrocarbon reservoir in southern Alberta Foothills, Canada. Bull. Am. Assoc. Petrol. Geol. 95, 1821–1849.

Cooper, M.A, 1996. Passive-roof duplexes, and pseudo-passive-roof duplexes at mountain fronts: a review. Bull. Can. Soc. Pet. Geol. 44, 410-421.

Cooper, M, A., Brealey, C., Fermor, P., Green, R., Morrison, M, 2004. Structural models of subsurface thrust-related folds in the foothills of British Columbia; case studies of sidetracked sas wells. Mem. Am. Assoc. Petrol. Geol. 82, 579-597.

Cooper, M., Warren, M. J., 2010, The Geometric Characteristics, Genesis and Petroleum Significance of Inversion Structures. Geol. Soc. Lond. Spec. Publ. 335, 827-846.

Coward, M. P., 1983. Thrust tectonics, thin skinned or thick skinned, and the continuation of thrusts to deep in the crust. J. Struct. Geol. 5, 113–123.

Coward, M.P., 1994. Inversion tectonics. In: Hancock, P.L. (Ed.), Continental deformation. Pergamon Press, Oxford, 289-304.

Coward, M.P., Siddans, A.W.B., 1979. The tectonic evolution of the Welsh Caledonides. Geol. Soc. Lond. Spec. Publ. 8, 187-198.

Dahlstrom, C. D. A., 1969. Balanced cross-sections. Can. J. Earth Sci. 6, 743-757.

Dahlstrom, C. D. A., 1970. Structural geology in the eastern margin of the Canadian Rocky Mountains. Bull. Can. Petrol. Geol. 18, 332 – 406.

De Donatis, M., Mazzoli, S., 1994. Kinematic evolution of thrust related structures in the Umbra-Romagnan parautochthon (northern Apennines, Italy). Terra Nova 6, 563-574.

Deville, E. & Chauvière, W., 2000. Thrust tectonics at the front of the western Alps: constraints provided by the processing of seismic reflection data along the Chambéry transect. C. R. Acad. Sci. Paris, Earth Planet. Sci. 331, 725-732.

Deville, E., Sassi, W., 2005. Contrasting thermal evolution of thrust systems: An analytical and modeling approach in the front of the western Alps. Bull. Am. Assoc. Petrol. Geol. 90, 887-907.

Doudoux B., Mercier de Lepinay B., Tardy M., 1982. Une interpretation nouvelle de la structure des massifs subalpins savoyards (Alpes occidentales): nappes de charriage oligocènes et déformations superposées. C.R. Acad. Sci. Paris, sII 295, 63–68.

Douglas, R. J. W., 1950. Callum Creek, Langford Creek and Gap map-areas, Alberta. Mem. Geol. Surv Canada 255, pp. 124.

Douglas, R. J. W., 1958. Mount Head map-area, Alberta. Mem. Geol. Surv Canada 291, pp. 24.

Eisenstadt, G., De Paor, D., 1987. Alternative model of thrust-fault propagation. Geology 15, 630-633.

Epard, J-L., Groshong, RH., 1993. Excess area and depth to detachment. Bull. Am. Assoc. Petrol. Geol. 77, 1291-1302.

Erslev, E., 1991. Trishear fault-propagation folding. Geology 19, 617-620.

Fallot, P., 1949. Les chevauchements intercutanés de Roya (A.-M). Ann Hebert et Haug: Trav. Lab. Géol. Fac. Sci., Université de Paris 7, 161-170.

Ferrill, D.A., 1988. Use of fault cut-offs and bed travel distance in balanced cross-sections: Discussion 2. J. Struct. Geol. 10, 313–314.

Ferrill, D.A., Groshong, R.H., 1993. Kinematic model for the curvature of the northern Subalpine Chain, France. J. Struct. Geol.15, 523-541.

Ferrill, D.A., Morris, A.P., Wigginton, S.S., Smart, K.J., McGinnis, R.N., Lehrmann, D., 2016. Deciphering thrust fault nucleation and propagation and the importance of footwall synclines. J. Struct. Geol. 85, 1-11.

Ferrill, D.A., Morris, A.P., McGinnis, R.N., Smart, K.J., Wigginton, S.S., Hill, N.J., 2017. Mechanical stratigraphy and normal faulting. J. Struct. Geol. 94, 275-302.

Findlay, A. L., 1974. The structure of the foothills south of the Kubor Range, Papua New Guinea. J. Aus. Petrol. Prod. Exp. Assoc. 14, 1, 14–20.

Fox., F.G., 1959. Structure and accumulation of hydrocarbons in southern foothills, Alberta, Canada. Bull. Am. Assoc. Petrol. Geol. 43, 992- 1025.

Frizon de Lamotte, D., Buil, D., 2002. La question des relations entre failles et plis dans les zones externes des chaînes de montagnes. Ebauche d'une histoire des idées au cours du XX^{e} siècle. Comité français d'Histoire de la Géologie 3ème série, 16, 47-62.

Geiser, P.A., 1988. The role of kinematics in the construction and analysis of geological cross-sections in deformed terranes. Geol. Soc. Am. Spec. Pap. 222, 47-76.

Goguel, J., 1952. Traité de Tectonique. Masson et Cie, Paris, pp. 383.

Gordy, P.L., Frey, F.R. and Norris, D.K., 1977, Geological Guide for the CSPG 1977 Waterton- Glacier Park Field Conference. Can. Soc. Petrol. Geol., 93pp.

Graham, R.H., 1981. Gravity sliding in the Maritime Alps. Geol. Soc. Lond. Spec. Publ. 9, 335-352.

Groshong Jr, R., Bond, C., Gibbs, A., Ratcliff, R. Wiltschko, D., 2012. 'Preface: Structural balancing at the start of the 21st century: 100 years since Chamberlin'. *J. Struct. Geol. 41, 1-5.*

Guellec, S., Mugnier, J.L., Tardy, M., Roure, F., 1990. Neogene evolution of the western Alpine foreland in the light of Ecors data and balanced cross-section. In: Mem. Soc. Géol. France 156, 165–184.

Guth, P.L., 1988. Microcomputer-assisted drawing of geologic cross sections. Math. Geosci. 20, 991-1000.

Heidmann, J-C., Durand, J., Mallard, P., Ballard, J-F., Moron, J-M., 2017. Discovery of a Bolivian Foothills giant gas field: Incahausi. Mem. Am. Assoc. Petrol. Geol. 113, 153-164.

Heim, A., 1878. Untersuchungen u¨ber den Mechanismusder Gebirgsbildung. Benno Schwabe, Basel.

Hill, K. C., 1991. Structure of the Papuan Fold Belt, Papua New Guinea. Bull. Am. Assoc. Petrol. Geol. 75, 5, 857-872.

Hill, K.C., Keetley, J.T., Kendrick, R.D., Sutriyono, E., 2004. Structure and hydrocarbon potential of the New Guinea fold belt. Mem. Am. Assoc. Petrol. Geol. 82, 494-514.

Hill, K. C., Bradey, K., Iwanec, J., Wilson, N. & Lucas, K., 2008. Structural exploration in the Papua New Guinea Fold Belt. In: Blevin, J. E., Bradshaw, B. E. & Uruski, C. (Eds), Eastern Australasian Basins Symposium III. Spec. Publ. Aus. Petrol. Expl. Soc., 225–238.

Hill, K.C., Lucas, K., Bradey, K., 2010. Structural styles in the Papuan Fold Belt, Papua New Guinea: constraints from analogue modelling. Geol. Soc. Lond. Spec. Publ. 348, 33-56.

Hobson, D. M., 1986. A thin skinned model for the Papuan thrust belt and some implications for hydrocarbon exploration. J. Aus. Petrol. Prod. Exp. Assoc. 26, 214–224.

Hughes, A.N., Benesh, N.P., Shaw, J.H., 2014. Factors that control the development of fault-bend versus fault-propagation folds: Insights from mechanical models based on the discrete element method (DEM). J. Struct. Geol. 68, 121-141.

Jamison, W.R., 1987. Geometric analysis of fold development in overthrust terranes. J. Struct. Geol. 9, 207-219.

Jaquet, Y. Bauville, A. Schmalholz, S.M., 2014. Viscous overthrusting versus folding: 2-D quantitative modeling and its application to the Helvetic and Jura fold and thrust belts. J. Struct. Geol. 62, 25-37.

Jones, P. B., 1982. Oil and gas beneath east-dipping under- thrust faults in the Alberta Foothills. In: R. B. Powers (ed.) Studies of the Cordilleran Thrust Belt. Rocky Mountain Assoc. Geol., 61 – 74.

Kostenko, O.V., Naruk, S.J., Hack, W., Poupon, M., Meyer, H.J., Mora-Glukstad, M., Anowai, C., Mordi, M. 2008. Structural evaluation of column-height controls at a toe-thrust discovery, deep water Niger Delta. Bull. Am. Assoc. Petrol. Geol. 92, 1615–1638.

Langenberg, C.W., Beaton, A., Berhane, H., 2002. Regional evaluation of the coalbed methane potential of the Foothills/Mountains of Alberta (second edition); Alberta Energy and Utilities Board, EUB/AGS Earth Sciences Report 2002-05.

Laubscher, H.P., 1977. Fold development in the Jura. Tectonophysics 37, 337-362.

Link, T.A., Moore, P.D., 1934. Structure of Turner Valley gas and oil field, Alberta. Bull. Am. Assoc. Pet. Geol. 18, 1417-1453.

Link, T.A., 1949. Interpretations of foothills structures, Alberta, Canada. Bull. Am. Assoc. Petrol. Geol. 33, 1475-1501.

McClay, K.R., 1992. Glossary of thrust tectonics terms. In: McClay, K.R. (Ed.), Thrust Tectonics. Chapman & Hall, London, 419-433.

McMechan, M. E., Thompson, R. I., 1989. Structural style and history of the Rocky Mountain fold and thrust belt. In: Ricketts, B.D. (Ed.), Western Canada Sedimentary Basin: A case history. Can. Soc. Petrol. Geol., Calgary, 47 – 72.

McQuarrie, N., 2004. Crustal scale geometry of the Zagros fold-thrust belt, Iran. J. Struct. Geol. 26, 519-535.

Mitra, S., 1990, Fault-Propagation Folds: Geometry, kinematic evolution, and hydrocarbon Traps. Bull. Am. Assoc. Petrol. Geol. 74, 921-945.

Mitra, S., Namson, J., 1989. Equal-area balancing. Am. J. Sci. 289, 565-599.

Monger, J. W. H., Price, R.A., Tempelman-Kluit, D.J., 1982. Tectonic accretion and the origin of two major metamorphic and plutonic welts in the Canadian Cordillera. Geology 10, 70–75.

Morley, C.K., 1994. Fold-generated imbricates: examples from the Caledonides of Southern Norway. J. Struct. Geol. 16, 619-631.

Morley, C.K., 2009. Geometry of an oblique thrust fault zone in a deepwater fold belt from 3D seismic data. J. Struct. Geol. 31, 1540-1555.

Mossop, G.D., Shetsen, l. (compilers), 1994. Geological Atlas of the Western Canada Sedimentary Basin. Calgary. Can. Soc. Petrol. Geol. and Alberta Res. Council, 510p.

Newson, A. C., 2015. Imaging the overturned limb of a footwall syncline and its Impact on exploration in fold and thrust belts, Can. Soc. Explor. Geophys. Recorder 2015, 28-33.

Parish. M., 2015. Changes in structural style along the frontal Papuan fold belt from seismic imaging. Am. Assoc. Petrol. Geol., pp. 25.

Peach, B.N., Horne, J., Gunn, W., Clough, C.T., Hinxman, L.W., Teall, J.J.H., 1907. The geological structure of the N.W. Highlands of Scotland. Mem. Geol. Surv. U.K. pp. 623.

Perry, W.J., 1978. Sequential deformation in the central Appalachians. Am. J. Sci. 278, 518-542.

Pfiffner. O.A., 1985. Displacements along thrust faults. Eclog. Geol. Helv. 78, 313-333.

Price, R. A., E. W. Mountjoy, E.W., 1970. Geologic structure of the Canadian Rocky Mountains between Bow and Athabasca rivers, a progress report. Geol. Assoc. Can. Spec. Publ. 6, 7–25.

Ramsay, J. G., 1963. Stratigraphy, Structure and Metamorphism in the Western Alps. Proc. Geol. Ass. 74, 3, 357-391.

Ramsay, J.G., 1989. Fold and fault geometry in the western Helvetic nappes of Switzerland and France and its implications for the evolution of the arc of the western Alps. Geol. Soc. Lond. Spec. Publ 45, 33-45.

Ramsay, J.G., Huber, M.I., 1987. The techniques of modern structural geology. Volume 2: folds and fractures. Academic Press, London, 309-700.

Rawnsley, K., De Keijzer M., Wei, L., Bettembourg, S., Asyee, L W. Massaferro, J.-L., Swaby, P., Drysdale, D., Boettcher, D., 2007. Characterizing fracture and matrix heterogeneities in folded Devonian carbonate thrust sheets, Waterton tight gas fields, Western Canada. Geol. Soc. Lond. Spec. Publ. 270, 265-279.

Reimer, D.A., 1989. Chapter 6 – Mississippian Reservoirs. In Anderson, N. L., Hills, L. V., Cederwall, D. A. (Eds.), Geophysical atlas of western Canadian hydrocarbon pools, Publs. Can. Soc. Expl. Geophys. and Can. Soc. Petrol. Geol., Calgary, Canada, pp. 344.

Rich, J.L., 1934. Mechanics of low-angle overthrust faulting as illustrated by Cumberland thrust block, Virginia, Kentucky and Tennessee. Bull. Am. Assoc. Petrol. Geol. 18, 1584-1596.

Rodgers, J., 1950. Mechanics of Appalachian folding as illustrated by Sequatchie Anticline, Tennessee and Alabama. Bull. Am. Assoc. Petrol. Geol. 34, 672-681.

Rodgers, J., 1963. Mechanics of Appalachian foreland folding in Pennsylvania and West Virginia. Bull. Am. Assoc. Petrol. Geol. 47, 1527-1536.

Rottenfusser, B., Langenberg, W., Mandryk, G., Richardson, R., Fildes, B., Olic, J., Stewart, S., Eccles, R., Evans, C., Spelrem, M., Sprecher, B., Brulotte, M., Gentizis, T., Wynne, D., Yuan, L.P., 2002. Regional Evaluation of the Coalbed Methane Potential in the Plains and Foothills of Alberta, Stratigraphy and Rank Study (digital version). Alberta Energy and Utilities Board, Alberta Geological Survey, Spec. Rep. 7, pp. 248.

Shaw, J., Connors, C., Suppe, J. (Eds.), 2005. Seismic interpretation of contractional fault-related folds. Am. Assoc. Petrol. Geol. Studies in Geology 53, pp. 156.

Slawinski, M. A., Parkin, J,M., 1996. Migration of a multioffset VSP: a case study in NE British Columbia. Can. J. Expl. Geophys. 32, 104–112.

Smart, K.J., Ferrill, D.A., Morris, A.P., McGinnis, R.N., 2012. Geomechanical modeling of stress and strain evolution in contractional fault-related folding. Tectonophysics 576-577, 171-196.

Smith, J. G., 1965. Orogenesis in western Papua and New Guinea. Tectonophysics 2, 1–27.

Stockmal G. S., McMechan, M.E., Lebel, D., MacKay, P.A., 2001, Structural style and evolution of the triangle zone and external foothills, southwestern Alberta; implications for thin-skinned thrust-and-fold belt mechanics. Bull. Can. Pet. Geol. 49, 472–496.

Suppe, J., 1983. Geometry and kinematics of fault bend folding. Am. J. Sci. 283, 648-721.

Thompson, R. I., 1979. A structural interpretation across part of the northern Rocky Mountains, British Columbia, Canada. Can. J. Earth Sci. 16, 1228–1241

Thorbjornsen, K.L., Dunne, W. M., 1997. Origin of a thrust-related fold: geometric vs kinematic tests. J. Struct. Geol. 19, 303-319.

Torvela, T., Bond, C.E., 2011. Do experts use idealised structural models? Insights from a deepwater fold–thrust belt. J. Struct. Geol. 33, 51-58.

Totake, Y., Butler, R.W.H., Bond, C.E., Aziz, A., 2018. Analyzing structural variations along strike in a deep-water thrust belt. J. Struct. Geol. 108, 213-229.

Tozer, R.S.J, Butler, R.W.H., Corrado, S., 2002. Comparing thin- and thick-skinned thrust tectonic models of the Central Apennines, Italy. EGU Stephan Mueller Special Publications Series, 1, 181-194.

von Tscharner, M., Schmalholz, S.M., Epard, J-L., 2016. 3-D numerical models of viscous flow applied to fold nappes and the Rawil depression in the Helvetic nappe system (western Switzerland). J. Struct. Geol. 86, 32-46.

Walsh, J. J., Watterson, J., 1987. Analysis of the relationship between displacements and dimensions of faults. J. Struct. Geol. 10, 239-247.

Welbon, A.I., 1988. The influence of intrabasinal faults on the development of a linked thrust system. Geol. Rundschau 77, 11-24.

Welbon, A.I., Butler, R.W.H., 1992. Structural styles in thrust belts developed through rift basins: a view from the western Alps. In: Larsen, R.M. (Ed.) Structural and Tectonic Modelling and its Application to Petroleum Geology, Norwegian Petroleum Society Spec. Publ. 1, 469-479.

Weil, A.B. and Yonkee, W.A., 2012 Layer-parallel shortening across the Sevier fold-thrust belt and Laramide foreland of Wyoming: spatial and temporal evolution of a complex geodynamic system. Earth Planet. Sci. Lett. 357–358, 405–420.

Wellmann, J.F., Regenauer-Lieb, K., 2012. Uncertainties have a meaning: Information entropy as a quality measure for 3-D geological
models. Tectonophysics 526, 207-216.

Wheeler, J. O., McFeely, P., 1991. Tectonic assemblage map of the Canadian Cordillera and adjacent parts of the United States of America: Geol. Surv. Canada Map 1712A, scale 1:20,000,000.

Williams, G. D., Chapman, T. J., 1983. Strains developed in the hangingwalls of thrusts due to their slip/propagation rate: a dislocation model. J. Struct. Geol. 5,563-571.

Yielding, G., Freeman, B., Needham, D.T., 1997. Quantitative fault seal prediction. Bull. Am. Assoc. Petrol. Geol. 81, 897-917.

Figure captions

Fig. 1 – Kostenko et al.'s (2008) post-drill interpretation of the Alpha structure, deep-water Niger delta showing the folded forelimb. Note that their inferred continuity of stratigraphic units cross-cuts the structure of seismic reflectors indicating problems with the seismic imaging.

Fig. 2. Parish's (2015) interpretation of part of the frontal fold and thrust belt in Papua New Guinea, drawn after the side-tracking of the ADTA2 well. Note the complex and steep forelimb structure containing faults and bounded by two forelimb thrust splays (the Agogo and Mosa Thrusts). The steep forelimb was not predicted before drilling as the existing seismic profile imaged subhorizontal reflectors in the footwall to the Agogo Thrust.

Fig. 3. Historical interpretations of fold-thrust systems. a) Part of Heim's 1878) classic evolutionary sequence for fold-thrust systems, indicating that faulting was preceded by folding. b) A record from Cadell's experimental notebook showing some of the results of his "experiments in mountain building" (Cadell (1888) that display imbricate thrusting without precursor folding. c) the idealised structural style, based on Cadell's experiments, used by Peach et al. (1907) in the construction of cross-sections in the Moine Thrust Belt. d) Rich's (1934) interpretation of the Powell Valley anticline as what is now known as a fault-bend fold. e) Buxtorf's (1916) often-reproduced cross-section through part of the Jura hills showing "detachment folding" of Mesozoic and Cenozoic strata above undeformed basement. f) a less-reproduced cross-section by Buxtorf (1916) that, along with "detachment folding" (Born Range), shows stacked imbricate thrusting.

Fig. 4. The array of fold-thrust geometries commonly mis-described as "end-member models", redrafted from Shaw et al. (2005). All are shown in layer-cake stratigraphy and are purely kinematic so that there is no layer-control on the deformation. a) fault-bend folding, b) fault-propagation folding, c) detachment folding, d) trishear folding.

Fig. 5. Natural outcrop examples of fold-thrust structures. Horizons have been selected (ornamented blue lines) to show the form of the folds and, where possible, to correlate across the faults. See text for further discussion. a) NW margin of Jebel Madmar, Oman (N of city of Adam); Cretaceous limestones. b) eastern Salt Range, Pakistan (east of Khewra mine); Cambrian sandstones and siltstones. c) Moine Thrust Belt, Sutherland, Scotland (58° 13’56” N; 04° 56’78” W); Cambrian quartz-arenites. d) Broadhaven, SW Wales (51° 47’12” N; 05° 13’80” W); sandstones and siltstones. e) Jura, France (45° 56’44” N; 05° 27’38” E); Jurassic limestones. f) Diois, NE of Orange, SE France; Jurassic limestones. g) Haut Giffre, France (46° 07’08” N; 06° 51’46” E); Jurassic limestones.

Fig. 6. The forelimb problem. (a) Seismic imaging (and shallow outcrop data) can resolve the overall shape of a structure and define how far an individual imaged horizon has been elevated above its “regional” (elevation and orientation: top diagram). However, the data do not preserve key information from the fold hinge and forelimb, causing an “uncertainty problem”. (b) continuity of this horizon into the forelimb area may be explained by an array of alternative interpretations (the “solution set”).

Fig. 7. Alternative models of folding and thrusting. a) The tip-line model of Williams and Chapman’s (1983) illustrated through the displacement-distance method for predicting the location of thrust tips and the offsets of other beds. b) Pfiffner’s (1985) model for thrust faults showing both the upward and downward termination of displacements, with both accompanied by distributed strain. c) Eisenstadt and dePaor’s (1987) model for the generation of staircases of ramps and flats through a rheological multilayer. d) Butler’s (1992b) depiction of kinematically linked, but spatially isolated, thrust faults.

Fig. 8. Location map for the Canadian Rockies showing the major tectonic provinces (modified from Wheeler and McFeely, 1991) and the locations of the

cross-sections (a-e) in Figures 9 and 10, together with the seismic data shown in Figures 12 and 13.

Fig. 9. Regional cross-sections through the foothills of Alberta and British Columbia. Section locations are shown on Fig. 8. a) Sukunka River Section modified and extended from the section of Cooper (1996, figure 13). b) Falls Creek Section, not previously published. c) Nordegg Area Section modified from the section D-D’ of Langenberg et al. (2002). d) Turner Valley Area Section modified from the Turner Valley cross-section of Stockmal et al. (2001, figure 13). E) Oldman River Area Section modified from the section G-G’ of Langenberg et al. (2002).

Fig. 10. The regional cross-sections through the foothills of Alberta and British Columbia from Fig 9 coloured by the dominant lithology of the formations shown in Fig 9 instead of being coloured by stratigraphic unit; see text and Fig. 11 for discussion. Section locations are exactly the same as those for Figure 9 (Shown on Fig. 8).

Fig 11. Variations in the stratigraphy (a) and lithology (b) from northern Montana to 60°N along the strike of the foothills in Alberta (AB) and British Columbia (BC). This profile is located broadly parallel to, and just west of, the eastern limit of the displaced cratonic margin shown on Figure 8. The figure, showing lateral variations in gross lithology, is based on a diagram by Gordy et al. (1977) for the Mesozoic in Alberta and has been supplemented by thickness data from the structural cross-sections and thickness data from Mossop and Shetsen (1994). The location of the cross-sections of Figures 9 and 10 are shown along the correlation profile (a-e). A comparison of the sections with the lithology of the units for the section location illustrates: (1) a decrease in overall shale content from North to South in the sections; (2) the Triassic is thicker in the BC Foothills than in Alberta; (3) the Jurassic to Lower Cretaceous is thicker in the BC Foothills than in Alberta; and (4) the changes in thickness and lithology noted above correlate with significant changes in mechanical stratigraphy that favours the development of folds with subsidiary faulting in the North but larger displacement thrusts and related hangingwall folds in the carbonate-dominated Paleozoic and smaller wavelength folds and related thrusts in the Mesozoic clastics.

Fig. 12. Seismic line through the Turner Valley oil and gas field modified from Reimer (1989, figure 6.22). Approximate location shown on Fig. 8.

Fig. 13. Pre- and post-sidetrack comparison of structure in the b-30-C/93-P-03 well, showing key well data, migrated VSP amplitude data (semi-transparent background) from the original wellbore and bedding form lines. Approximate location shown on Fig. 8

Fig. 14. Simplified map of the Subalpine areas of the Bauges and Bornes-Aravis (SE France; modified after Butler, 1989), illustrating the location of various published cross-sections (Fig. 15), outcrops (Fig. 16,17) and modified examples of cross-sections (Fig. 18). Inset a) location in SE France; b) representative stratigraphic columns.

Fig. 15. Selected published cross-sections through the Bauges and Bornes-Aravis areas of the Subalpine chains of SE France (section lines on Fig. 14). Note that these are not shown as laterally equivalent sections but to illustrate how different authors interpret structural style and inherent stratigraphic variations. a) The interpretation of Charollais et al. (1996) of the front of the Bornes massif and inherent stratigraphic variations as encountered in wells (FAY-1, LBL-1 and BZN). The Arve valley strike-slip fault system is not considered significant here. b) Guellec et al.'s (1990) section through the Bornes-Aravis sector. c) Butler's (1991) section through the Bornes-Aravis. d) Beck et al.'s (1998) section through the central Bauges sector. e) Deville and Chauviere's (2000) section through the Chambery area.

Fig. 16. Interpretion of the fold-thrust structures in the Tithonian limestone in the Subalpine chains. a) The Arpenaz fold pair in the Arve valley. b) imbricated Tithonian limestone at the southern edge of the Bauges massif. The purple unit

is a marker horizon within the Tithonian limestone used for correlation across the thrust faults. c) the lithological and dip-meter data for the Brizon well (located on Fig. 14).

Fig. 17. Variations in structural geometry seen in cross sections along the Arve valley transect (a) and the Bornes gorge (b). See Fig. 14 for locations and text for further details. Colours as in Figure 16c.

Fig. 18. The frontal thrusts in the Arve valley transect (Fig. 15a) and their relationship to pre-existing faults. a) field photograph and Welbon and Butler's (1992) interpretation (b-c) in time to show the evolution of the thrusts and folds.

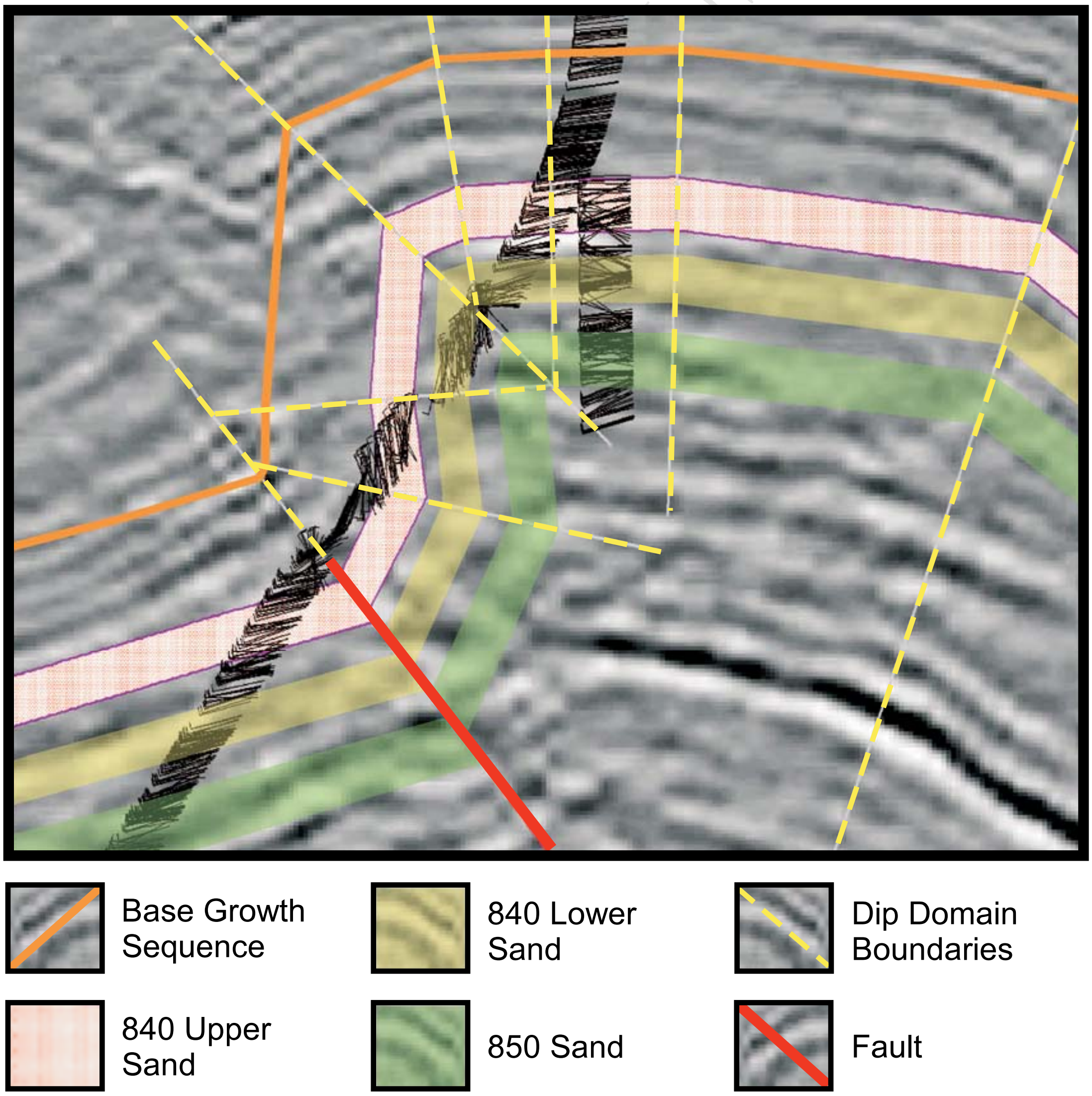
Fig. 19. Contrasting the stratigraphic templates and folding styles between the Canadian Rockies and French Subalpine chains. (a) Large wavelength fold in the Cretaceous Urgonian limestones characterised by rounded fold hinges, Tête de Bossetan, Haute-Savoie. (b) Lower Jurassic strata deformed into tight, short wavelength folds compared with those in the Urgonian, upper Giffre valley, Haute-Savoie. (c) Simplified stratigraphic column for the Subalpine areas of the Bauges and Bornes-Aravis. (d) Simplified stratigraphic column for the Central Foothills of Alberta. (e) Short wavelength folding in Cretaceous clastics, Bragg Creek, Alberta Foothills. (f) Characteristic kink-band fold of the well-layered Mississippian carbonates, Mt Kidd, Alberta Rocky Mountains.

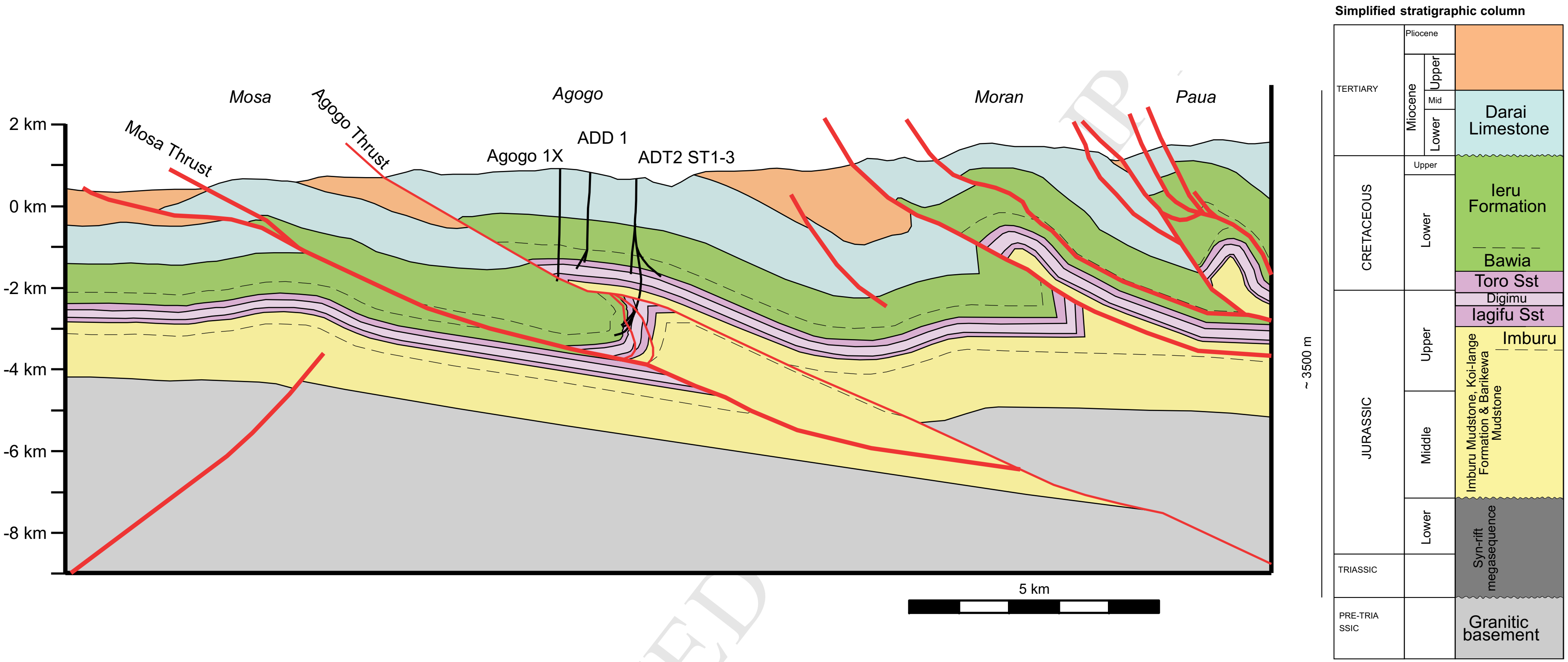
Fig. 20. Ambiguities in the subsurface structure of fold-thrust complexes, modified after Tozer et al. (2002). a) shows typical observations used to construct sections while, b) and c) illustrate competing interpretations of the subsurface using a modified fault-bend fold model, and inversion of a pre-existing basement-rooted normal fault, respectively.

Fig. 21. Various interpretations over time for the frontal fold and thrust belt of Papua New Guinea. a) Thin-skinned interpretation of Hobson (1986) showing detachment of thrust sheets above a basement panel. b) Hill's (1991) interpretation with a combination of basement inversion and thrust detachment.

c) Buchanan & Warburton's (1996) section with rather small displacements on reactivated basement faults, d) simplified stratigraphic column and key.

Fig. 22. The Gobe Anticline, Papua New Guinea. (a) seismic line through the Gobe Anticline showing problematic imaging at depth that cannot distinguish between two geometries: (b) thin-skinned deformation model above a Lower Mesozoic detachment. (c) basement-fault inversion model.


Base Growth Sequence
840 Lower Sand
Dip Domain Boundaries
840 Upper Sand
850 Sand
Fault


Mosa
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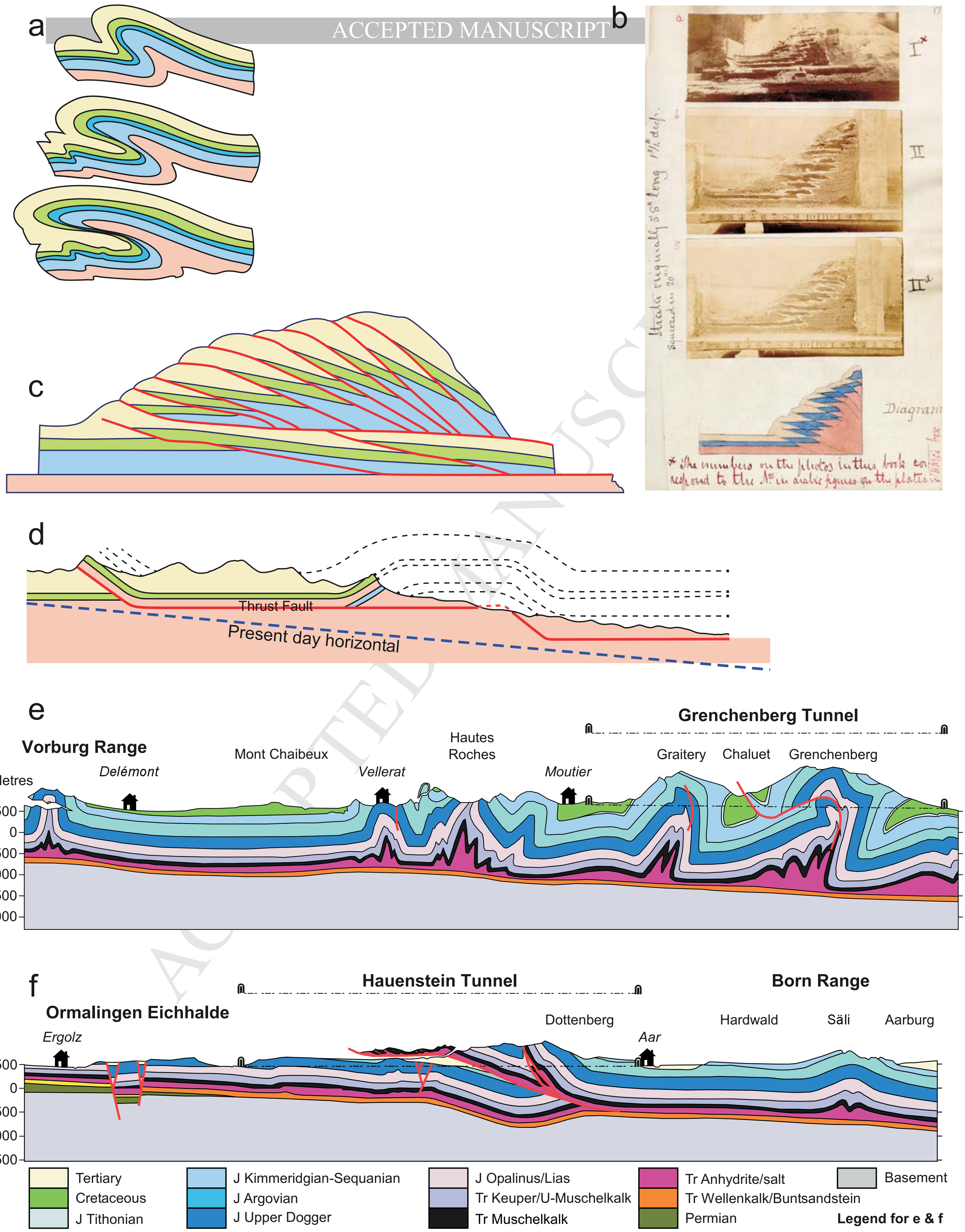
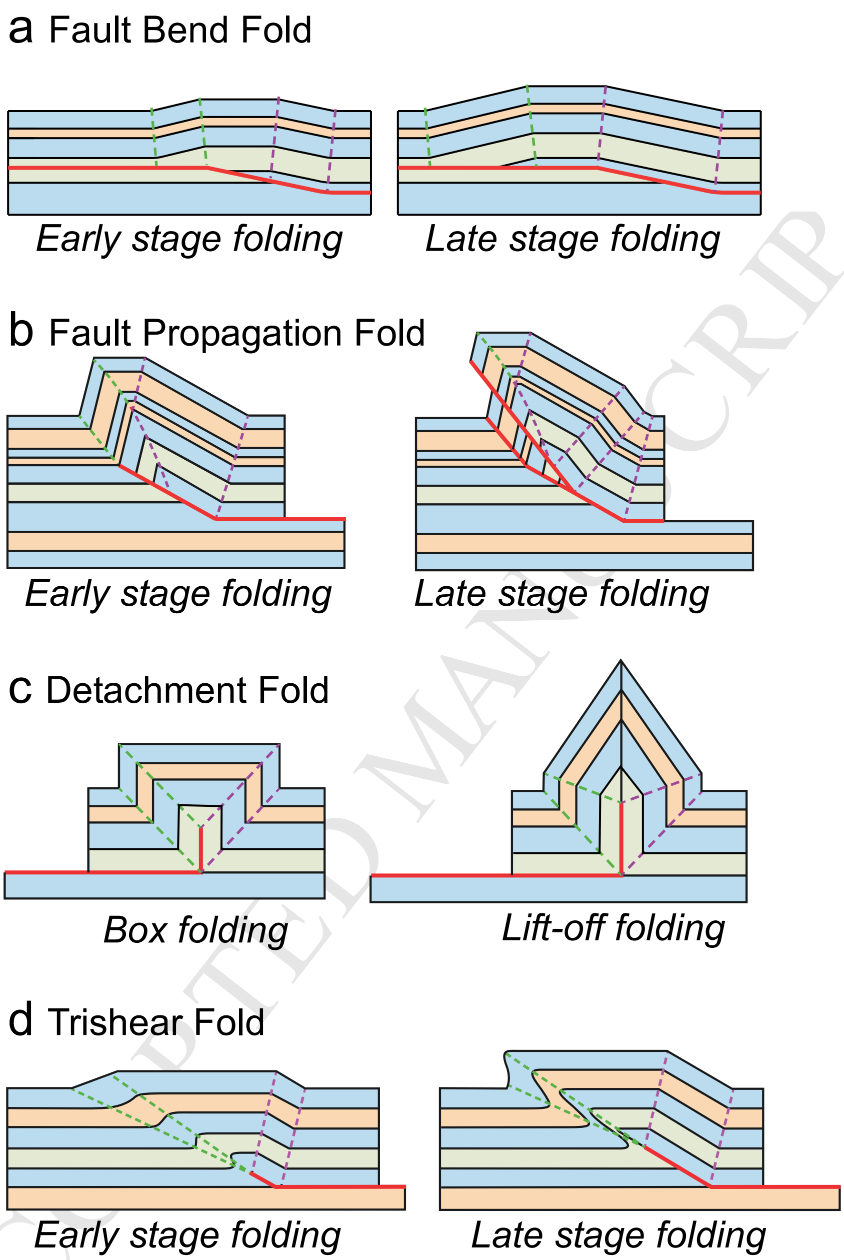
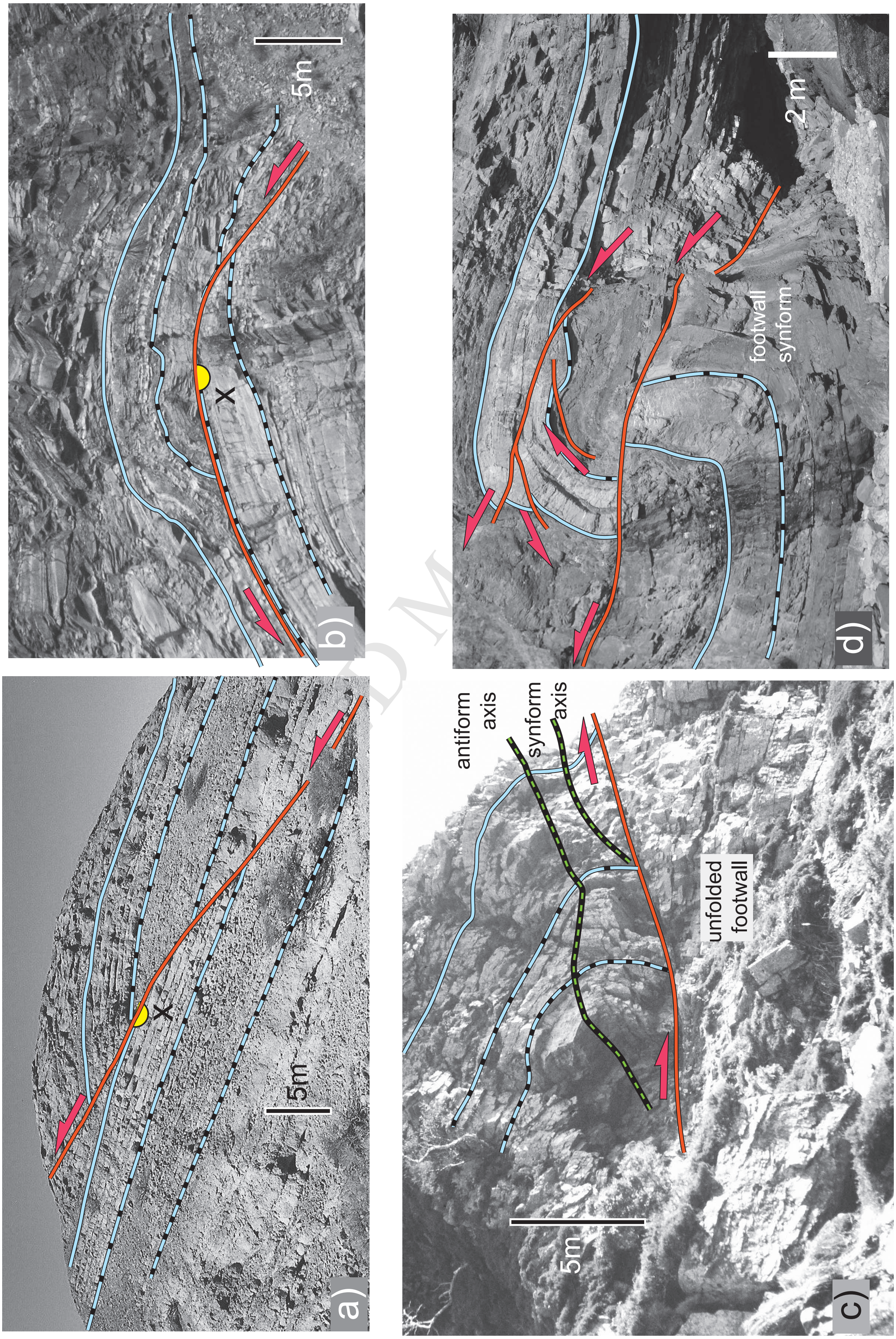
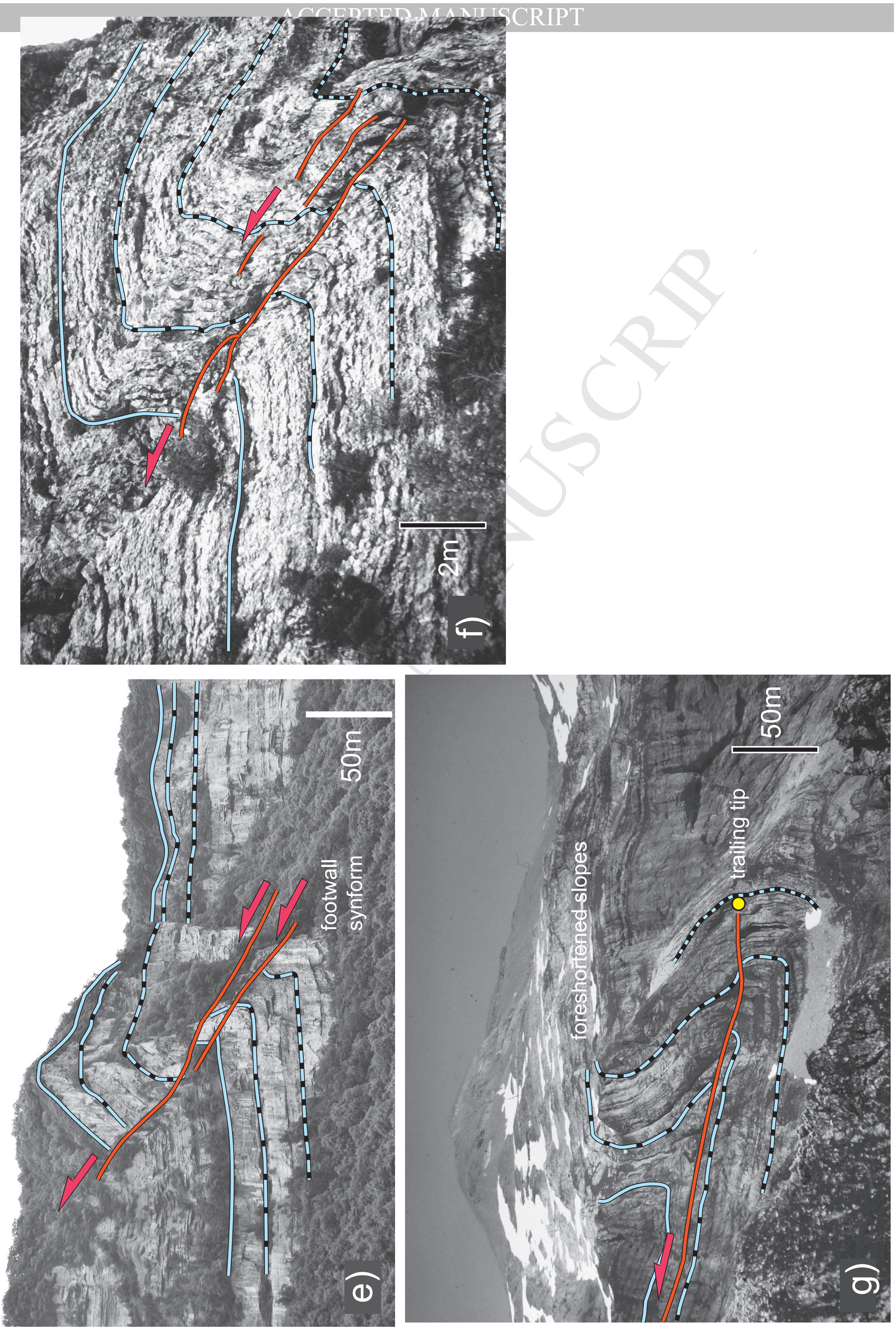
Lower
Ieru Formation
Bawia
Toro Sst
Digimu
Iagifu Sst
JURASSIC
Upper
Middle
Lower
Imburu
Imburu Mudstone, Koi-lange Formation & Barikewa Mudstone
TRIASSIC
Syn-rift megasequence
PRE-TRIASSIC
Granitic basement

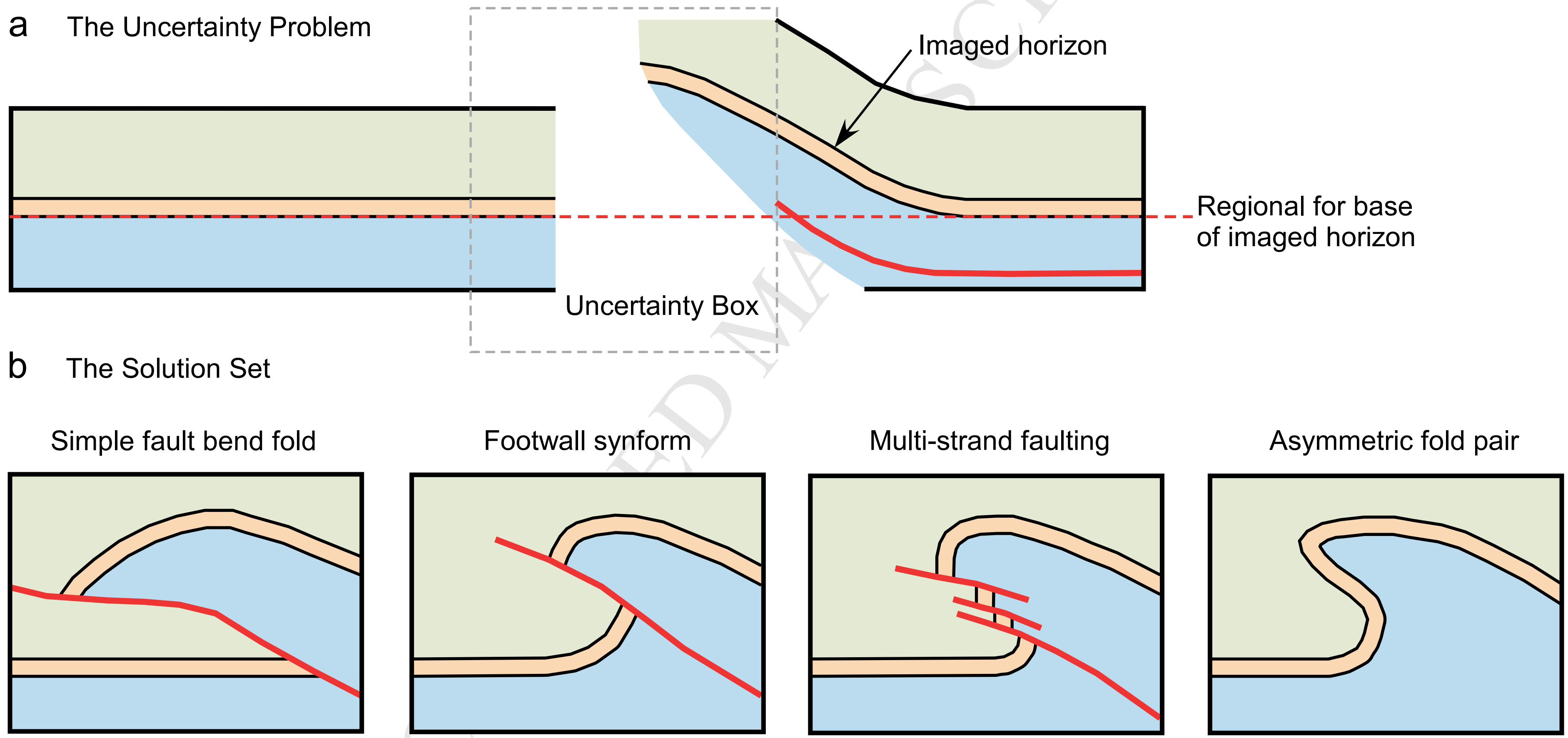

a
b
c
Diagram
d
Thrust Fault
Present day horizontal
e
Grenchenberg Tunnel
Vorburg Range
Mont Chaibeux
Hautes Roches
Graitery
Chaluet
Grenchenberg
Metres
Delémont
Vellerat
Moutier
500
0
-500
-1000
-1500
-2000
f
Hauenstein Tunnel
Born Range
Ormalingen Eichhalde
Dottenberg
Hardwald
Säli
Aarburg
Ergolz
Aar
500
0
-500
-1000
-1500
Tertiary
Cretaceous
J Tithonian
J Kimmeridgian-Sequanian
J Argovian
J Upper Dogger
J Opalinus/Lias
Tr Keuper/U-Muschelkalk
Tr Muschelkalk
Tr Anhydrite/salt
Tr Wellenkalk/Buntsandstein
Permian
Basement
Legend for e & f



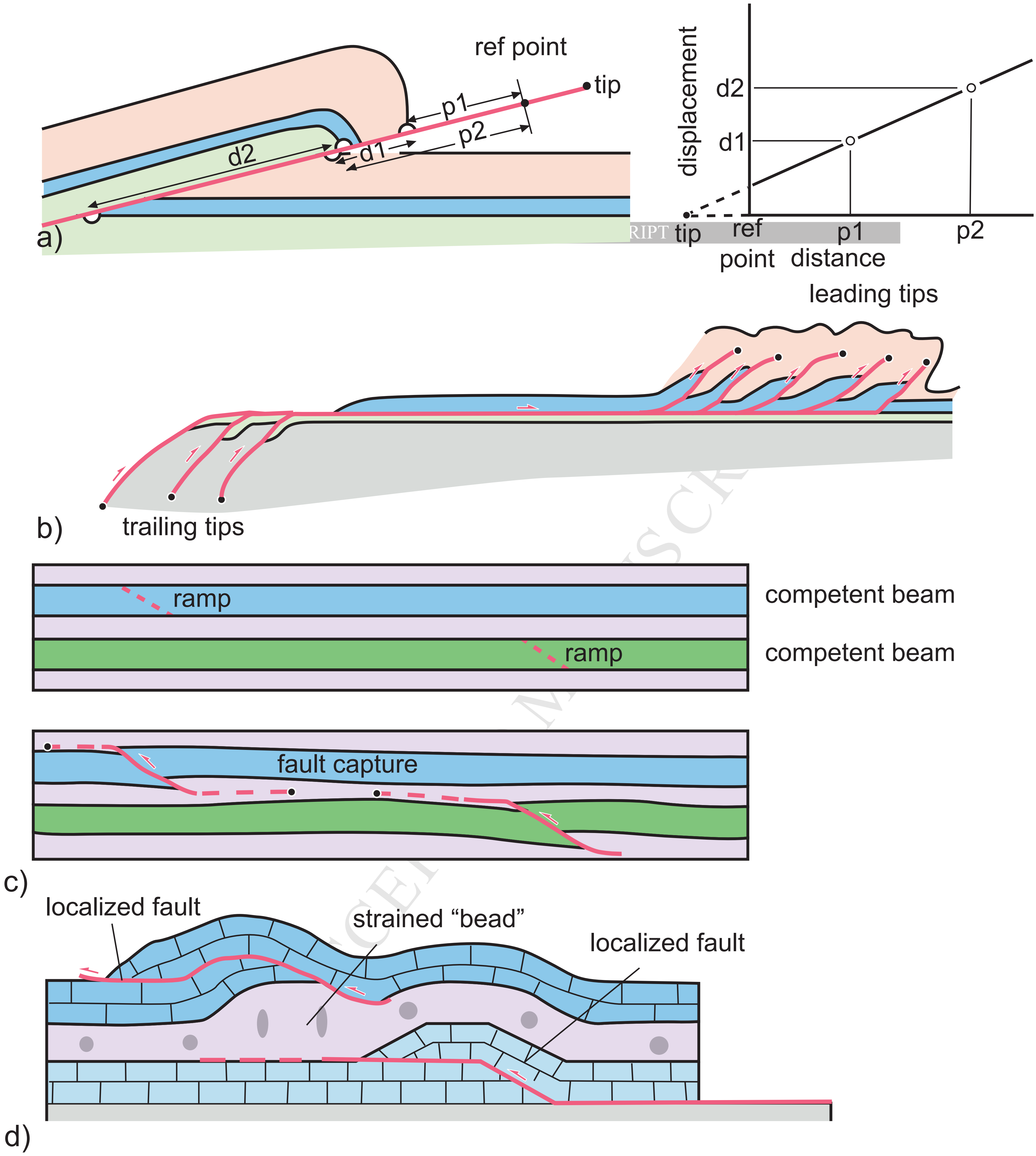
a Fault Bend Fold
Early stage folding
Late stage folding
b Fault Propagation Fold
Early stage folding
Late stage folding
c Detachment Fold
Box folding
Lift-off folding
d Trishear Fold
Early stage folding
Late stage folding

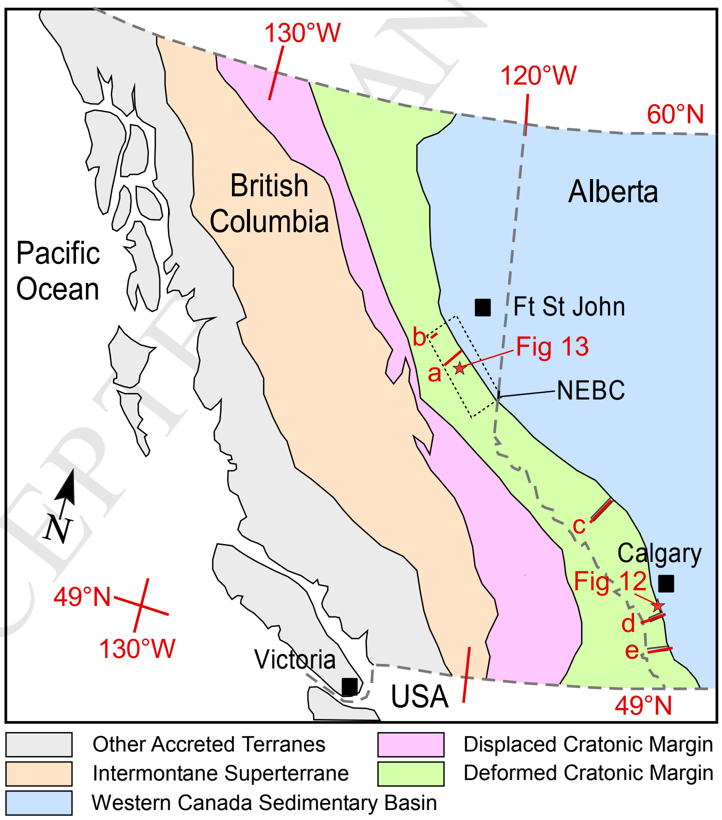

a)
5m
X
b)
5m
X
c)
5m
antiform axis
synform axis
unfolded footwall
d)
2 m
footwall synform

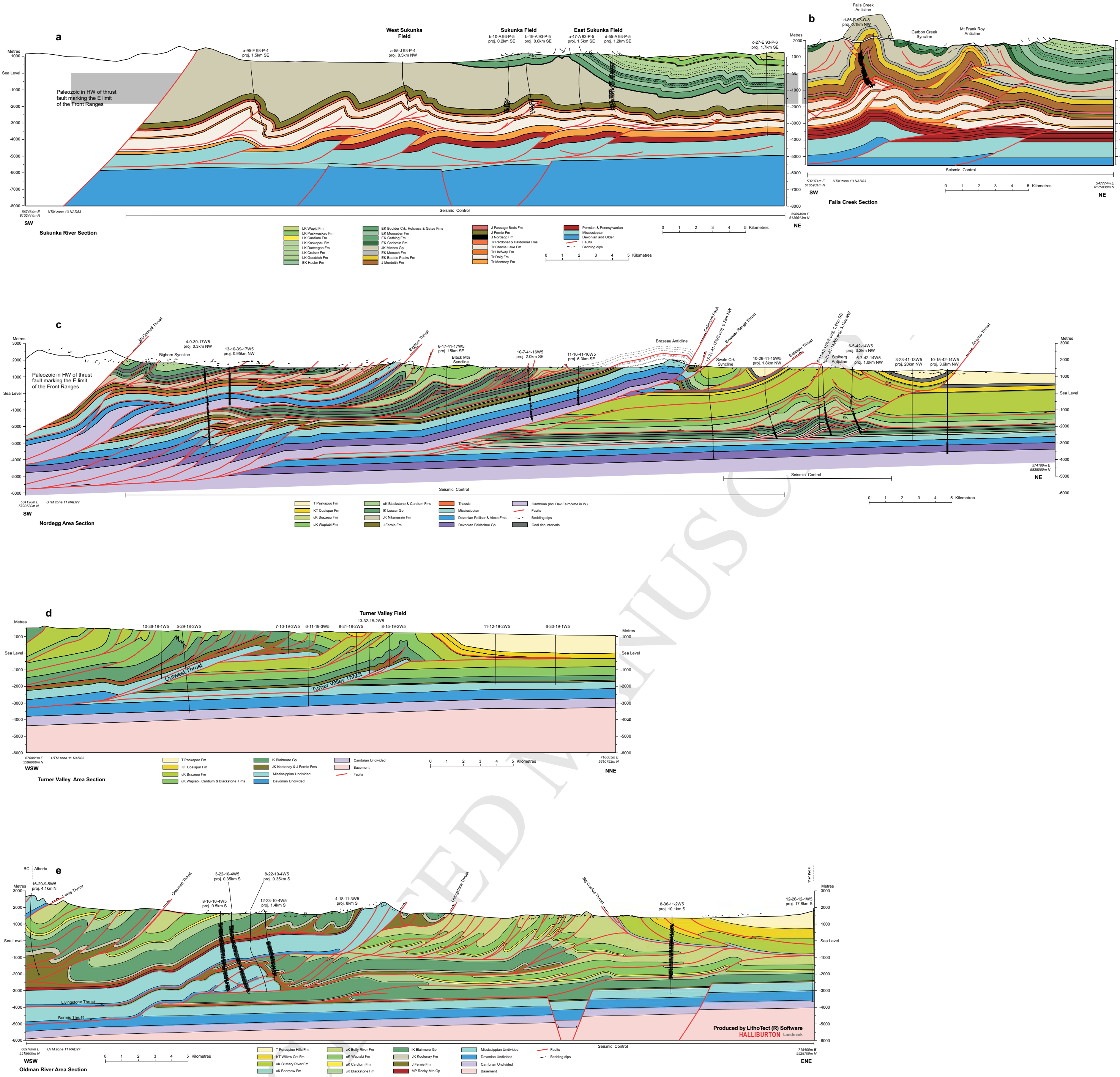

f)
2m
e)
50m
footwall
synform
g)
50m
trailing tip
foreshortened slopes



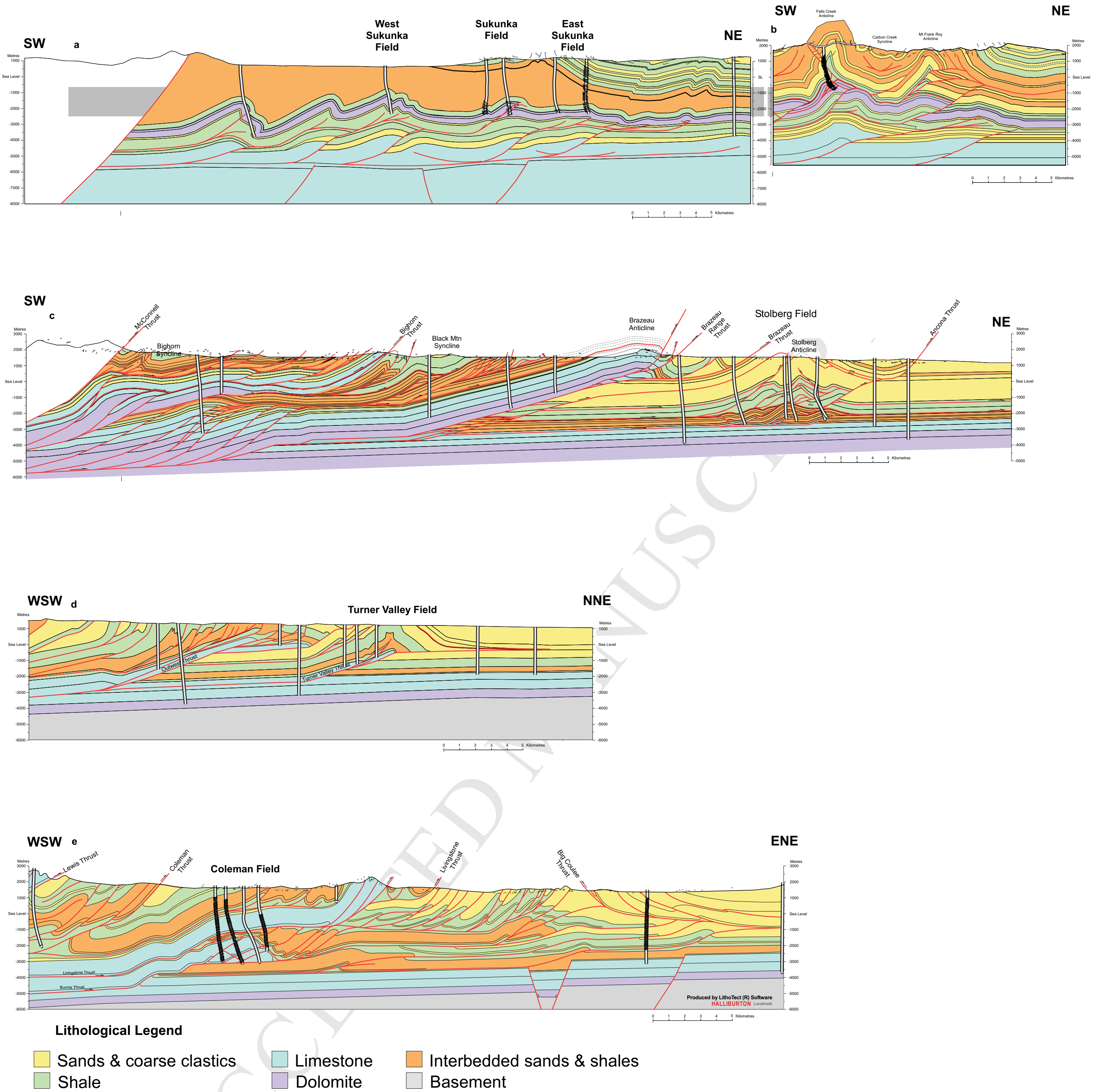
a
The Uncertainty Problem
Imaged horizon
Regional for base
of imaged horizon
Uncertainty Box
b
The Solution Set
Simple fault bend fold
Footwall synform
Multi-strand faulting
Asymmetric fold pair


ref point
tip
p1
p2
d1
d2
a)
displacement
d2
d1
tip
ref
point
p1
p2
distance
leading tips
b)
trailing tips
ramp
ramp
competent beam
competent beam
fault capture
c)
localized fault
strained “bead”
localized fault
d)

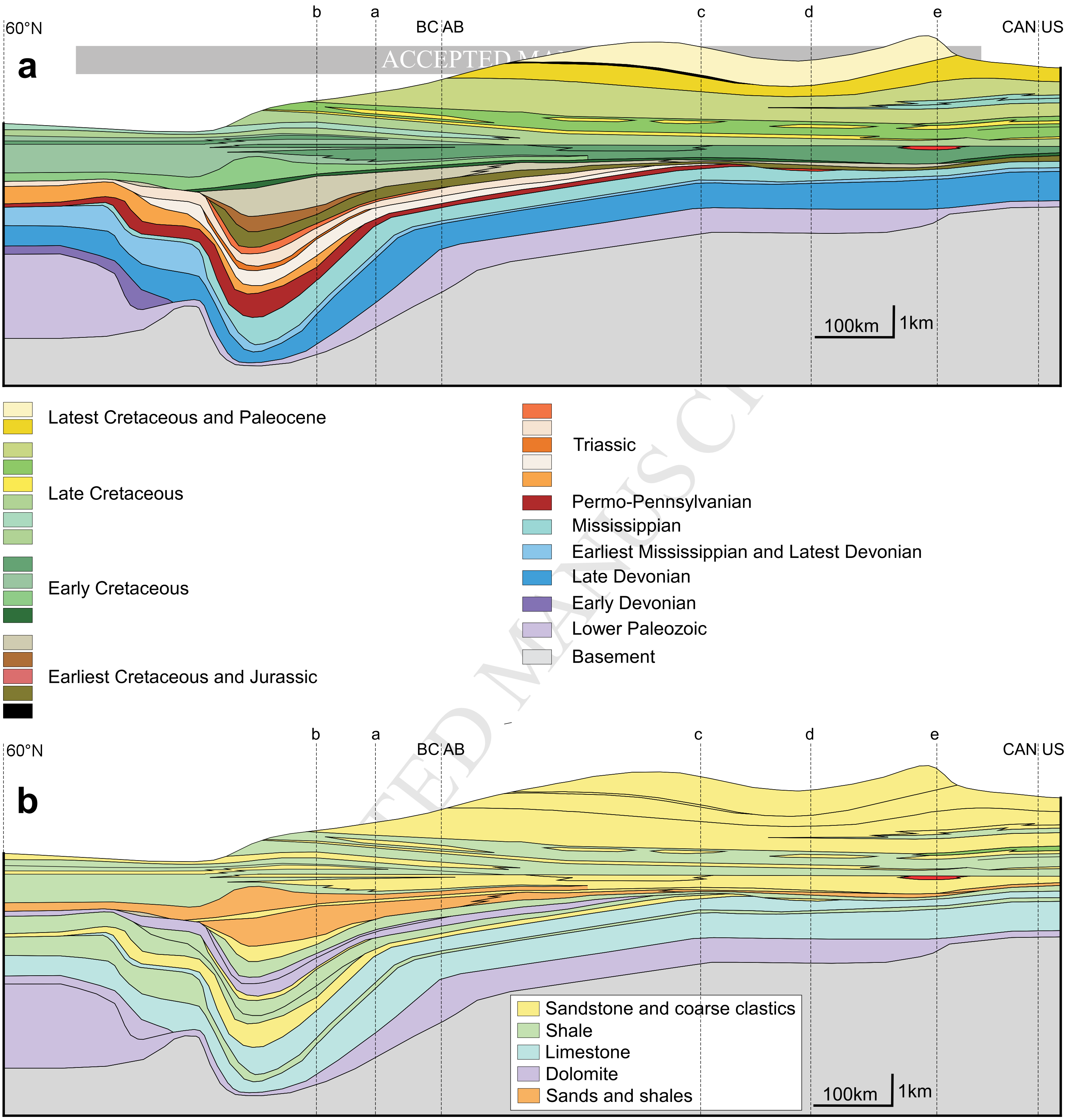

130°W
120°W
60°N
British Columbia
Alberta
Pacific Ocean
Ft St John
Fig 13
NEBC
b
a
c
Calgary
Fig 12
d
e
N
49°N
130°W
Victoria
USA
49°N
Other Accreted Terranes
Intermontane Superterrane
Western Canada Sedimentary Basin
Displaced Cratonic Margin
Deformed Cratonic Margin

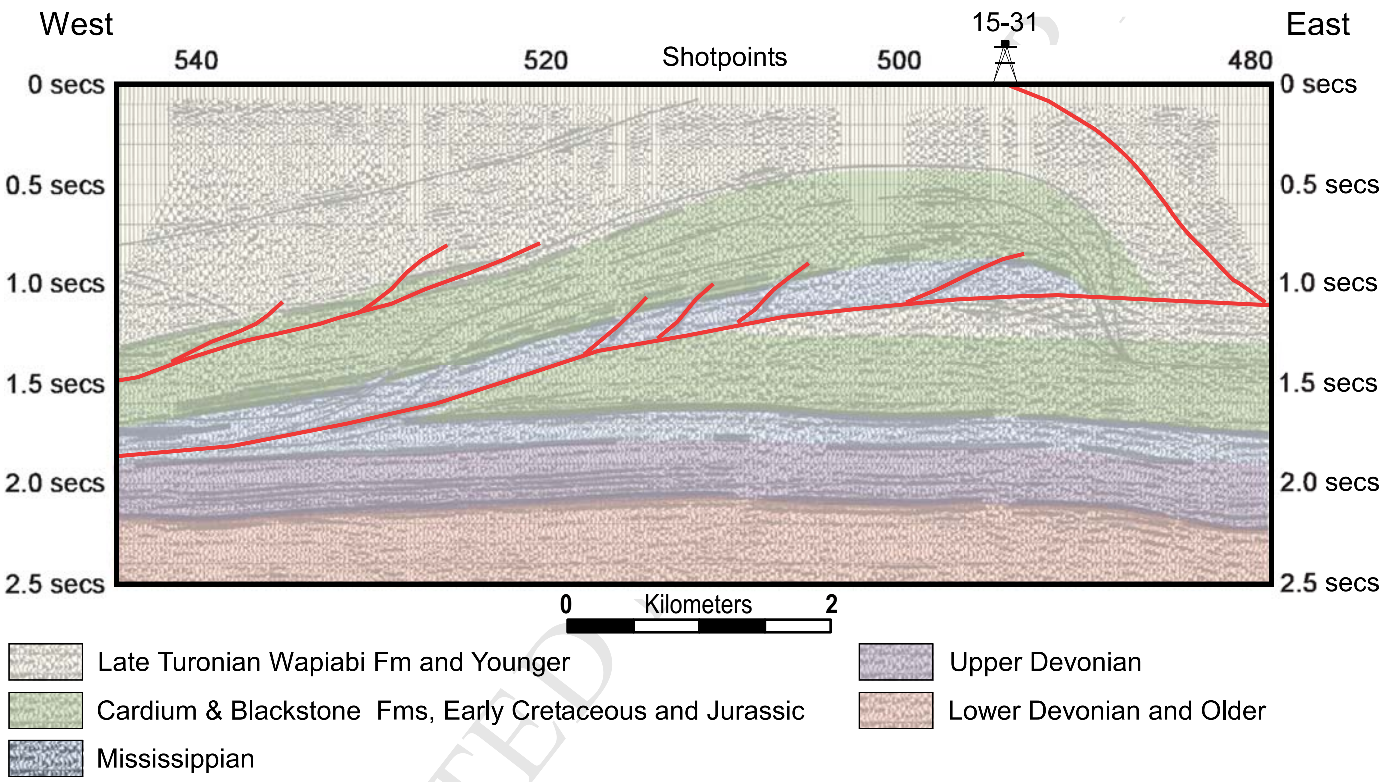


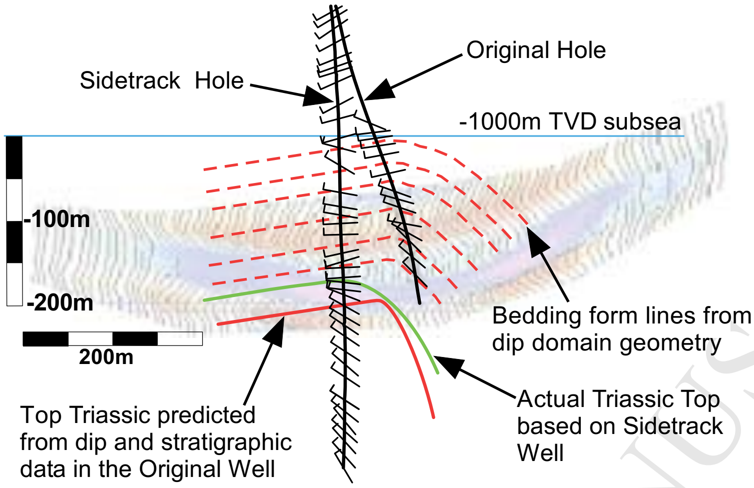
a
West Sukunka Field
Sukunka Field
East Sukunka Field
Paleozoic in HW of thrust fault marking the E limit of the Front Ranges
Metres
Sea Level
Seismic Control
UTM zone 10 NAD83
SW
NE
Sukunka River Section
LK Wapiti Fm
LK Puskwaskau Fm
LK Cardium Fm
LK Kaskapau Fm
LK Dunvegan Fm
LK Cruiser Fm
LK Goodrich Fm
EK Hasler Fm
EK Boulder Crk, Hulcross & Gates Fms
EK Moosebar Fm
EK Gething Fm
EK Cadomin Fm
JK Minnes Gp
EK Monach Fm
EK Beattie Peaks Fm
J Monteith Fm
J Passage Beds Fm
J Fernie Fm
J Nordegg Fm
Tr Pardonet & Baldonnel Fms
Tr Charlie Lake Fm
Tr Halfway Fm
Tr Doig Fm
Tr Montney Fm
Permian & Pennsylvanian
Mississippian
Devonian and Older
Faults
Bedding dips
Kilometres
b
Falls Creek Anticline
Carbon Creek Syncline
Mt Frank Roy Anticline
Falls Creek Section
c
McConnell Thrust
Bighorn Syncline
Brazeau Thrust
Black Mtn Syncline
Brazeau Anticline
Paleozoic in HW of thrust fault marking the E limit of the Front Ranges
Seale Crk Syncline
Stolberg Anticline
Nordegg Area Section
T Paskapoo Fm
KT Coalspur Fm
uK Brazeau Fm
uK Wapiabi Fm
uK Blackstone & Cardium Fms
lK Luscar Gp
JK Nikanassin Fm
J Fernie Fm
Triassic
Mississippian
Devonian Palliser & Alexo Fms
Devonian Fairholme Gp
Cambrian (incl Dev Fairholme in W)
Faults
Bedding dips
Coal rich intervals
d
Turner Valley Field
Outwest Thrust
Turner Valley Thrust
WSW
NNE
Turner Valley Area Section
T Paskapoo Fm
KT Coalspur Fm
uK Brazeau Fm
uK Wapiabi, Cardium & Blackstone Fms
lK Blairmore Gp
JK Kootenay & J Fernie Fms
Mississippian Undivided
Devonian Undivided
Cambrian Undivided
Basement
Faults
e
BC
Alberta
Lewis Thrust
Coleman Thrust
Livingstone Thrust
Big Coulee Thrust
Livingstone Thrust
Burmis Thrust
Produced by LithoTect (R) Software
HALLIBURTON Landmark
WSW
ENE
Oldman River Area Section
T Porcupine Hills Fm
KT Willow Crk Fm
uK St Mary River Fm
uK Bearpaw Fm
uK Belly River Fm
uK Wapiabi Fm
uK Cardium Fm
uK Blackstone Fm
lK Blairmore Gp
JK Kootenay Fm
J Fernie Fm
MP Rocky Mtn Gp
Mississippian Undivided
Devonian Undivided
Cambrian Undivided
Basement
Faults
Bedding dips



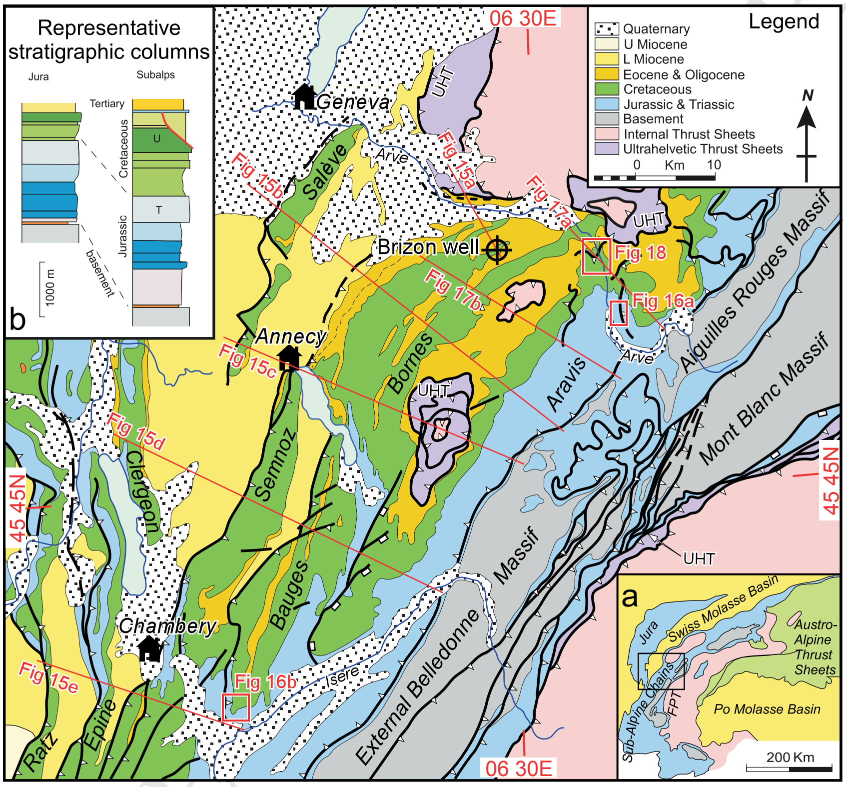
SW
a
West Sukunka Field
Sukunka Field
East Sukunka Field
NE
SW
NE
b
Falls Creek Anticline
Carbon Creek Syncline
Mt Frank Roy Anticline
SW
c
McConnell Thrust
Bighorn Syncline
Bighorn Thrust
Black Mtn Syncline
Brazeau Anticline
Brazeau Range Thrust
Stolberg Field
Brazeau Thrust
Stolberg Anticline
Ancona Thrust
NE
WSW
d
Turner Valley Field
NNE
Outwest Thrust
Turner Valley Thrust
WSW
e
Lewis Thrust
Coleman Thrust
Coleman Field
Livingstone Thrust
Big Coulee Thrust
ENE
Livingstone Thrust
Burmis Thrust
Produced by LithoTect (R) Software
HALLIBURTON Landmark
Lithological Legend
Sands & coarse clastics
Shale
Limestone
Dolomite
Interbedded sands & shales
Basement

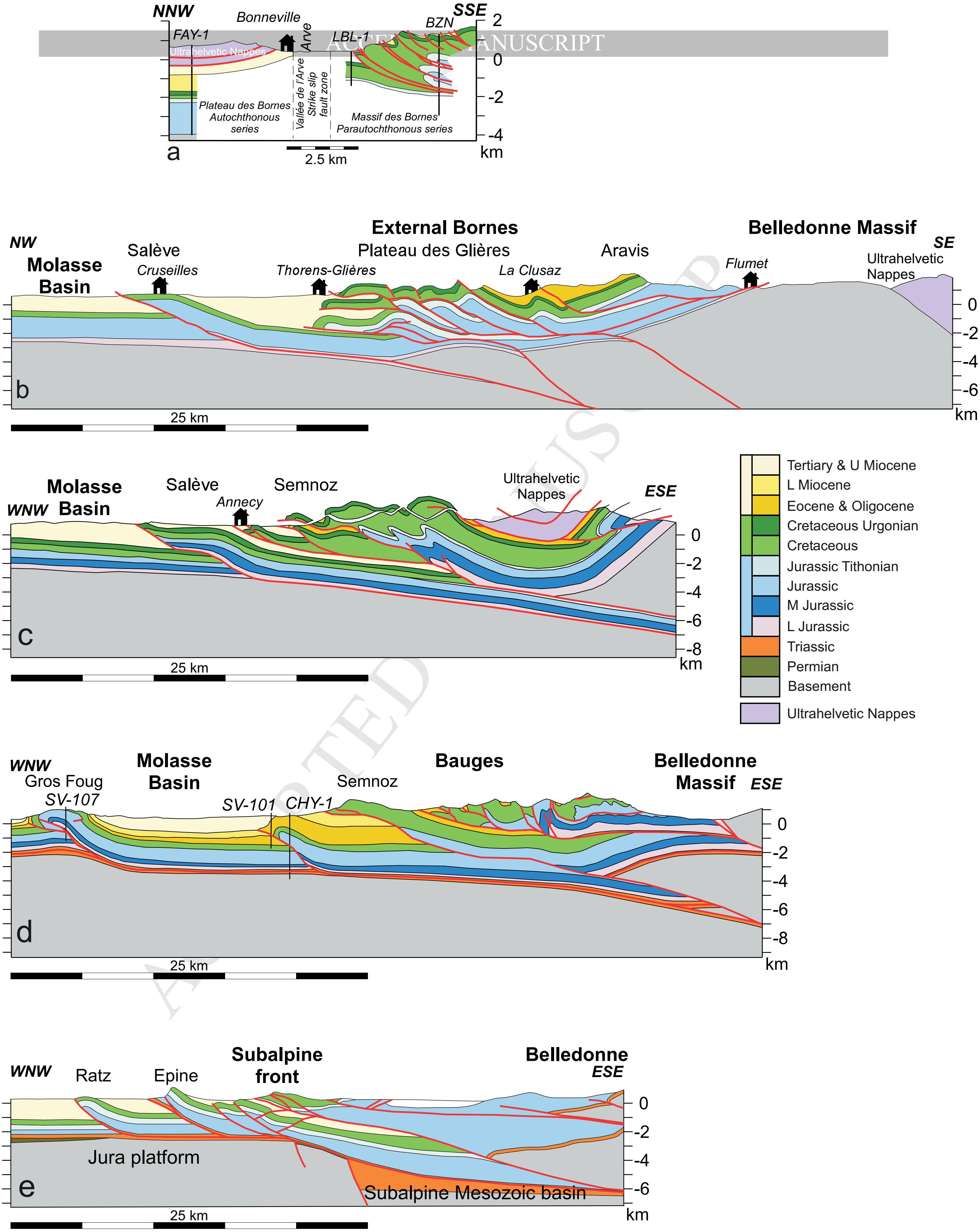

60°N
a
b
a
BC AB
c
d
e
CAN US
100km
1km
Latest Cretaceous and Paleocene
Late Cretaceous
Early Cretaceous
Earliest Cretaceous and Jurassic
Triassic
Permo-Pennsylvanian
Mississippian
Earliest Mississippian and Latest Devonian
Late Devonian
Early Devonian
Lower Paleozoic
Basement
60°N
b
b
a
BC AB
c
d
e
CAN US
Sandstone and coarse clastics
Shale
Limestone
Dolomite
Sands and shales
100km
1km


West
East
15-31
540
520
Shotpoints
500
480
0 secs
0.5 secs
1.0 secs
1.5 secs
2.0 secs
2.5 secs
0 secs
0.5 secs
1.0 secs
1.5 secs
2.0 secs
2.5 secs
0 Kilometers 2
Late Turonian Wapiabi Fm and Younger
Cardium & Blackstone Fms, Early Cretaceous and Jurassic
Mississippian
Upper Devonian
Lower Devonian and Older

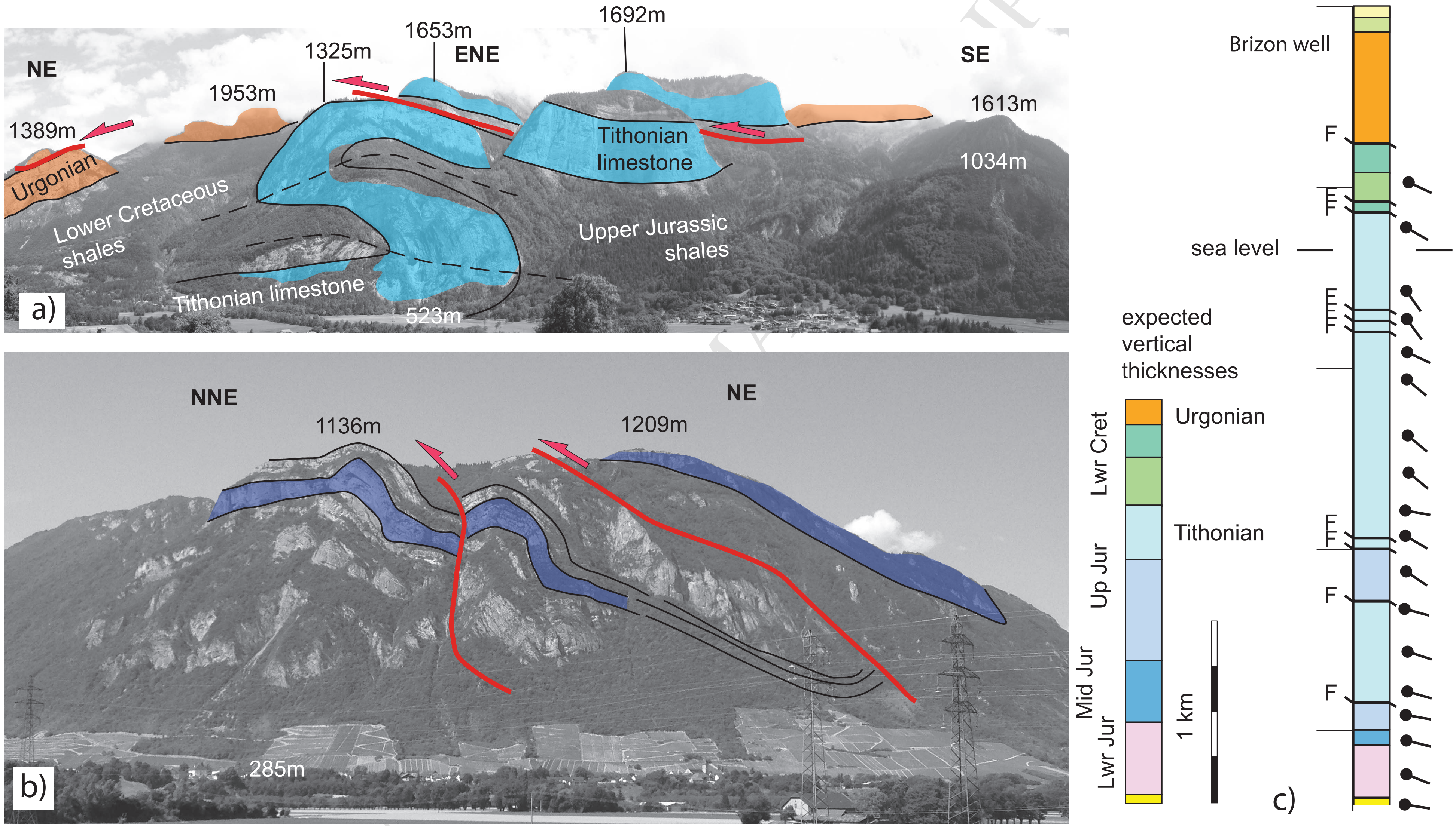


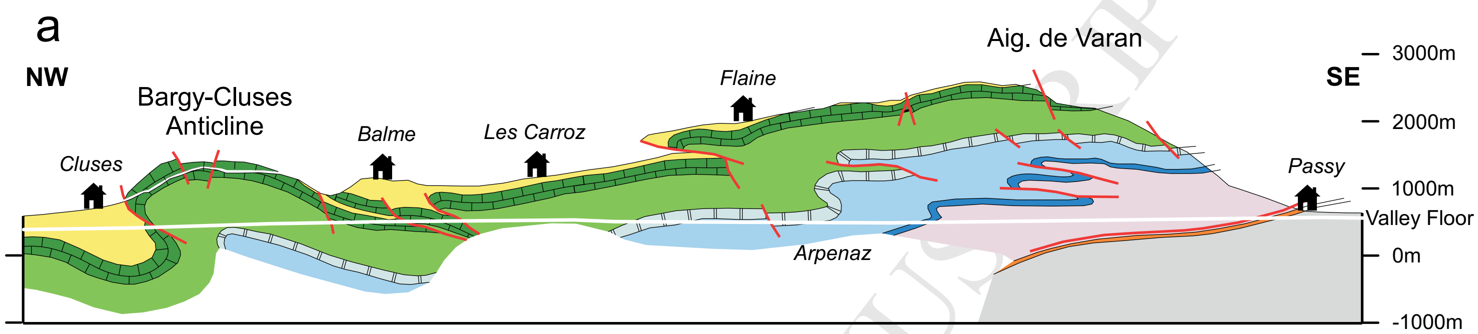
Original Hole
Sidetrack Hole
-1000m TVD subsea
-100m
-200m
200m
Bedding form lines from dip domain geometry
Top Triassic predicted from dip and stratigraphic data in the Original Well
Actual Triassic Top based on Sidetrack Well

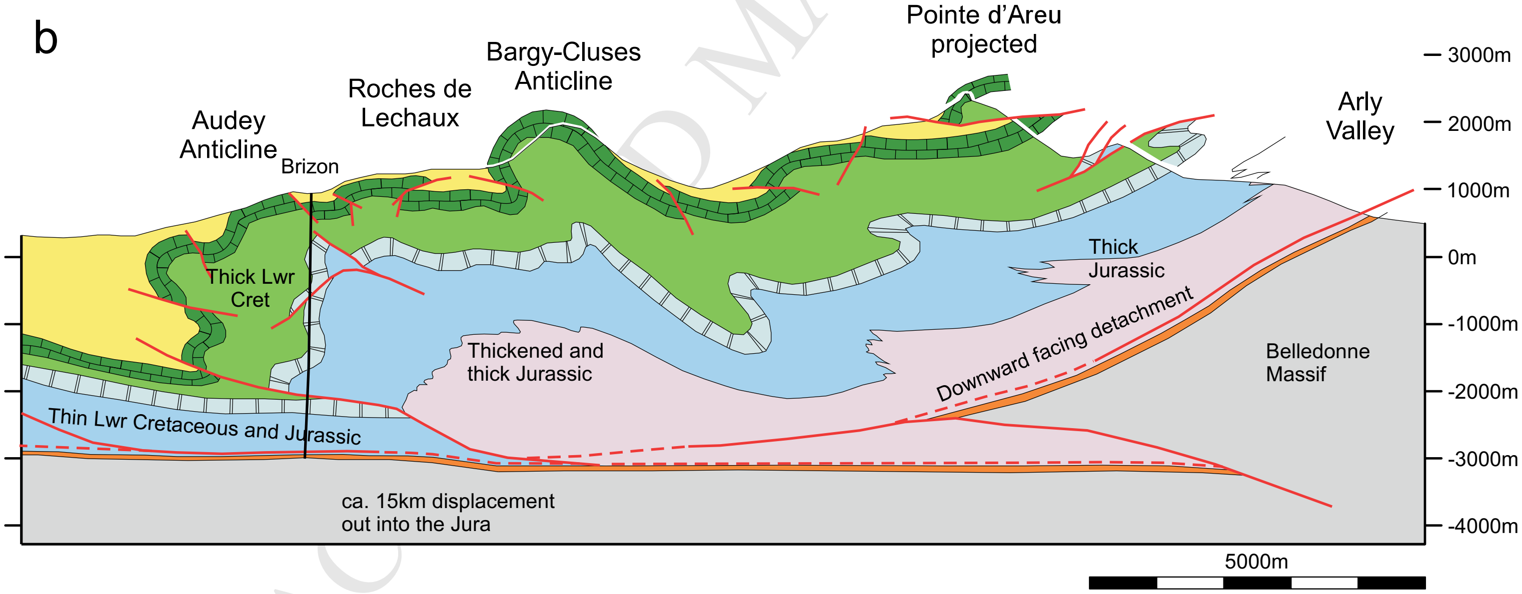

Representative stratigraphic columns
Jura
Subalps
Tertiary
Cretaceous
Jurassic
basement
U
T
1000 m
b
Legend
Quaternary
U Miocene
L Miocene
Eocene & Oligocene
Cretaceous
Jurassic & Triassic
Basement
Internal Thrust Sheets
Ultrahelvetic Thrust Sheets
0 Km 10
N
06 30E
Geneva
UHT
Salève
Arve
Fig 15a
Fig 15b
Fig 17a
Brizon well
Fig 18
Fig 17b
Fig 16a
Annecy
Fig 15c
Fig 15d
Bornes
Aravis
Aiguilles Rouges Massif
Mont Blanc Massif
Semnoz
Clergeon
45 45N
Bauges
External Belledonne Massif
Chambery
Fig 15e
Fig 16b
Isere
Ratz
Epine
a
Jura
Swiss Molasse Basin
Austro-Alpine Thrust Sheets
Sub-Alpine Chains
FPT
Po Molasse Basin
200 Km

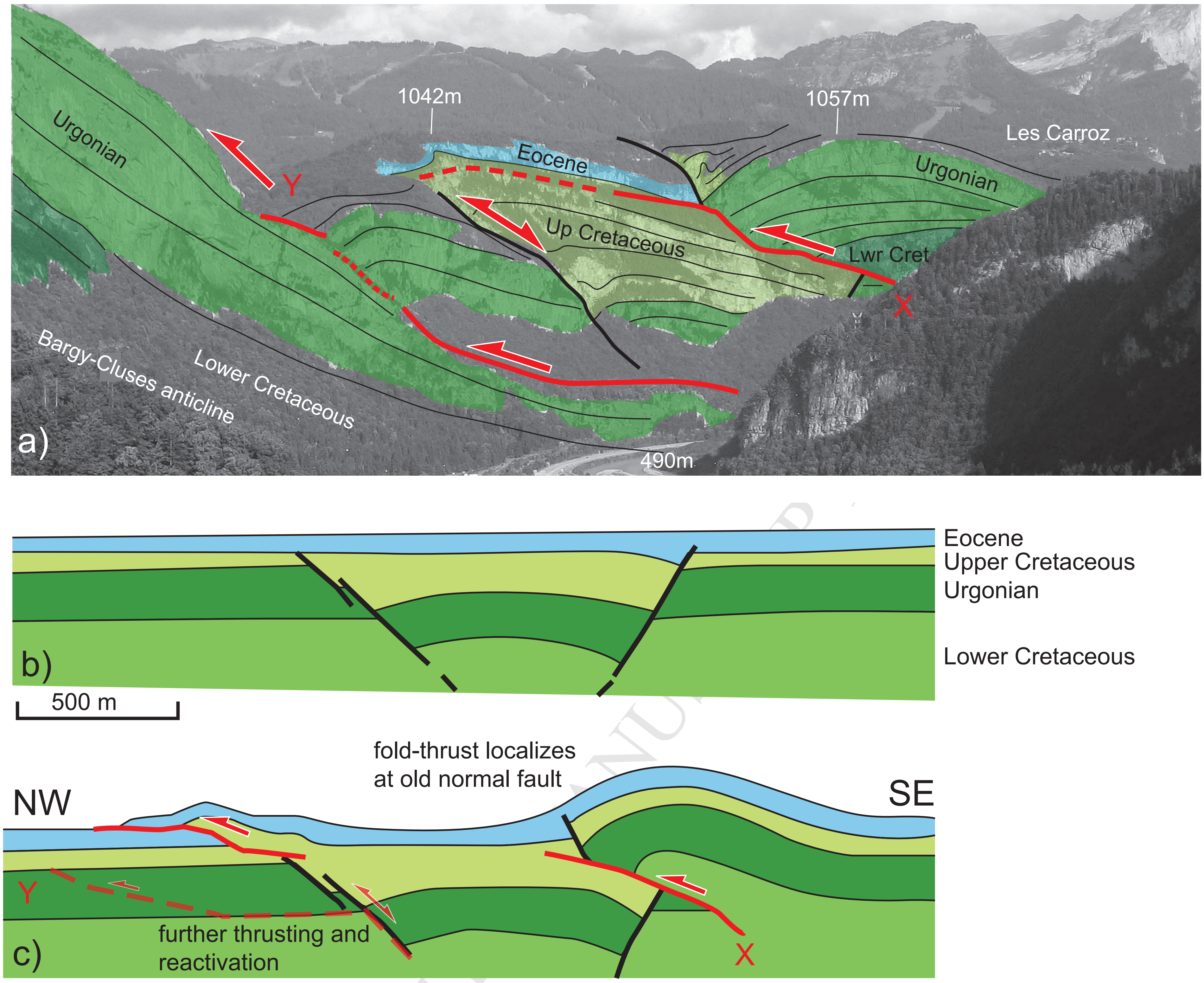


NNW
SSE
Bonneville
Arve
FAY-1
LBL-1
BZN
Ultrahelvetic Nappes
Plateau des Bornes
Autochthonous
series
Vallée de l'Arve
Strike slip
fault zone
Massif des Bornes
Parautochthonous series
2
0
-2
-4
km
a
2.5 km
NW
SE
Molasse
Basin
Salève
Cruseilles
Thorens-Glières
External Bornes
Plateau des Glières
La Clusaz
Aravis
Belledonne Massif
Flumet
Ultrahelvetic
Nappes
0
-2
-4
-6
km
b
25 km
Molasse
Basin
WNW
Salève
Annecy
Semnoz
Ultrahelvetic
Nappes
ESE
0
-2
-4
-6
-8
km
c
25 km
Tertiary & U Miocene
L Miocene
Eocene & Oligocene
Cretaceous Urgonian
Cretaceous
Jurassic Tithonian
Jurassic
M Jurassic
L Jurassic
Triassic
Permian
Basement
Ultrahelvetic Nappes
WNW
Gros Foug
SV-107
Molasse
Basin
SV-101
CHY-1
Semnoz
Bauges
Belledonne
Massif
ESE
0
-2
-4
-6
-8
km
d
25 km
WNW
Ratz
Epine
Subalpine
front
Belledonne
ESE
Jura platform
Subalpine Mesozoic basin
0
-2
-4
-6
km
e
25 km

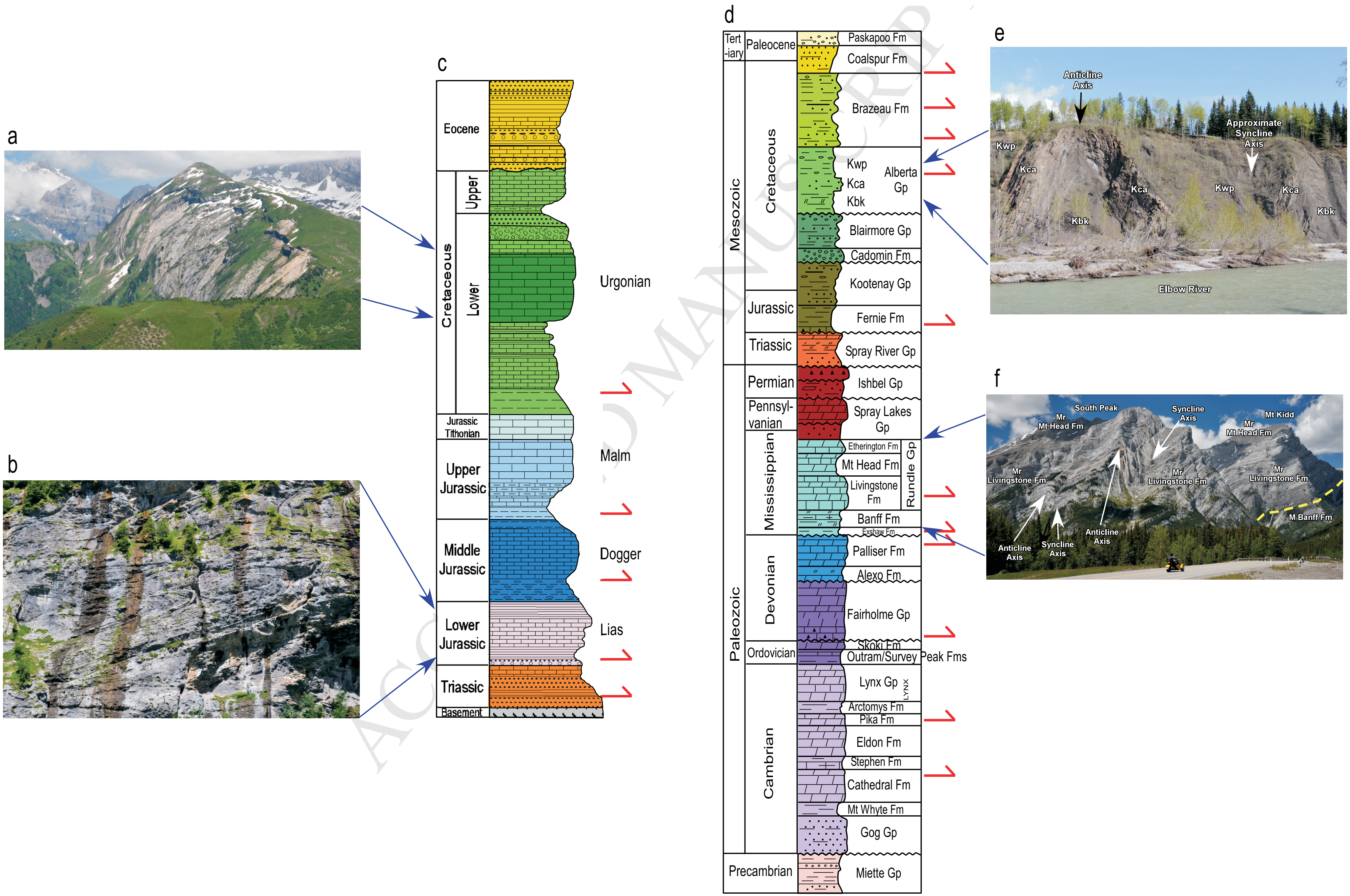

NE
1389m
1953m
1325m
1653m
ENE
1692m
SE
1613m
1034m
Urgonian
Lower Cretaceous
shales
Tithonian
limestone
Upper Jurassic
shales
Tithonian limestone
523m
a)
NNE
NE
1136m
1209m
285m
b)
Brizon well
F
sea level
expected
vertical
thicknesses
Lwr Cret
Urgonian
Tithonian
Up Jur
Mid Jur
Lwr Jur
1 km
c)

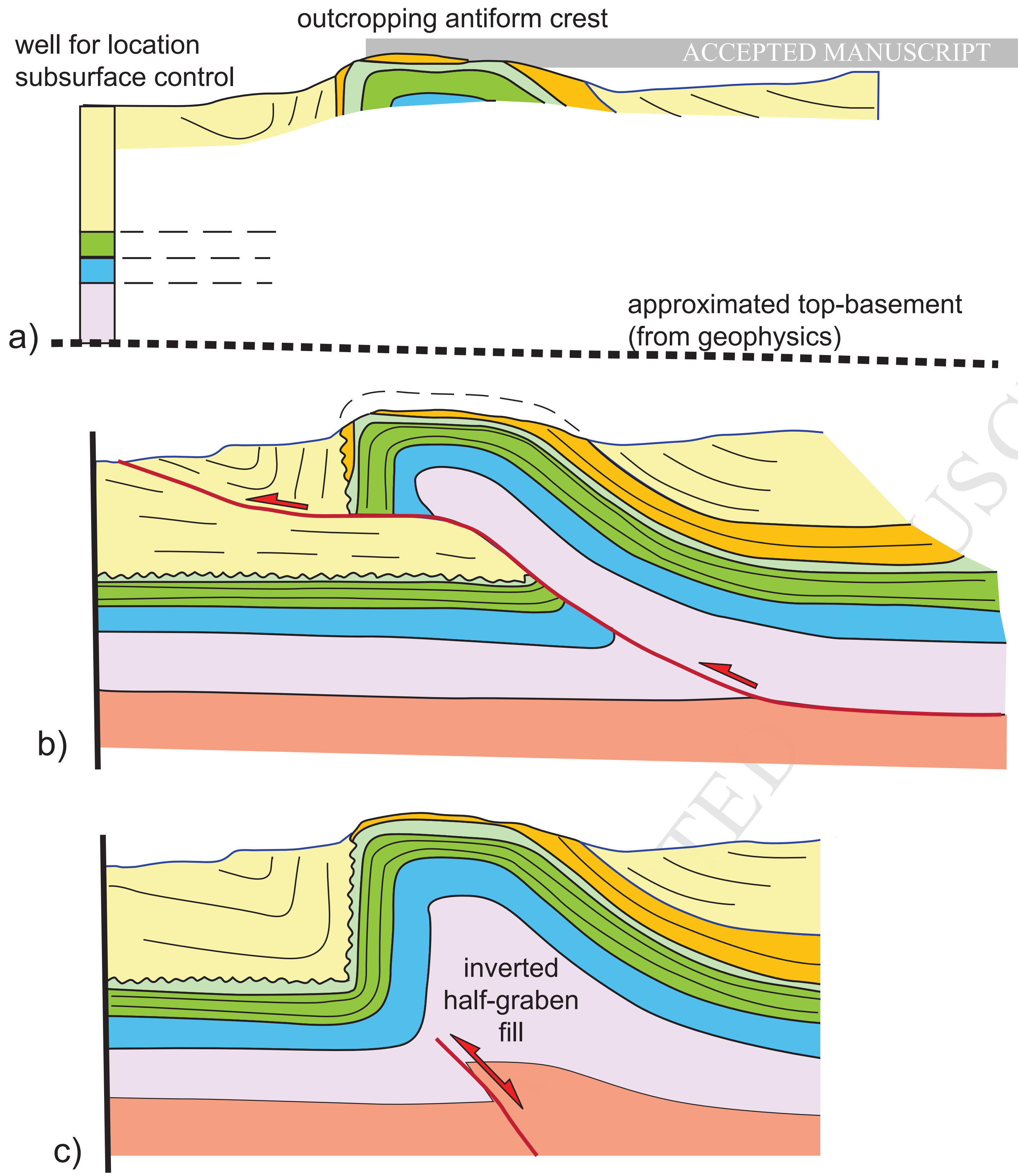

a
NW
SE
Bargy-Cluses
Anticline
Cluses
Balme
Les Carroz
Flaine
Aig. de Varan
Passy
Arpenaz
3000m
2000m
1000m
Valley Floor
0m
-1000m

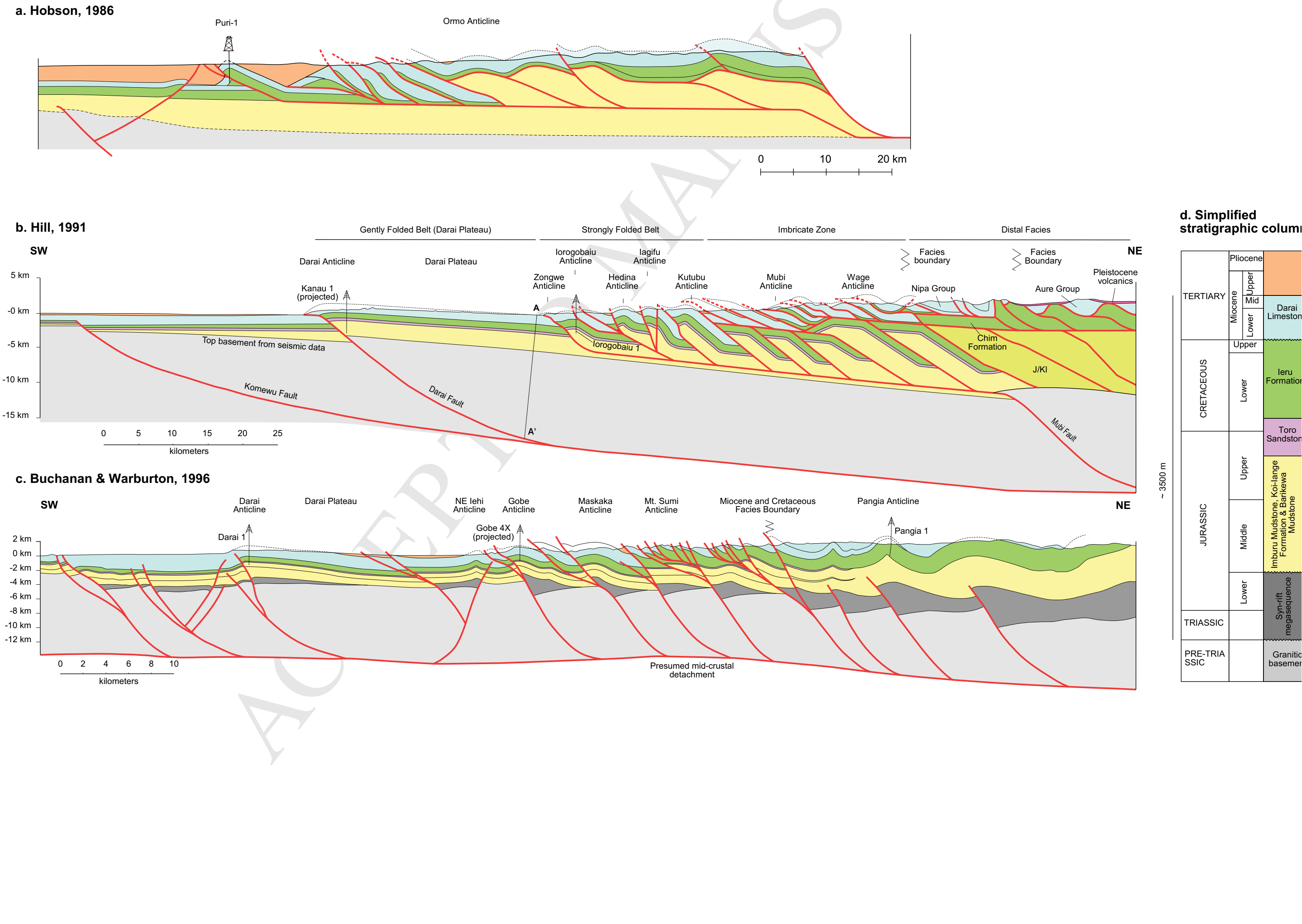

b
Audey
Anticline
Brizon
Roches de
Lechaux
Bargy-Cluses
Anticline
Pointe d'Areu
projected
Arly
Valley
Thick Lwr
Cret
Thick
Jurassic
Thickened and
thick Jurassic
Downward facing detachment
Belledonne
Massif
Thin Lwr Cretaceous and Jurassic
ca. 15km displacement
out into the Jura
3000m
2000m
1000m
0m
-1000m
-2000m
-3000m
-4000m
5000m

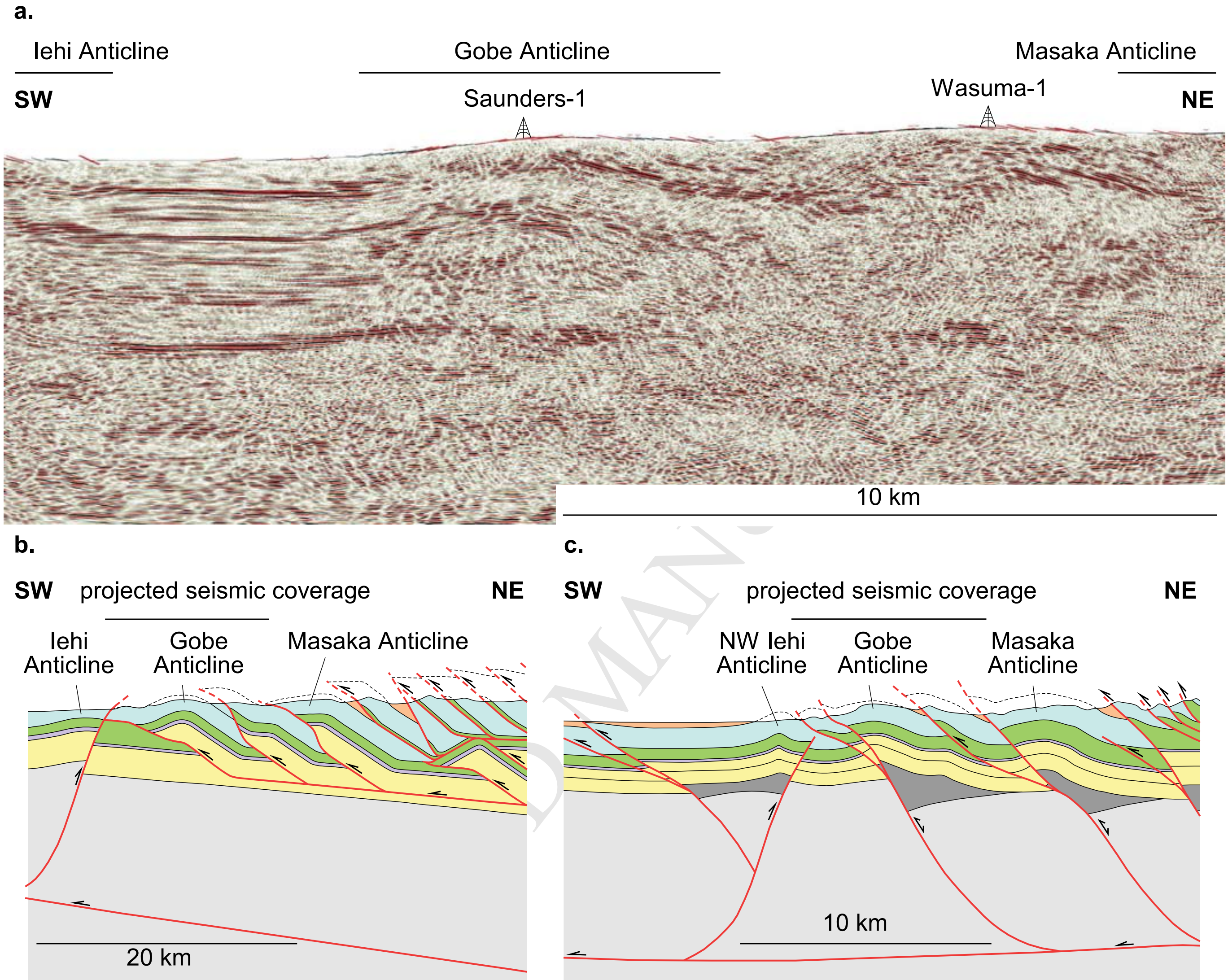


1042m
1057m
Les Carroz
Urgonian
Eocene
Y
Up Cretaceous
Urgonian
Lwr Cret
X
Bargy-Cluses anticline
Lower Cretaceous
a)
490m
Eocene
Upper Cretaceous
Urgonian
Lower Cretaceous
b)
500 m
fold-thrust localizes
at old normal fault
NW
SE
Y
further thrusting and
reactivation
c)
X


a
b
c
Eocene
Cretaceous
Upper
Lower
Jurassic Tithonian
Upper Jurassic
Middle Jurassic
Lower Jurassic
Triassic
Basement
Urgonian
Malm
Dogger
Lias
d
Tert -iary
Paleocene
Mesozoic
Cretaceous
Jurassic
Triassic
Paleozoic
Permian
Pennsyl-vanian
Mississippian
Devonian
Ordovician
Cambrian
Precambrian
Paskapoo Fm
Coalspur Fm
Brazeau Fm
Kwp
Kca
Kbk
Alberta Gp
Blairmore Gp
Cadomin Fm
Kootenay Gp
Fernie Fm
Spray River Gp
Ishbel Gp
Spray Lakes Gp
Etherington Fm
Mt Head Fm
Livingstone Fm
Rundle Gp
Banff Fm
Exshaw Fm
Palliser Fm
Alexo Fm
Fairholme Gp
Skoki Fm
Outram/Survey Peak Fms
Lynx Gp
LYNX
Arctomys Fm
Pika Fm
Eldon Fm
Stephen Fm
Cathedral Fm
Mt Whyte Fm
Gog Gp
Miette Gp
e
Anticline Axis
Approximate Syncline Axis
Kwp
Kca
Kbk
Elbow River
f
South Peak
Syncline Axis
Mt Kidd
Mr Mt Head Fm
Mr Livingstone Fm
M Banff Fm
Anticline Axis
Syncline Axis


outcropping antiform crest
well for location
subsurface control
a)
approximated top-basement
(from geophysics)
b)
c)
inverted
half-graben
fill


a. Hobson, 1986
Puri-1
Ormo Anticline
0
10
20 km
b. Hill, 1991
SW
NE
Gently Folded Belt (Darai Plateau)
Strongly Folded Belt
Imbricate Zone
Distal Facies
Darai Anticline
Darai Plateau
Iorogobaiu Anticline
Iagifu Anticline
Facies boundary
Facies Boundary
Kanau 1 (projected)
Zongwe Anticline
Hedina Anticline
Kutubu Anticline
Mubi Anticline
Wage Anticline
Nipa Group
Aure Group
Pleistocene volcanics
5 km
-0 km
-5 km
-10 km
-15 km
A
A'
Top basement from seismic data
Iorogobaiu 1
Chim Formation
J/Kl
Komewu Fault
Darai Fault
Mubi Fault
0
5
10
15
20
25
kilometers
c. Buchanan & Warburton, 1996
SW
NE
Darai Anticline
Darai Plateau
NE Iehi Anticline
Gobe Anticline
Maskaka Anticline
Mt. Sumi Anticline
Miocene and Cretaceous Facies Boundary
Pangia Anticline
Darai 1
Gobe 4X (projected)
Pangia 1
2 km
0 km
-2 km
-4 km
-6 km
-8 km
-10 km
-12 km
0
2
4
6
8
10
kilometers
Presumed mid-crustal detachment
d. Simplified stratigraphic column
TERTIARY
Pliocene
Miocene
Upper
Mid
Lower
Darai Limestone
CRETACEOUS
Upper
Lower
Ieru Formation
Toro Sandstone
JURASSIC
Upper
Middle
Lower
Imburu Mudstone, Koi-Iange Formation & Barikewa Mudstone
Syn-rift megasequence
TRIASSIC
PRE-TRIASSIC
Granitic basement
~ 3500 m


a.
Iehi Anticline
Gobe Anticline
Masaka Anticline
SW
Saunders-1
Wasuma-1
NE
10 km
b.
SW
projected seismic coverage
NE
Iehi Anticline
Gobe Anticline
Masaka Anticline
20 km
c.
SW
projected seismic coverage
NE
NW Iehi Anticline
Gobe Anticline
Masaka Anticline
10 km

Highlights

A range of natural and interpreted fold-thrust structures are presented.

Changes in structural style are related to pre-existing stratigraphic variations.

2D seismic data can be insufficient to choose between structural interpretations.

Idealized fold-thrust models do not adequately represent natural structures.

Uncritically adopting idealized models can bias subsurface interpretation.